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DARPA TECHNICAL ACCOMPLISHMENTS
VOLUME II

AN HISTORICAL REVIEW OF SELECTED DARPA PROJECTS

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This is the second of three volumes on the history of DARPA accomplishments and their implications. The first two volumes include histories of selected DARPA projects. The purpose of these histories is to record, for projects and programs having important outputs and for which adequate and appropriate data could be gathered, the chronological and technical histories in such a way that (a) the influence of the projects or programs on defense and civilian technology could be traced, and (b) implementation lessons could be extracted that would help DARPA manage future programs in such a way as to enhance their chances of success. This volume describes program histories of 21 DARPA projects. Each history describes the genesis of the project or program and the major participants and events in its lifetime. Each project review ends with observations about the project's success and the nature of its impact. Volume II, along with Volume I, comprises the source material for Volume III, which analyzes the projects in the broader context of DARPA's history and the influences of the external environment on the agency.

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INTRODUCTION TO VOLUME II

This is the second of three volumes on the history of DARPA accomplishments and their implications. The first two volumes include histories of selected DARPA projects: they are the source material for Volume III, which will analyze these projects in the broader context of DARPA's history and the influences of the external environment on the agency. Volume III distills lessons learned as a help toward guiding future strategic planning and project management by DARPA. To obtain an adequate picture of the scope and nature of DARPA accomplishments and their impacts, therefore, it will be necessary for the reader to peruse both Volumes I and II. For an analysis of the implications of DARPA's accomplishments for management, Volume III should be read.

At the outset a single volume was planned. However, in response to a direct request from Dr. C. Fields, then DARPA director, Volume I was produced on a shortened time scale, and Volume II was begun. Subsequent discussions with Dr. Reis, the current director, led to new guidance, mainly a new emphasis on an overall analysis, which led to Volume III and the elimination of some topics in the original list of contents for Volume II. Consequently, the new list of topics included in Volume II differs from that stated in Volume I. However, the general criteria for selection and addition of topics remained the same as outlined in the introduction to Volume I, which should also be read in conjunction with Volume II. The programmatic groupings of topics are also nearly the same as in Volume I.

In both Volumes I and II there are topics that belong to early programs such as DEFENDER (the Anti-Ballistic Missile program) and to Tactical Technology (which began to be identified as such after the Vietnam War). Volume II also contains several topics in the materials area--an area that had origins in the earliest days of ARPA, took somewhat its present form in the mid-1970s, and is ongoing today.

Several researchers made significant contributions to Volume II in addition to the main authors. Their names and the chapters to which they contributed are: P. Albright (TEAL RUBY, Chapter IX), Earl Alluisi (SIMNET, Chapter XVI), David Bushnell (Ada, Chapter XV), Erland Heginbotham (VLSI, Chapter XVII and XVIII), A. Hull and David Markov (Armor-Antiarmor, Chapter VIII), Robert Knapper (Interactive Graphics, Chapter

XIII), David Markov and Stephen Wooley (Image Understanding, Chapter XIV) and Stephen Wooley, (X-29, Chapter XI and GaAs, Chapter XIX). Despite the multiple authorship, every effort was made in the individual chapters to retain the textual format set in Volume I.

In general, the topics in Volume II are of more recent vintage than those in Volume I. As such, their history and, even more, their impact have been only partly developed. It was realized that it would be more difficult to determine the real history of these more recent projects, for which available information may often be expected to reflect current arguments, program justifications, and personal feelings. Volume I with its older topics was simply easier to do than Volume II. Some of the topics in the original list for Volume II have been eliminated for this reason. Also, a few of the missing topics have been associated with projects which are now highly classified; in these cases it proved impossible to write a meaningful account, satisfying our criteria, in an unclassified document.

In the materials area in particular there are fewer topics than planned and different topics from those in the original materials list for Volume II. These changes reflect two factors. First, to track specific impacts in the materials area proved quite complex. The development of materials seems in many, if not most, cases to be like a skein with many weavers. Partly because of an early appreciation of this difficulty, tackling the materials area was put off to Volume II. The reality, however, proved more difficult than the expectation. Second, the materials list changes are symptomatic of the fact that in general the entire project has been, in a sense, experimental: we did not know, at the outset, to what extent it would be possible to determine and express the roles and impacts of DARPA; it was a process of learning by doing the necessary investigating, which proved to be close to sleuthing in many cases.

DARPA's real role and impact were particularly hard to discern and unravel in the materials area. This was disappointing because it was generally recognized DARPA has had a particularly broad and deep impact in the materials area: the performance of almost all military systems is limited by materials characteristics. To include and emphasize materials was also felt to be important to convey a properly balanced perspective on DARPA programs. Materials efforts have interacted strongly with other DARPA programs such as lasers, strategic and tactical technology, and information sciences. We regret that to delineate the *specific* impact of DARPA's role in these areas did not prove feasible in this effort for more than a few cases. The two new materials topics added, IDLs and

Retirement for Cause, seemed to be exceptional cases for which the DARPA role was very important, the impact large, and ready documentation was available.

Finally, as mentioned above, the textual format of the topical writeups has been largely retained in Volume II, but a few of the time-track diagrams are missing. This was due in part to the feeling that in cases in which impacts are still developing, such time tracks could present a misleading picture.

DEFENDER ANTI-BALLISTIC MISSILE

I. PRESS

A. BRIEF OVERVIEW

Project PRESS (Pacific Range Electromagnetic Systems Studies) was the major field measurement element of ARPA's research on phenomenology of the reentry into the earth's atmosphere of inter-continental ballistic missiles (ICBMs) under its DEFENDER program. The largest part of DEFENDER, which was transferred to the Army in 1967, PRESS and the Army's follow-on Kiernan Reentry Measurements Systems (KREMS) facilities and measurements have played a key role in assuring credibility of the U.S. ICBM offensive deterrent and in U.S. decisions about Ballistic Missile Defense (BMD) R&D and system deployment. The TRADEX, ALTAIR, and ALCOR radar systems resulting from PRESS are in use today by KREMS at the Army's Kwajalein Test Site where they support R&D for Air Force penetration systems and Army and Strategic Defense Initiative (SDI) BMD efforts. These systems are also in operational use by the Air Force in SPADATS and for Space Objects Identification (SOI) work. Airborne optical and IR measurements, originated under PRESS and continued under DARPA Strategic Technology Office (STO) sponsorship, have contributed to the design of sensors for midcourse terminal homing intercept systems under SDI.

B. TECHNICAL HISTORY

1. Background

In the late 1950s a number of U.S. government actions resulted from a sharply growing appreciation of the Soviet ICBM potential, fueled by the Soviet's test of a ballistic missile of intercontinental range and their successful launching of SPUTNIK. There was an acceleration of efforts on the defensive side with the NIKE-ZEUS BMD system then being carried on by Bell Telephone Laboratories (BTL) under Army sponsorship (then a top DoD priority) and also with the Air Force's long range WIZARD radar, space based ABM (Anti Ballistic Missile) projects, and MIDAS early warning satellite effort. On the offensive side--the prime basis of U.S. deterrent to date--Air Force efforts toward an operational ICBM system were speeded up. There were several high-level studies of the technical aspects of the ICBM problem which emphasized particularly the need for better understanding of ICBM reentry phenomena in order to enable the defense to discriminate between decoy debris and reentry vehicles containing warheads. These studies also addressed countermeasures which could assure penetration of U.S. offensive missiles through Soviet BMD systems that were then believed to be under development.[1]

A key related action of the Eisenhower administration was the establishment of ARPA. To get the United States going in space in a reasonable way without Service-related bias (the Army and the Air Force were in strong competition for missions in space) was, chronologically, ARPA's first assignment. The second major assignment, with the same flavor of helping the president deal with inter-Service rivalry,[2] was DEFENDER, oriented toward advanced approaches to BMD. While this DEFENDER assignment was second chronologically, the earliest ARPA Congressional hearings indicate it was first in priority.[3] The DEFENDER assignment was to:[4]

> ....undertake research, experimentation, development and long term feasibility demonstrations to obtain technologically advanced defense against extra-atmospheric offensive vehicles, including space vehicles and ballistic missiles. It is intended that this project be pointed toward the exploitation of fundamental phenomena; the development of new systems concepts; and the applications of new techniques as opposed to development and refinement of authorized defense systems which will be the responsibility of the military departments.

NIKE ZEUS was, at the time, such a major authorized defensive system with development started by the Army, but responsibility for it was given also to ARPA. However, NIKE ZEUS was quickly evaluated by Roy Johnson, the first ARPA director, as too close to a procurement decision to fit ARPA's assignment. One of the first ARPA actions was to return the responsibility for NIKE ZEUS to the Army,[5] and to concentrate

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[1] High-level studies of the feasibility of what were eventually called "penetration aids" included those conducted under the Gaither Committee (in 1957) and, a little later, by the DoD Reentry Body Identification Group and by a special panel of PSAC. Many of the same people participated in all these studies, which were chaired by W. Bradley, who later joined and IDA's ARPA Support Group. "The ABM Debate," by E.R. Jayne, MIT thesis, 1969, p. 452, and H. York, "Multiple Warhead Missiles," in *Scientific American*, Vol. 29, Nov. 1973, p. 2004. Earlier Service studies went back to the early 1950s.

[2] According to Gen. Goodpaster, Special Assistant to President Eisenhower, this was the president's primary motif in establishing ARPA. Discussion with Gen. Goodpaster, 4/88.

[3] Hearings before Defense Subcommittee on Defense Appropriations, for 1959 85th Congress, 2nd session, statement of R. Johnson, p. 292.

[4] DoD directive 5129.33, Dec. 30, 1959.

[5] R. Johnson, op. cit., pp. 320 and 338. ARPA was also given the Air Force's 117L Satellite Program, which it returned, modified, to the Air Force. The Air Force and Navy ballistic missile efforts, less controversial, were not given to ARPA.

its efforts on the more fundamental unknowns and advanced approaches mentioned in its assignment.

Another related ARPA assignment, mentioned in the same DoD directive, was to investigate advanced technologies for "penetration aids" for ICBM warheads. The Air Force had already begun some effort in this direction.[6] It was recognized early-on that the same type of measurements of reentry phenomenology were essential to the penetration aids programs as for BMD programs.

An outline of specific directions for project DEFENDER was provided by previous studies, notably by the Bradley PSAC and RBIG (Reentry Body Identification Group) panels. The ARPA DEFENDER effort, guided in part by these studies, encompassed a very wide range of technologies underlying early warning, long range and terminal BMD approaches and penetration aids, including phased array and over-the horizon radars, high power electronic tubes, long range BMD and ASAT systems, nuclear effects and non-nuclear hypervelocity impact systems for destruction of reentry vehicles (RVs), lasers, and charged particle beams as directed-energy weapons, infrared emissions from rocket plumes and reentry, and a new ionospheric probe (ARECIBO) with a 1,000-foot antenna. The Bradley studies had emphasized the complexity of the BMD problem, and pointed out that there were many unknowns in the reentry phenomenology, which might or might not be critical for BMD system design. Among these were not only the phenomena associated with the hypersonic reentry of RVs into the normal atmosphere, but also the effects of nuclear explosions which were expected to be frequent in the reentry scenarios then discussed.[7] In response, many of the earliest ARPA orders under project DEFENDER were concerned with the nuclear effects areas,[8] and included extensive programs in relevant atomic and molecular physics, and in the physics, chemistry and hypersonic aerodynamics of reentry. These ARPA activities built on the previous and ongoing related DoD and Atomic Energy Commission (AEC) work.[9] Field measurements were understood to be of major importance and were undertaken by ARPA with a wide range of active and passive sensors, using and expanding available Service and NASA facilities at Wallops Island, the Army White Sands Missile Range (WSMR), and the Atlantic Missile Range (AMR). Some

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[6] H. York, *Does Strategic Defense Breed Offense*, Harvard University Press, 1986, p. 13.

[7] ARPA funded some of the field experiments in the Pacific nuclear tests in 1958 and 1962.

[8] A.O.'s 5 of 4/58, and 6 of 6/58, included many efforts following up on the Bradley recommendations in such scenarios. Cf. also Richard J. Barber Associates, *History of the Advanced Research Projects Agency*, 1958-1975, NTIS 1975, p. III-55.

[9] Some work in these areas had been going on since the mid-1950s.

significant extensions of these field capabilities were also made by ARPA, notably in the outfitting of the DAMP (Down Range Anti-Ballistic Measurement Program) ship.[10] (See Figure 1-1.)

ARPA became the strongest player in the field measurement game, not only to carry out its responsibility under the DEFENDER directive, but also because the White House wanted an "honest broker" between the Air Force, with its rapidly developing, primarily offensive ICBM orientation, and the Army with its defensive ABM effort. Besides, there was an urgent demand for more reentry data, especially field data, by all involved, and ARPA could move quickly to obtain it [11]

There was an early appreciation by ARPA's leadership of the difficulties of integrating a very complex measurements effort when it would all get underway, especially the experimental field work which would include measurements on the Atlantic test range, on land, and some on the DAMP ship.[12] Accordingly, one of the earliest actions of ARPA's top staff was to approach MIT's Lincoln Laboratory as to whether they could undertake a major responsibility to pull together the national effort.[13] However, Lincoln did not choose to take on such a major responsibility at this time. It did "leave the door open" and agreed to increase their field measurements effort, together with an expansion of laboratory and theoretical efforts on hypersonic phenomena, and an increased effort on data processing specifically requested by ARPA in anticipation that this would eventually become a major problem area for BMD. Lincoln also lent one of their key reentry scientists to ARPA/IDA, which is discussed at length below. Lincoln had already been involved with NASA and the Air Force in setting up a suite of sensors (both radar and optical) at the NASA Wallops Island test facility, where tests of rockets and reentry vehicles were going

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[10] DAMP, RCA brochure (UNCLASSIFIED) 1960. By 1961 DAMP included a data measurement analysis laboratory at Moorestown, N.J. Early funding was provided by A.O.'s 51 of 12/58 and 127 of 1/60; also discussion with A. Rubenstein, IDA 12/87.

[11] ARPA BMD Technology Program Review, IDA-ARPA TR 59-8, Aug. 1959 (declassified), p. 13.

[12] A review of radar measurements and facilities to August 1960 was given by R. Leadabrand of SRI and of IR and Optical Measurements by M. Nagel of AFCRL, in an ARPA review of project DEFENDER for the DDR&E, Aug. 1960 (declassified).

[13] Richard J. Barber Associates, op. cit., p. III-55. This first approach to Lincoln was apparently made in May 1958. Earlier, Lincoln had finished R&D for design of the BMEWS radar system for the Air Force and did not yet have another major project to replace it.

USAS AMERICAN MARINER

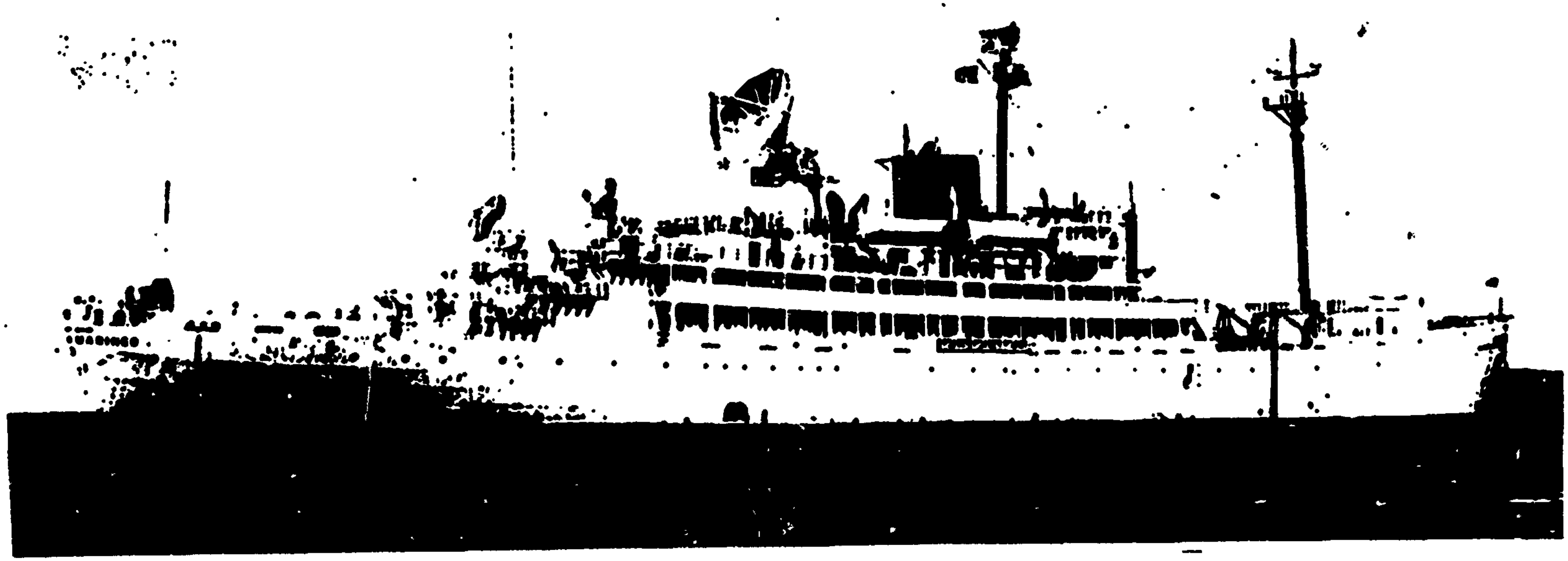

Figure 1-1. DAMP Ship, USAS American Mariner

on, and making distant observations of these objects with its MILLSTONE HILL radar.[14] This early Lincoln effort had a remarkably "unfettered" charter for its research.

ARPA's field measurements program continued for more than a year after Lincoln's turn-down, under direction of the DEFENDER IDA/ARPA group. In particular, ARPA proceeded to quickly develop and exploit the DAMP ship which had the important features of positional mobility with respect to the trajectories of reentry vehicles, and because optical, microwave radiometric, and IR measurements could be all made from the same stabilized platform on the ship.[15] A similar effort was made to use aircraft for optical and infrared observations, some of which had been outfitted previously. Some of these aircraft were "drafted" to make the first U.S. observations of reentry events provided by Soviet ICBM tests in 1960. The first ARPA measurements of U.S. ICBM reentry events were made by DAMP on the AMR in 1961. DAMP made valuable measurements also during the FISHBOWL nuclear test series in 1962, but was terminated in 1963.

In the late 1950s ARPA also made arrangements with the United Kingdom to make measurements associated with tests of their BLACK KNIGHT ICBM at the Australian Woomera Test Range.[16] Particular interest attached to the advanced "low observable" RV designed for this missile by the U.K.'s Royal Radar Establishment.

A particularly important feature of this early DEFENDER work was that ARPA soon came to regard it as a program of scientific measurement and analysis. To this end ARPA set up several mechanisms for data archiving and organized scientific exchange on topics of importance. One of these was a series of regular AMRAC (Anti-Missile Research Advisory Committee) Symposia held biennially until 1969 through an ARPA contract with the University of Michigan, at which scientific discussions of the results of all relevant work could take place. The BAMIRAC project, also at the University of Michigan, provided for archiving missile phenomenology data and modeling, initially encompassing all aspects from launch to reentry; later, BAMIRAC specialized more in IR phenomenology. The scientific archives of AMRAC and BAMIRAC have been invaluable also for the BMD efforts carried on after DEFENDER by the Services and SDI.[17] Later, in

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[14] J.S. Shortal, *A New Dimension: Wallops Island Test Range, the First 15 Years*, NASA Reference, publication 1028, Dec. 1978, p. 538; and discussion with L. Sullivan, Lincoln Labs, 12/89.

[15] A. Rubenstein, discussion op. cit. Earlier shipboard observations had been made by the Army's Operation GASLIGHT, cf., "Missiles & Rockets," July 14, 1958, p. 14.

[16] E.g., A.O. 114 of 11/59.

[17] A.O. 236 of 6/61 provided explicitly for BAMIRAC. Earlier related efforts and the AMRAC meetings had been funded by ARPA in 1959 under A.O.'s 6 and 30.

1963, Dr. C. Herzfeld, then DEFENDER project director, started the *Journal of Missile Defense Research* (JMDR) which became in 1968 the present *Journal of Defense Research* as a medium for classified scientific communication in the area, with a degree of quality control by "peer review."

In roughly the same time frame, the Bell Telephone Laboratories (BTL) had constructed NIKE ZEUS radars at WSMR and also a NIKE-ZEUS target-track radar facility at Ascension Island, near the region of reentry of ICBMs being tested at the AMR, and beginning in 1961 had subcontractors (AVCO and Cornell Aero labs) making related optical and infrared observations in aircraft.[18] These field efforts were supplemented by laboratory and theoretical work. Together with the DAMP and other available data, these early BTL observations were used in attempts to find some single discriminants or combination of such, to identify and track reentry vehicles (RVs) among missile tankage, debris, and decoys. The first discriminants investigated included aerodynamic deceleration in the atmosphere, and the associated doppler and scintillation characteristics of radar returns at different frequencies, polarizations and pulse formats, and emissions in the optical, infrared, and microwave spectral regions. Extensive discussions of such BMD discriminants are chronicled in the early AMRAC processing and issues of JMDR.[19]

The HARDTACK series of nuclear explosions in the fall of 1958 included the TEAK and ORANGE high altitude events, which were aimed in part at measuring the attenuation of electromagnetic waves in the large affected atmospheric volumes, important for selection of radar frequencies of BMD systems which were expected to operate in such environments.[20] Such measurements were made during TEAK and ORANGE under ARPA auspices and also by the BTL NIKE ZEUS group. The results, together with those from later experiments in the FISHBOWL series in 1962, and an appreciation of the difficulty and cost of constructing radars at different frequencies, developed partly by the ongoing ARPA efforts on high power sources, had a major eventual impact on the design of the reentry measurement radars in DAMP and elsewhere, and on the NIKE X and later BMD systems.[21]

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[18] *ABM Project History*, Bell Telephone Laboratories, Oct. 1975, pp. I-32, I-46, and I-50.

[19] Part of the original ARPA motif was to help "backfit," if possible, improvements into NIKE ZEUS, cf. testimony of H. York in DoD Appropriations Hearing for FY1959, House of Representatives, 85th Congress, 2nd Session, p. 257.

[20] BTL states, however, that nuclear effects were not considered in the design of NIKE ZEUS, not having been specified by the Army. BTL, op. cit., p. I-19.

[21] An ARPA-supported comprehensive study of "blackout" by IDA in 1965, using this data, decisively affected the choice of frequencies of NIKE X. See, e.g., BTL *History*, op. cit., p. I-44.

Lincoln Laboratory, with a strong background from their earlier BMEWS and MILLSTONE HILL radar design experience, had participated in the design of the radars on the DAMP ship which were built by RCA. In 1958, shortly after ARPA's beginning, Lincoln "lent" Dr. G. Pippert to the IDA/ARPA division.[22] One of Dr. Pippert's first activities was to discuss with RCA (which had built several precision range tracking radars, including those used on the DAMP ship and the BMEWS radars) a concept for a large ground-based radar for accurate ICBM tracking and measurements, featuring coherent operation and ability to generate a variety of pulse trains. The need for such a ground-based precision tracking radar, to make accurate measurements of trajectories and in order to guide other sensors, had been underlined by experience on the AMR.[23] The flexibility provided by the different pulse trains together with the coherence, was also expected to allow measurements of the ionized hypersonic RV wake structure, as well as of the RV bodies' scattering characteristics. RCA quickly developed a proposal for this radar, eventually called TRADEX (tracking and detection experiment radar) which was accepted by ARPA.[24] TRADEX was mechanically steered, but its signal formats gave it high range resolution for accurate tracking as well as measurement. It was first planned to operate at UHF. Work soon began on the radar, apparently before the final decision had been made as to where it would be located.

In 1958-9, partly because of advantages for polar orbits for satellite launches, the Air Force constructed its main ICBM launch complex at Cooke AFB, later named Vandenberg AFB.[25] In the same time period the Army selected Kwajalein atoll in the Pacific as a test site for its NIKE ZEUS system. To provide RVs for test of NIKE ZEUS, the Army proposed to launch its JUPITER Intermediate Range Ballistic Missiles (IRBMs) from Johnson Island, with rockets to augment downward reentry velocity (as had been done at Wallops) to simulate ICBM reentry. It was expected by DoD planners that the Air Force would soon launch ICBMs into the Pacific Missile Range from Vandenberg, which could provide realistic RVs for test of NIKE ZEUS. Because of "inter-Service rivalry," magnified by the arguments between the Strategic Offense (AF) and Defense (Army), there may have been some Air Force reluctance to allow its RVs to be used for NIKE ZEUS

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[22] "KREMS, The History of the Kiernan Reentry Measurements Site," by M.D. Holtcamp, U.S. Army BMDSC, Huntsville, 1980, p. 18. The "loan" was typical for the ARPA's IDA support staff at the time.

[23] A. Grobecker, ARPA , 1959, BMD Technology Program Review, op. cit., p. 99.

[24] A.O. 49 of 12/58, TRADEX ($38.5 million).

[25] *SAMSO Chronology, 1954-79, Air Force Systems Command Space Division*, Chief of Staff, History Office, 1980, pp 52 and 59.

tests, and on the other hand the Army preferred an "organic" operation under its control.[26] In any case, the DoD plans, which were in line with Pres. Eisenhower's desire to keep the Army out of the missile launch picture, prevailed. Dr. H. York, the first DDR&E, ruled in early 1960, when he found out about the situation, that only real ICBM RVs would be shot into the Kwajalein area.[27]

2. Project PRESS

ARPA recognized the difficulties of doing accurate measurements on the AMR, and the opportunity and great economy involved in using the same reentry events as would NIKE ZEUS in a location for which logistics and other arrangements were being made by the Army, as well as the advantage of being able to interact closely with the NIKE ZEUS observations being made by the system being built by BTL at Kwajalein. Consequently, in Fall 1959, ARPA set up project PRESS with its major facilities to be located in the reentry area, on Roi Namur, another island in the Kwajalein atoll chain.[28] The original plans for the PRESS facilities included the PINCUSHION experimental radar, another ARPA-funded project, and TRADEX.[29]

Through the persistent efforts of Dr. J. Ruina, then Assistant DDR&E, Lincoln Laboratory accepted a coordinating role for the entire national reentry measurements efforts, as well as technical supervision and coordination of all military efforts on penetration aids, target identification and reentry physics, as well as technical direction of project PRESS.[30] Preliminary to this, Lincoln had apparently reviewed an ARPA study of the PRESS role in the overall reentry measurements problem, and in response recommended that a single organization be in charge. It was envisioned in this study that PRESS would involve TRADEX and possibly other radars later, together with various ground and air based optical and IR sensors. The PRESS radar facilities were planned to

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[26] G. Kistiakowsky, *A Scientist at the White House*, Harvard 1977, p. 319, 323, and 327.

[27] H. York, *Making Weapons, Talking Peace*, Basic Books, 1987, p. 177-8. Somewhat later, however, some (Air Force) IRBM shots from Johnson did occur in the Kwajalein area.

[28] Unsuccessful attempts were made to locate PRESS facilities in the island of Kwajalein itself. AO 110 of 10/59, Project Press Roi Namur Facility, also AO 121 of 12/59.

[29] Apparently there was also a delay of about 1 year between the decision to go ahead with TRADEX and the decision of its frequency band. The first recommendation for TRADEX, Nov. 1958, was for UHF, despite the nuclear effects data from HARDTACK, which showed significant absorption at UHF. L-band was eventually added to UHF for the first version of TRADEX. A. Grobecker, IDA TE 184, Oct. 1959 (CLASSIFIED).

[30] E. Michael Papa, *Historical Chronology of the Electronics System Division (ESD), 1947-86* History Office, Air Force ESD, Hanscom AFB, Bedford, MA, Oct. 1987, p. 6.

be all under computer control, and to have extraordinary data reading capabilities.[31] This preliminary Lincoln review also recommended against going further with PINCUSHION because of anticipated technical difficulties with its new design and with the high-power S-band transmitters required.[32]

Construction of TRADEX and associated PRESS facilities began at Roi-Namur in early 1961.[33] TRADEX incorporated a new high-power L-band transmitter tube developed under ARPA sponsorship. In April 1962, TRADEX began operations by RCA, and shortly afterwards Lincoln personnel arrived to take over. In June of that year, TRADEX successfully tracked the first Air Force ICBM reentry event at Kwajalein, along with the NIKE ZEUS radars. In July 1962 the first successful NIKE ZEUS intercept of an ICBM occurred at Kwajalein. TRADEX (see Figure 1-2) was the first and only dedicated measurements radar at Kwajalein till 1968, and after many successive upgrades, remains in use to date.[34]

Between 1960 and 1962, apparently, the level of activity at Lincoln associated with PRESS was not high.[35]. Shortly after Lincoln staff arrived at Roi-Namur, ICBMs began to arrive and much data began to be gathered on reentry phenomena. The PRESS capabilities at Roi Namur were soon augmented to include an optical telescope and a Baker-Nunn open slit spectrograph, similar to those that had been used at Wallops Island, and the WSMR, and also other optical and infrared systems. Optical and IR instruments on existing aircraft were also improved, and another aircraft was specially outfitted for PRESS.[36] Data analysis done initially at Roi Namur was found to be difficult to manage there because of the time required and complexity of preparing for the frequent reentry events. As a result, data packages were soon air mailed back to Lincoln for analysis.

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[31] Computer control has taken place gradually, cf. Holtcamp, op. cit., p. 72, and discussion with Gen. K. Cooper (Ret.), 6/90.

[32] Also, there was dissatisfaction in ARPA with the rate of progress on PINCUSHION. Discussion with A. Rubenstein, 5/90.

[33] Holtcamp, op. cit., p. 32.

[34] TRADEX current specifications are given in K. Roth, et al., "The Kiernan Reentry Measurements System at Kwajalein AFB," *Lincoln Laboratory Journal*, Summer 1989, Vol. 2, No. 2, p. 255.

[35] Discussion with Dr. M. Balser, 9/89. Lincoln work related on reentry physics, however, was substantial at the time. Cf., e.g., C. McLain, "A Study on General Recommendations for Experimental Field Measurements," Project DEFENDER, May 1961 (UNCLASSIFIED).

[36] A.O. 127 of 1/60, "PRESS Aircraft."

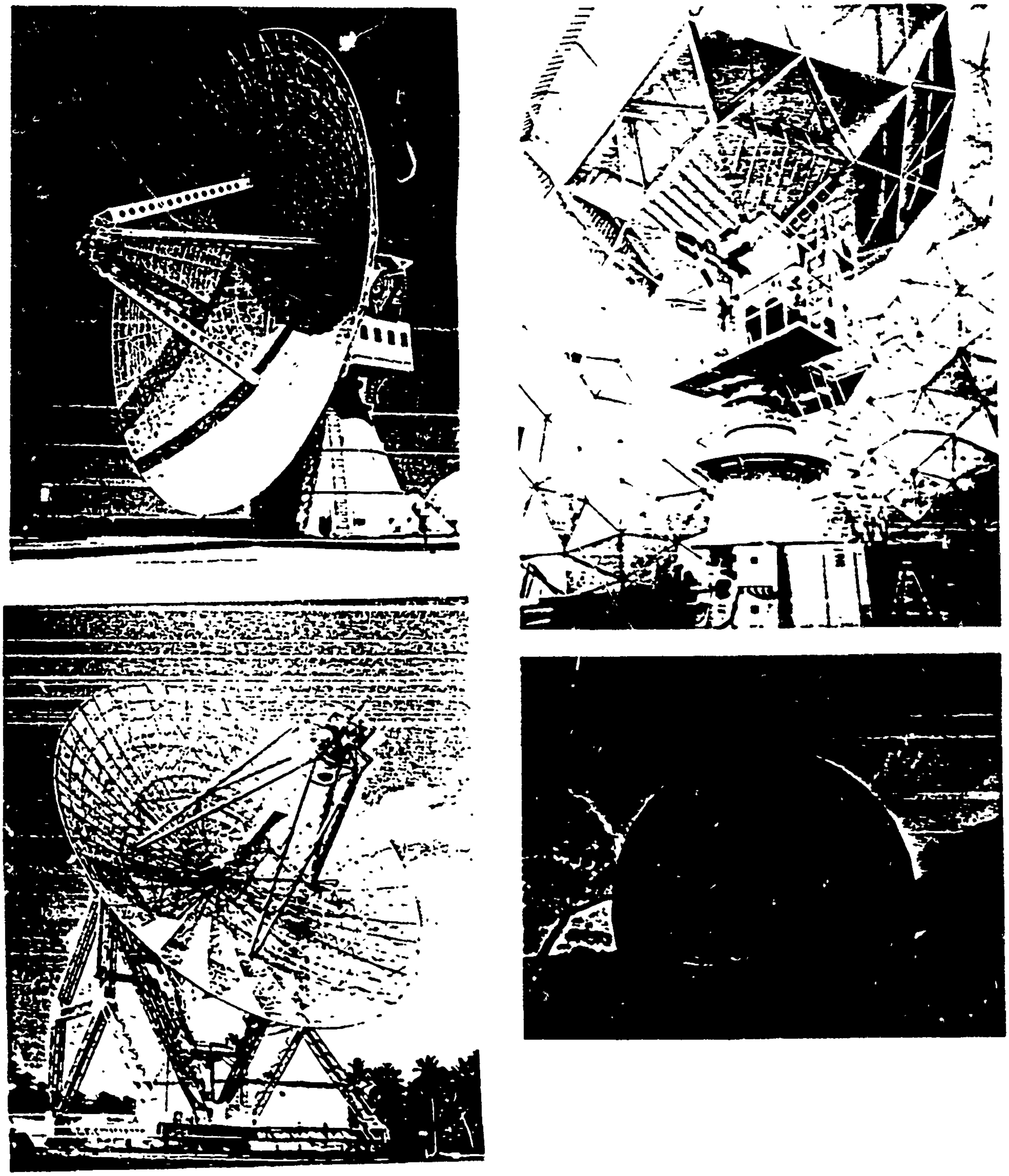

Figure I-2. The PRESS Radar Antennas. (From *Lincoln Laboratory Journal* op cit.)

The optical and IR sensors in the PRESS aircraft after some initial difficulty eventually were directed successfully using TRADEX. The optical results were particularly valuable for investigation of emissions associated with chemical phenomena in wakes, which were especially complex from ablating RVs.

The scientific data from PRESS, along with some from the parallel BTL Range Measurements Program (RMP), were reviewed in monthly meetings starting in early 1959 and a little later presented, along with relevant analyses, in the ARPA-sponsored AMRAC symposia. Many different types of RV targets were observed. A synergism developed rapidly using results of the laboratory and theoretical efforts on reentry phenomena together with the field results.[37] Some of the NIKE ZEUS radars, which initially had modest coherent capability, eventually increased coherence bandwidth partly as a result of TRADEX's performance.[38]

Beginning in 1962 when concern rose about the potential of Soviet BMD systems, the Air Force began a major effort on penetration aids, initially with ARPA funding, and the Navy's plans for POLARIS included multiple reentry vehicles (MRVs).[39] Later (in 1963) the Air Force was given the assignment of coordinating U.S. penetration aids efforts under project ABRES.[40] ARPA funding of a program dedicated to R&D on "Penaids" continued through 1966, and thereafter on a more opportunistic basis. In 1965 ARPA also funded the "Pen X" study, which reviewed the problem of Penaids versus multiple independent reentry vehicles (MIRVs). Pen X provided some input to the DoD decisions to deploy MIRVs. However, this decision seems to have been primarily due to simple economic considerations related to missile costs.[41]

As mentioned above there was an early appreciation of the need to thoroughly understand both offensive and defensive systems' capabilities in order to make decisions on the balance required for cost-effective national security. The key question for the

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[37] C. McLain, op. cit.

[38] This apparently took place after the cancellation of NIKE ZEUS, in 1963, when the BTL RMP program was expanded in support of NIKE X. BTL, op. cit., p. 1-41. It was paid for in part by ARPA. A.O. 702 of 3/65, "Modification of NIKE TTR."

[39] Apparently, about $1 billion was spent for penetration aids, etc., between 1962-68. Cf., A.C. Enthoven and W.K. Smith, *How Much is Enough*, Harper, 1972, p. 190.

[40] About this time ARPA also conducted a comprehensive study in this area for WSEG. PENAIDS are discussed more fully in Chapter IV of this volume.

[41] Apparently the inspiration for Pen X came from the then Assistant DDR&E for Defensive Systems, Dan Fink. Discussion with BGen R. Duffy (Ret.), 3/90. The MIRV economics is discussed in *All in a Life Time*, by I. Getting, Vantage Books, 1989, p. 479.

defense was whether some practically useful discrimination phenomenon or combination of phenomena existed to lessen the defense's burden of identifying RVs in time to be able to launch and guide a missile to destroy it. The offensive (penetration) side of the same problem was the search for ways to minimize or mask the RV's observables for some critical length of time, and the key question was how many, how heavy and large penetration aids, which displaced destructive warhead payload, would be cost effective. While the Army and Air Force had opposite sides of this problem, ARPA was set up to be able to work both sides, and indeed PRESS was set up to make accurate quantative measurements of the same phenomena which affected both sides. Not long after PRESS was underway, DDR&E sponsored regular meetings involving offensive and defensive sides with Lincoln and ARPA as active participants and "honest brokers." Key to being able to do this, of course, was DDR&E H. York's 1960 decision to force both Services to use the same reentry site at Kwajalein, and in ARPA's setting up the PRESS operation there to provide high quality scientific information to both sides (defensive and offensive), as well as enabling independent analyses be done by and through ARPA.

Before the end of 1962, President Kennedy made the decision, after many studies and debates, not to deploy NIKE ZEUS because of the apparent vulnerability of NIKE ZEUS to simple countermeasures.[42] It is not clear what part, if any, PRESS had in this decision. Not many reentry measurements had yet been made by PRESS and apparently few penetration aids of any sophistication had been tested.[43] The BTL history of BMD states that the decision was due to a change in the threat from one-on-one engagements (a single NIKE ZEUS installation could only handle one RV/missile at a time) to a high traffic threat, involving simultaneously many RVs and many interceptors. Multiplication of individual NIKE ZEUS type systems to meet this new threat was not considered cost effective.[44] Other considerations involved were: the fact that the ZEUS missile speed required launch before "atmospheric filtering" of RVs from lighter decoys, debris, craft, etc., could take place; the reality of the Soviet penetration aids threat for U.S. BMD, which

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[42] *Jayne*, op. cit., p. 173.

[43] *Jayne*, op. cit., and p. 185. See also "Strategic Warfare," by Daniel J. Fink, *Science and Technology*, Oct. 1968, p. 64. Several RVs had been tested, but penetration aids, such as low observability, required tradeoffs. High "Beta" RVs were assumed to have low-observable geometry. The first ABRES flight test apparently took place on the AMR in 1963. Cf., SAMSO chronology, ibid., p. 120. The available data from DAMP, PRESS and BTL were reviewed in the IDA Intercept X Study, in 1962, which provided some input to the NIKE ZEUS decision.

[44] BTL., op. cit., p. 2-15. Until about 1964, penetration aids were apparently mainly "on paper." D. Fink, op. cit.

remained a matter of contention throughout the BMD project;[45] and the vulnerability to nuclear blasts of the mechanically steered NIKE ZEUS radars. After the President's decision, NIKE ZEUS continued through 1962, making successful intercepts of several types of ICBMs, and the BTL target tracking and discrimination radars continued to make reentry measurements for several years.

While cancelling NIKE ZEUS, the administration also gave its backing to continued ABM R&D, specifically along the lines of a concept called NIKE X, involving a hardened phased array radar and a high acceleration missile to make close-in intercept after atmospheric screening-out of light decoys and other debris. The name NIKE X was apparently due to Dr. J. Ruina, then ARPA director, who had the task of laying out the options for DoD and the President's Science Advisory Committee (PSAC).[46] BTL describes NIKE X as a transition R&D phase toward the next generation BMD system. Apparently from about 1960 a high acceleration missile had been under study at BTL and a phased array also, after the stimulation of ARPA's successful ESAR project and an explicit request by DoD.[47]

In early 1963, apparently prompted in part by intelligence about Soviet ABM developments, as well as about their prospective offensive capabilities, the Secretary of Defense ordered the priority development of NIKE X. The NIKE program by then had begun construction at WSMR of a hardened phased array radar, the MAR,[48] and of a short range high velocity missile (SPRINT); in 1964 the program incorporated a thermonuclear warhead, on a longer range version of the ZEUS missile (SPARTAN)[49] for exoatmospheric X-ray kill of RVs, providing a kind of area defense.

The fact that SPRINT and SPARTAN had nuclear warheads emphasized the importance of understanding the characteristics of ABM systems operation under conditions in which nuclear explosions occurred in and above the atmosphere. Many then felt that the theoretical assessment of such situations should have been compared with dedicated experiments involving real nuclear explosions. However, with the atmospheric

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[45] BTL, op. cit., p. 3-7.

[46] Ruina had previously been assistant to DDR&E for Air and Missile Defense. His briefing on NIKE X was given to PSAC and apparently to the President directly, *Jane's*, op. cit., p. 179.

[47] BTL, op. cit., p. 2-1, and J. Ruina, op. cit.

[48] Cf. Chapter VI of Vol. 1 of this study.

[49] BTL, op. cit., p. 10-1.

nuclear test ban, no further experiments occurred.[50] ARPA funded several related experiments connected with the FISHBOWL nuclear test series in 1962, and some of the data analysis.[51]

As part of NIKE X, in 1964 BTL intensified its own reentry measurements and analysis program.[52] Overall reentry test requirements. in the mid 1960s, began to be coordinated in a tri-Service coordinating group and an ARPA-Army agreement was established specifically to coordinate the RV measurements program.[53] The respective responsibilities, described from the viewpoint of BTL, were as follows:[54]

1. Bell Laboratories. Specified program objectives, reentry hardware performance requirements, and target delivery (trajectory and deployment) requirements. Operated the NIKE radar sensors and EC121 optical aircraft. Reduced and analyzed collected data.
2. Army. Procured target vehicles and delivery systems through the Air Force. Coordinated test requirements, program objectives, and schedules. Provided the Kwajalein Test Range support. Coordinated inter-Service data exchanges.
3. Air Force. Provided the reentry hardware, booster systems, and the ETR (Reentry Test Range) facilities (i.e., delivered targets to Kwajalein Test Site). Exchanged technical data and coordinated their reentry study program, ABRES, to support missions of mutual interest.
4. Lincoln Laboratory. Supplied technical consultation and coordinated design of reentry experiments and data analysis exchange. Operated additional sensors (data sources) of the PRESS facilities at KTS.

In the early 1960s intelligence about a Soviet ABM radar, and an appreciation that penetration aids were as yet used in very few of the U.S. ICBMs, suggested a specific need to better understand reentry phenomenology as observed by radars operating in the VHF frequency range.[55] This led to Lincoln design, about 1964 of a new, higher power

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[50] Apparently Sec. of Defense McNamara had argued against ABM deployment partly due to the absence of such data, but a while later argued for a test ban on the grounds that the uncertainty did not outweigh the general advantages of a test ban. Later ABM deployments, it was agreed, would involve radar frequencies which could "see through," and a distribution of radars which could "see around" the nuclear effects.

[51] AO 310 of 2/62, STARFISH.

[52] BTL, op. cit., p. 2-15.

[53] AO 648 of 12/64, ARPA-Army Agreement on RV Measurements Programs.

[54] BTL, op. cit.

[55] *Jane's*, op. cit., p. 257. The NIKE ZEUS and NIKE X radars did not operate at VHF. However, apparently driven by considerations of practicality and cost of high power tubes, for a while there was serious consideration of VHF for the later U.S. BMD systems. BTL History, op. cit., p. 8-10.

radar with dual frequency capability, at VHF and UHF, called ALTAIR (ARPA Long Range Tracking and Instrumentation Radar) as the next major PRESS sensor at Roi-Namur (see Figure 1-2). The primary motif for ALTAIR apparently was to simulate the Soviet BMD radars' capabilities against U.S. RVs.[56] It was also considered important to obtain accurate experimental data on reentry phenomena at different frequencies, even if some of them were low enough to be significantly affected by nuclear explosions. Before ALTAIR was built, however, TRADEX was modified to provide some interim VHF observational data. Like TRADEX, the construction of ALTAIR was funded separately.[57] ALTAIR became operational about 1969.

Shortly after commencing work on ALTAIR, Lincoln proposed that a large bandwidth, high resolution C-band radar [ALCOR (ARPA - Lincoln C-band observable radar)] be constructed. (See Figure 1-2.) TRADEX and other data had indicated that high resolution images of RVs and of the structure of their wakes might be very important. To obtain very high resolution, a wider bandwidth (500 MHz) and a higher radar frequency were required than provided by TRADEX and ALTAIR.[58] Like TRADEX, ALTAIR and ALCOR (and the later millimeter wave radar), as experimentally oriented systems, were mechanically steered, not having the multiple-target BMD problems which required a phased array. ALCOR became operational about 1970 at Roi-Namur.

Figure 1-3 outlines the history of upgrades of radars originating in PRESS, up to 1980. In the mid 1960s a wide bandwidth, similar to ALCOR's, was included in the ARPA Synthetic Spectrum Radar, built by Westinghouse and used in SOI studies and in the design studies of ADAR (Advanced Array Radar), for hardened site defense systems with capabilities beyond that then planned for NIKE X.[59]

Throughout this period (early to mid-1960s) there were a large number of ICBM and SLBM tests involving different types of RVs and penetration aids. Some of these were of special design for the ABM projects, and some RVs carried instruments to make special measurements on board to determine the properties of plasma sheaths and wakes. A

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[56] Holtcamp, op. cit., p. 73.

[57] A.O. 668 of 2/65, PRESS UHF/VHF Radar.

[58] There were earlier ARPA efforts to explore approaches to a wide bandwidth synthetic spectrum radar (AO 145 of 5/60). Cornell Aero Labs., a BTL subcontractor, had also pointed out the value of short pulse lengths. Lincoln later upgraded the bandwidth of its HAYSTACK radar to improve its SOI (Space Object Identification) imaging capability.

[59] The ADAR studies began under the blanket AO 498, of 7/63 to Lincoln, for "discrimination studies." Other aspects of the ARPA hard point defense concept included the HAPDAR low cost, hardened phased array radar, and the HIBEX missile. See Chapter III. of this volume.

number of experiments, with ATHENA intermediate-range missiles and special RVs were also conducted in the mid-1960s at WSMR.[60] The WSMR radars used for these experiments included BTL's NIKE ZEUS and MAR radar, and ARPA's AMRAD measurements radar, operated at first by the Columbia University electronics laboratory group, (later the Riverside Research Institute) and eventually turned over to Lincoln. The WSMR measurements, lacking real ICBMs, but under somewhat better control, and often allowing a closer comparison with laboratory reentry physics experiments, were a valuable complement to those at Kwajalein and Roi Namur. These WSMR activities continued to the mid-1970s.

In the late 1960s several summary studies were conducted to assess the state of understanding of reentry phenomenology and its applicability to NIKE X.[61] While these and other similar studies underlined the continuing difficulty of discrimination problems, at the same time they apparently indicated a sufficient level of capability of a NIKE-X type system against a presumed unsophisticated penetration-aids threat from China to help persuade DoD in 1967 to propose deployment of a "thin" BMD system, called SENTINEL.

In 1967, at about the same time as the SENTINEL decision, the major part of project DEFENDER was transferred from ARPA to the Army, along with some key personnel and the PRESS facilities.[62] Dr. J. Foster, then DDR&E, directed the transfer,noting that DEFENDER's objectives had been largely reached, and that the Kwajalein facilities, including PRESS, should be regarded as national assets. In response the then Army Chief of R&D, Gen. A. Betts, who had been an earlier ARPA director, reorganized his command to identify clearly its ABM-related R&D effort in an Advanced Technology Program of which the ex-ARPA personnel were now in charge. As specified by the DDR&E, the Army continued Lincoln's management of PRESS in support of ABM R&D and the Air Force's ABRES project. The PRESS facility was renamed the Kiernan Reentry Measurements Facility (KREMS) after LtCol Joseph Kiernan, who had managed the ARPA PRESS program from 1963 to 1966 and was killed in Vietnam.[63]

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[60] Cf., AO 254 of 8/16 and AO 379 of 6/62.

[61] See e.g, "BMD Discrimination Study," IDA/JASON Study S-298 (CLASSIFIED) 1966. At about the same time, the Pen X and other studies of the utility of penetration aids versus MIRVs were made, favoring the latter.

[62] Cf. Holtcamp, op. cit., p. 44-5, and Richard J. Barber, *History*, op. cit., pp. VII-11, VII-38 and VIII-29.

[63] The renaming of the facility was also due to Gen. Betts, Holtcamp, op. cit., p. 46. Apparently Lincoln also had an internal debate about this time as to whether continued PRESS-type responsibility was compatible with the laboratory's research mission. M. Balser, op. cit.

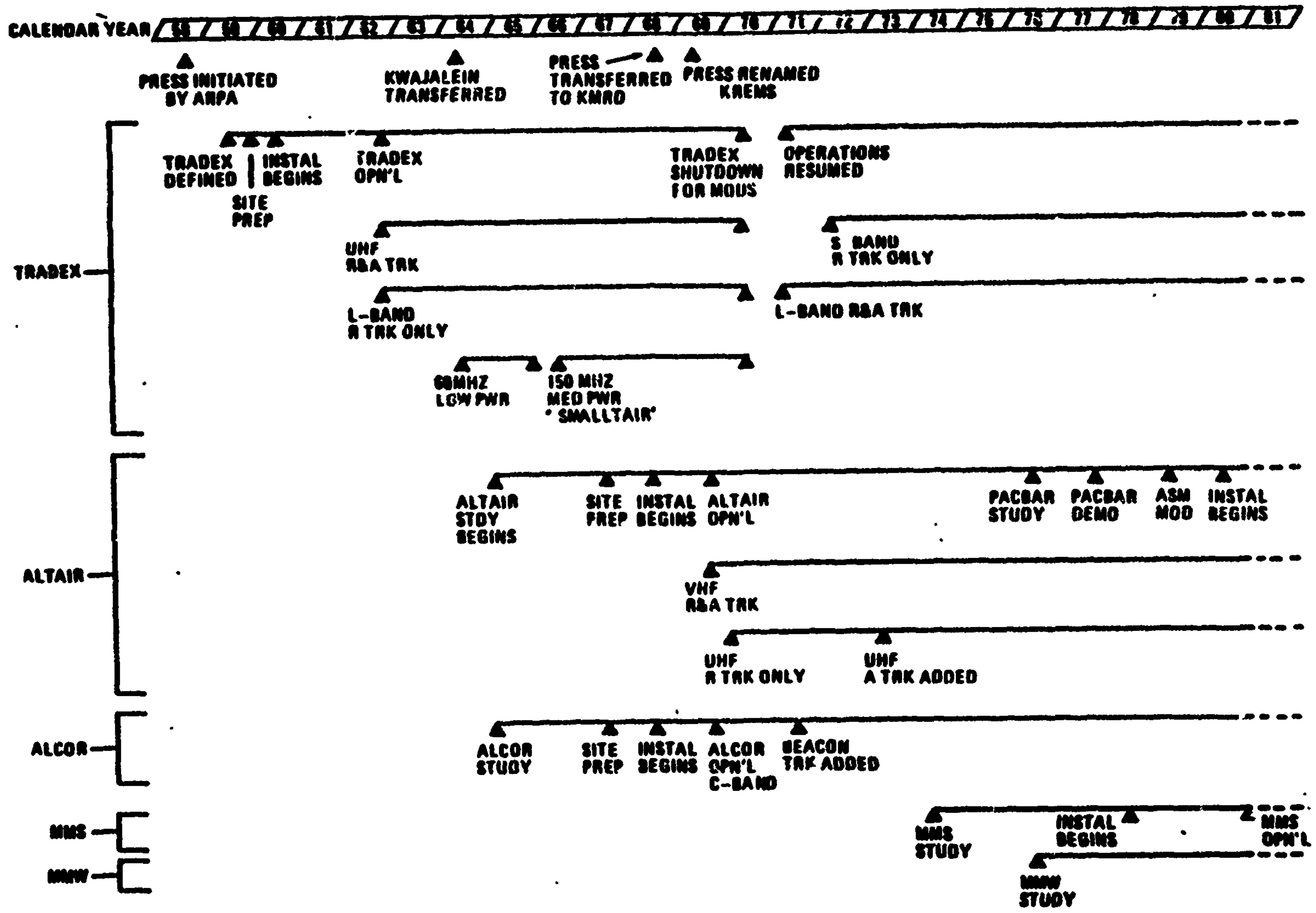

Figure 1-3. Chronology of Radar Changes (from Holtcamp, op. cit.)

In summer 1968 an ad hoc committee, including representatives from ARPA, cognizant Army agencies, DDR&E, and the major contractors BTL and Lincoln, developed a coordinated plan for continued use of some of the Kwajalein radars and retirement of others, which was then approved by the DDR&E reentry programs review group overseeing the transfer and subsequent actions. In fall 1968 the same committee devised plans for integration of these sensors, providing a measure of independence along with improved communications by which the radars would provide data to each other and to an upgraded central data processing system. Previous to this, apparently, BTL had set up a high-capacity data link between PRESS and their NIKE X radars.[64] In the 1967-72 period, there was very close collaboration of the Lincoln and BTL groups not only on reentry measurements, but also on system-related activity, such as determining miss distance of the SPRINT and the SPARTAN intercept events.[65] Figure 1-4 depicts the complex PRESS facilities in 1969.

By the early 1970s considerable confidence was expressed in the ability to successfully model reentry phenomena, based on PRESS and related data, and when integrated with the laboratory and theoretical work on reentry physics under DEFENDER.[66] Because of the progressively higher cost of reentry tests there was (and is) a major economic payoff to a successful reentry modelling effort. However, there were also qualifications to such statements as they related to defensive discrimination.[67] The BTL history also expresses some skepticism about the then current theoretical extrapolations, and some frustration due to the lack of threat radar signature data available to them to design their SAFEGUARD system.[68]

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[64] "Ballistic Missile Defense Testing in the Pacific: 1960-1976," by C.A. Warren, Bell Laboratories Record, 1977, p. 204.

[65] Cf., e.g., "Radar Reentry Data," by L. Rechtin (Lincoln) and T. Philips (BTL) in *Journal of Defense Research*, Vol. 2B, 3, 1970, p. 85 (CLASSIFIED), and (regarding SPARTAN) BTL *History*, op. cit., p. 5-37.

[66] Cf., e.g., C.E. McLain, "State of the Art of Reentry Physics," *Journal of Defense Research*, Vol. 2A, No. 1, 1970, p. 2. (CLASSIFIED), and Richard J. Barber, *History*, quoting Dr. C. Herzfeld.

[67] McClain, op. cit., p. 5.

[68] BTL History, op. cit., Chapter III-7, states that the necessary intelligence information could have been gathered, but wasn't.

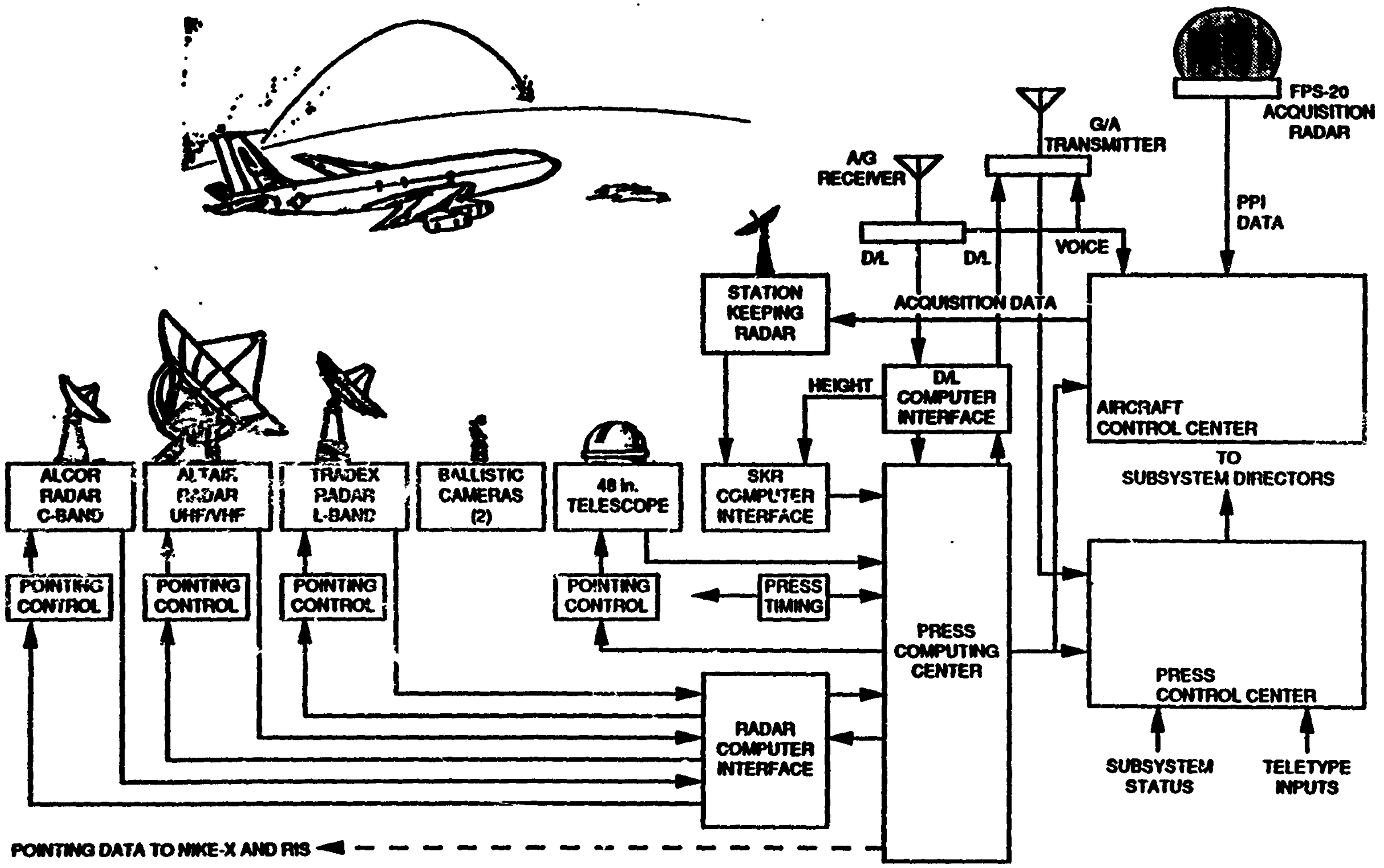

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Figure 1-4. PRESS Instrumentation - 1969

After the transfer of most of DEFENDER, ARPA formed its Strategic Technology Office (STO) which continued to support optical and IR research using the PRESS aircraft, until the early 1970s.[69] This research provided much of the the basis for sensor developments later undertaken by SDI. The PRESS ground-based optical and IR systems went to KREMS, and operated until 1972 with some changes. The Army began to install a new generation of ground-based optical instrumentation, emphasizing IR and active laser systems at KREMS in 1973. The TRADEX Optical Adjunct (TOAD), an optical telescope boresighted with TRADEX and featuring a CCD focal plane array, was installed in about 1980. TOAD images RVs against a star background, enabling highly accurate angular measurements.[70] The AOA (Airborne Optical Adjunct) work under SDI has also revived interest in the possibilities of direct use of aircraft as sensor platforms for BMD systems.

Figure 1-5 outlines the history of the PRESS and KREMS optical systems to 1980. Figure 1-5 also shows the current KREMS instrumentation system, including a local-area network intercomputer communication system. In the early 1970s ALTAIR was modified to simulate the SENTINEL-SAFEGUARD system's PAR radar, since the PAR, then being constructed near Grand Forks, S.D., could not observe any test reentries. In the mid-1970s the Air Force expressed a need for a radar sensor in approximately the Kwajalein geographic location for their SPADATS system, in order to deal with launches of satellites from the USSR or China. ALTAIR demonstrated related capabilities in the late 1970s and was modified soon afterwards for both low altitude and deep space satellite observations. In 1981 ALTAIR began SPADATS operations on a round-the-clock basis.[71] TRADEX, operating in a new pulse-compression mode, also backs up ALTAIR for spacetrack capabilities. TRADEX also serves as an illuminator for the new precision, multistatic reentry tracking system at KREMS.[72]

In the mid-1970s, the Army's SAFEGUARD program was terminated. However, a Hard Site Defense System, oriented to defense of ballistic missile launch sites was later designed and, in part, constructed and tested by the Army at the Kwajalein test site.

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[69] Holtcamp, op. cit., p. 79.

[70] Ibid.

[71] *Lincoln Laboratory Journal*, op. cit., p. 259.

[72] Ibid, p. 262.

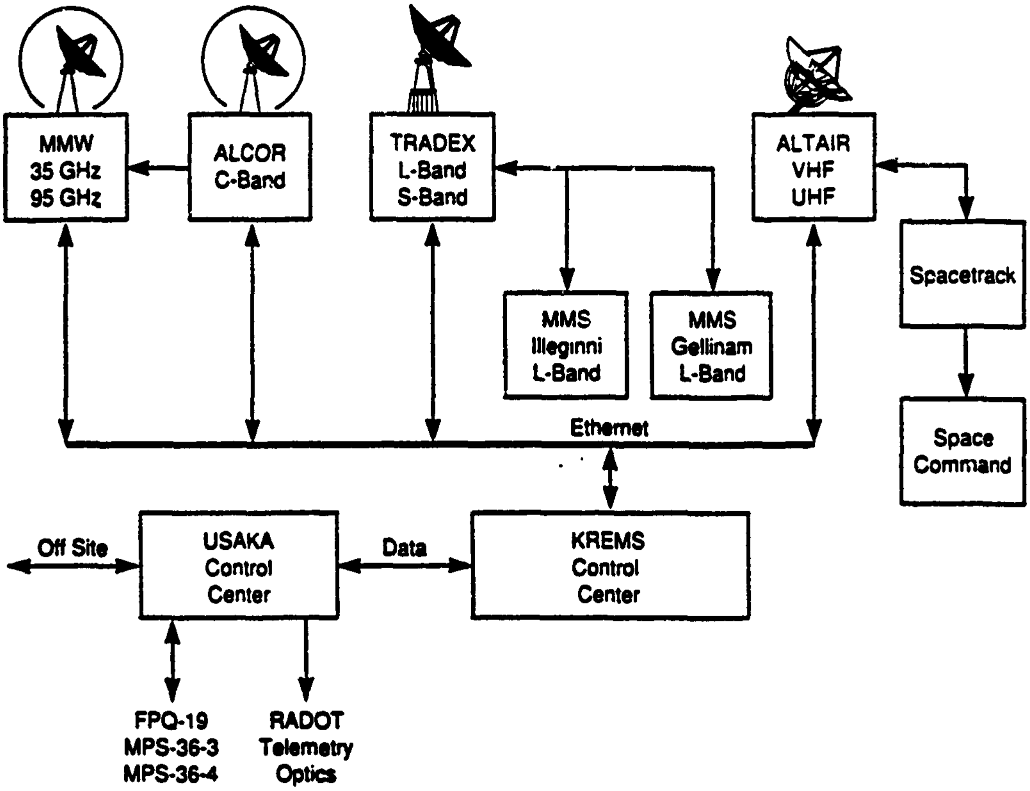

Figure 1-5. The KREMS Instrumentation Network (From *Lincoln Laboratory Journal*, op. cit.)

ALCOR has now been upgraded to routinely generate two-dimensional images of objects in orbit, in support of the Air Force's SOI (Space Orbit Identification) activities. Its bandwidth also allowed it to track beacons in RVs. A Lincoln-designed millimeter wave radar, to achieve higher resolution, is the latest addition to KREMS.

KREMS is now the major part of the national R&D facility, operated by the Army's Strategic Defense command, and serving all Service and SDI needs for measurements of RVs and BMD. A particularly good, if somewhat dated, description of its value and activities was given by the Army BMD commander in 1979.[73]

> The BMD Program Manager is also responsible for the operation of Kwajalein Missile Range (KMR), a national range. KMR is not dedicated solely to the support of BMD; it is the major test range for our strategic

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[73] Testimony of MG Stewart C. Meyer, Defense Authorization Hearing for FY 1980, 96th Congress, 1st Session, pp. 314-15.

missile force, offensive and defensive. KMR is unique in two major respects; first the unique quality of the data collected by its highly accurate sensors is essential to the successful development of the new generations of strategic offensive missiles (e.g., MX and TRIDENT II) and second, it provides unique opportunities for coordination, and cooperation between the offensive and defensive technical communities. Virtually all ICBMs fired into KMR serve both the offensive and defensive communities for data collection.

Major fiscal year 1980 test programs at KMR include:

The Advanced Ballistic Reentry Systems (ABRES) test of RV material characteristics, penetration aids, arming and fuzing technology, and maneuvering RV design.

The Minuteman development tests of Special Test Missiles and Production Verification Missiles to evaluate modifications and improvements to the Air Force reentry systems.

The Strategic Air Command (SAC) tests of Minuteman II and III missiles into KMR to provide training for SAC crews and evaluation of weapon system performance. Selected test vehicles have additional data requirements in support of offensive system development objectives.

The BMD Advanced Technology Center Detection, Designation and Discrimination Program, which utilizes the Kiernan Reentry Measurement Site radars (Tradex, Altair and Alcor) to provide the primary source of techniques.

The Systems Technology Test Facility on Meck Island to support evaluation of BMD components for potential application to future BMD systems.

An evaluation of the effectiveness of the ALTAIR radar to meet Air Force Aerospace Defense Command requirements for collecting data was successfully completed in fiscal year 1978. Full time support of ADC requirements is under consideration at this time.

Range planning for the following future testing will be accomplished in fiscal year 1980.

Homing Overlay Experiment tracking scenarios.

Interceptor Technology Tested Program.

Tracking analysis and miss distance measurement techniques for Space Defense Program.

Testing to examine the technology required for non-nuclear kill of reentry vehicles.

The importance of KMR to the success of these and other test programs cannot be overemphasized. The U.S. possesses no comparable capability to collect exo-atmospheric signature data, record missile reentry phenomena, provide terminal trajectory and impact data, record missile

> reentry phenomena, provide terminal trajectory and impact data, recover reentry vehicles when required, and transmit near real-time data to the mission sponsors. The instrumentation required is extensive; moreover, the data provided by these instruments must be of the highest quality. High confidence in our test data leads to high confidence in our missile development programs and ultimately in our operational capabilities.
>
> The collection of our offensive and defensive test activities at KMR is particularly beneficial. In the process of testing our offensive systems, the BMD Program takes full advantage of the opportunity to test new BMD technologies and components against the most sophisticated targets available. The result is the mutual accomplishment of test objectives with a minimum of missile firings and a continuous interchange of data between our offensive and defensive development programs.

Recent steps to further upgrade KREMS for SDI are described in a recent issue of the *Lincoln Laboratory Journal,*[74] and of IEEE's *Spectrum.*[75] The SDI plans for the Kwajalein site also include a supercomputer for range control, and construction of a new generation phased array radar (GBR-X or GSTS) for early acquisition, tracking and discrimination of RVs, and guidance of exo- and endo-atmospheric, interceptors on the site of one of the radar foundations built by BTL in the early 1970s. Incorporating solid state technology, GBR-X is to operate in the microwave frequency range, desired in the late 1950s but then considered economically impractical.

C. OBSERVATIONS ON SUCCESS

DEFENDER had the objective of doing advanced research relating to BMD and its penetration. A "map" of needed R&D had been provided by earlier studies, and an efficient start for ARPA's work was due in part to the fact that some of the participants in these studies were key players in the early DEFENDER project. It was clear from the beginning of DEFENDER that field measurements of ICBM reentry would play a major, if not decisive, role for decisions about the continued credibility of the U.S. deterrent against Soviet ABM efforts, and about the practicality of a U.S. BMD deployment. PRESS was the ARPA response to the need to do this kind of high quality measurements. PRESS began as an ARPA initiative, but the continuing participation of a major high quality non-profit laboratory was a very important factor because of the complexity of the measurements and the key role that these measurements would play. Lincoln at this time

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[74] *Lincoln Laboratory Journal*, op. cit.

[75] "Kwajalein's New Role; Radar for SDI," by Glenn Zorpette, *IEEE Spectrum*, March 1989, p. 64. This article also outlines some of the current operations [illegible]S.

was "available" because its BMEWS job was done, but was reluctant at first, due to the politics involved in being an Air Force contractor.

A key decision was made by H York as DDR&E to combine assets, the Air Force ICBM shots and the Army's ABM R&D efforts, at Kwajalein atoll. ARPA made a similar key decision to take advantage of this combination, which would mean that the measurements made by the PRESS sensors could be provided equally to the offensive and defensive side.

The early ARPA measurements of reentry made before PRESS primarily with the DAMP ship indicated that discrimination of RVs was difficult and helped toward the national decision not to deploy ZEUS. However, the major factor in this decision was probably the NIKE ZEUS inability to handle multiple RVs. NIKE X was the follow-on option recommended by Dr. J. Ruina, then ARPA director, and assumed that atmospheric filtering could play a key role in simplifying the discrimination problem, at the expense of compressing the time available for action, and so requiring a very high acceleration missile. This early judgement was proved correct by subsequent intensive measurements made by PRESS, and also by BTL. The TRADEX radar and the correlated optical and IR measurement systems were the "workhorse" of this period. BTL recognized the value of the PRESS data and used it for their BMD systems effort. An increase in bandwidth of the NIKE ZEUS target tracking radar (TTR) was partly paid for by ARPA, and there seems to have been some impact of the coherent PRESS radar data on the NIKE X system design. PRESS data also influenced the ADAR effort under DEFENDER, which in turn influenced the later Army BMD system designs.

From about the time of the NIKE X decision, the priority of the PRESS effort seems to have been on the offensive, penetration problem. ALTAIR, the second PRESS radar, was originally designed to mimic the Soviet ABM radars. ALCOR, on the other hand, seems to have been designed largely to explore the possibilities the highest practicable resolution instrument could offer for BMD discrimination. Both ALTAIR and ALCOR were begun under ARPA, but were not used until after the transfer of DEFENDER. The value of TRADEX, ALTAIR, and ALCOR is indicated by their continued use today. These systems, upgraded in several ways and linked in a computer network, are the core of the National Kwajalein Test Site (KTS) facility and now part of the Army's Advanced Technology Center, and are used by the Air Force as part of their operational SPADATS systems and for SOI.

Optical sensors, after receiving initial emphasis, seem to have been relegated to a secondary role during the PRESS period. However, the PRESS optical (and IR) sensor systems did not all go to the Army in the DEFENDER transfer. ARPA, STO, kept the airborne sensors optical development and measurements, as well as the AMOS facility, looking to the future possibilities of exoatmospheric discrimination from an elevated platform. These possibilities have been followed up in later Army and SDI programs.

The transfer of DEFENDER seems to have been a "top down" decision of Dr. J. Foster, then DDR&E, in view of the DoD decision to deploy "the best available BMD system" and the subsidence of inter-Service rivalry over the years. By the time of transfer the objectives of "keeping both offensive and defensive sides honest," setting up a high quality scientific effort in the area, and acting as competition to improve the quality of the Army work had been accomplished. Key tools to carry out further research were in place. These tools included modeling, which integrated theory and laboratory reentry physics with PRESS results, to allow more cost-effective design of expensive reentry tests, and to lend assurance to the major decisions about deployment of BMD.[76] Despite these accomplishments, apparently there were some strong feelings, at the time of DEFENDER's transfer, that there was considerable research yet to do and that ARPA should have remained in charge.[77] Some of this research was continued under ARPA's STO, transferred in the early 1980s to the SDI R&D program.

ARPA expenditures for PRESS from project records are about $200 million. The Army and SDI have spent nearly $1 billion in subsequent R&D and upgrading efforts at the KREMS follow-on facility at Roi-Namur. The Air Force had spent over $1 billion on penetration aids by 1970. Typical complex reentry tests now cost over $100 million each. It is difficult to estimate the savings due to the ability to reduce the numbers of ICBM tests required, the negative decisions not to deploy a BMD system, and to put a dollar figure on the positive credibility assurance provided to our deterrent systems.

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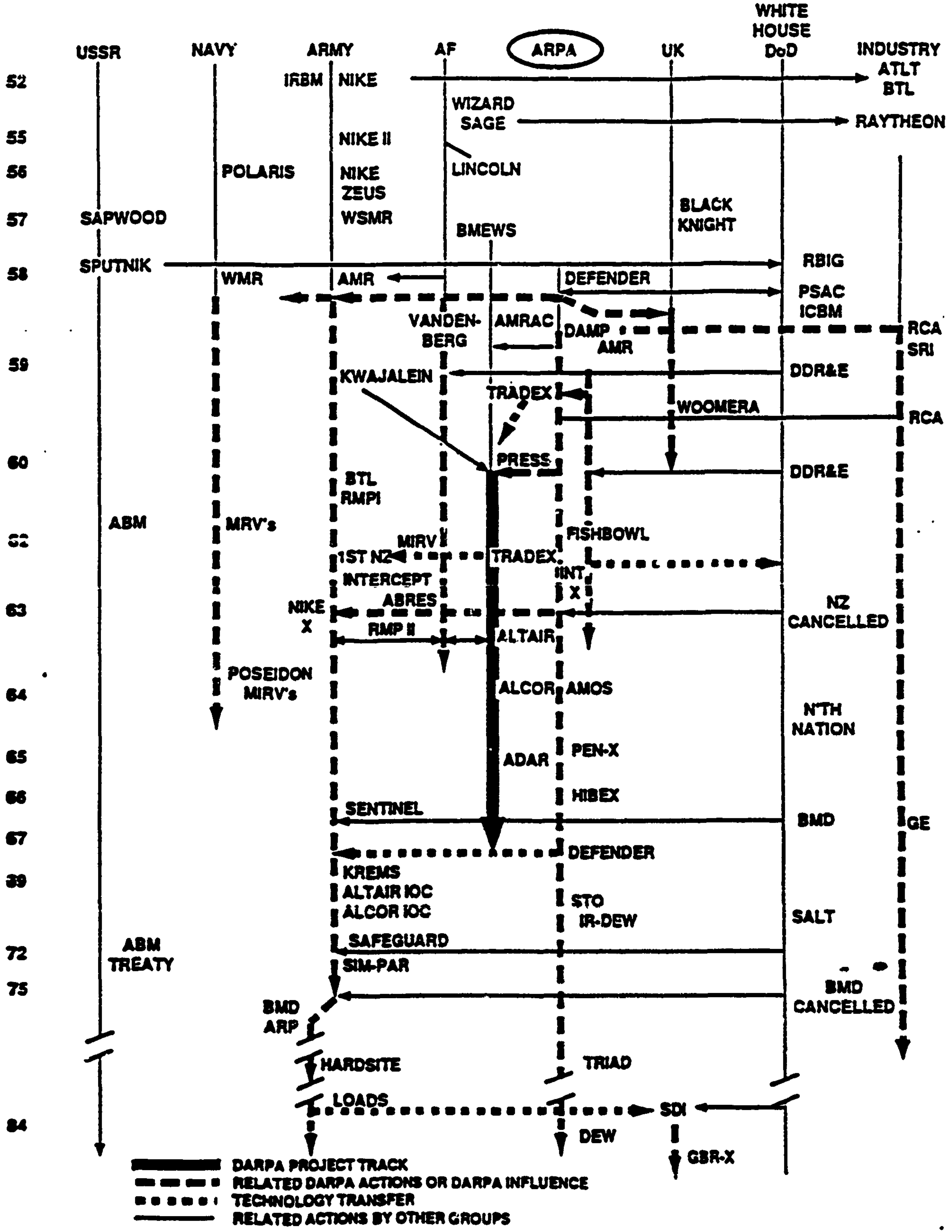
[76] These tests, currently, can require several years preparation and intensive rehearsals, costing over $100 million each, cf., *Lincoln Laboratory Journal*, op. cit., p. 252.

[77] These feelings are described in Richard J. Barber, op. cit., pp. VII-11-12.

PRESS


USSR
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WIZARD SAGE
RAYTHEON
NIKE II
POLARIS
NIKE ZEUS
LINCOLN
SAPWOOD
WSMR
BMEWS
BLACK KNIGHT
SPUTNIK
RBIG
WMR
AMR
DEFENDER
PSAC
ICBM
VANDEN-BERG
AMRAC
DAMP
AMR
RCA
SRI
KWAJALEIN
DDR&E
TRADEX
WOOMERA
RCA
PRESS
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POSEIDON MIRV's
ALCOR
AMOS
N'TH NATION
ADAR
PEN-X
HIBEX
SENTINEL
BMD
GE
DEFENDER
KREMS
ALTAIR IOC
ALCOR IOC
STO
IR-DEW
SALT
ABM TREATY
SAFEGUARD
SIM-PAR
BMD ARP
BMD CANCELLED
HARDSITE
TRIAD
LOADS
SDI
DEW
GBR-X
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS
5-11-80-7M

II. ARECIBO

A. BRIEF OVERVIEW

The ARECIBO 1,000-foot antenna of Cornell University's National Astronomical and Ionosphere Center is the largest in the world. Built in 1959-63 with ARPA support, and transferred to the National Science Foundation in 1969, the ARECIBO facility has assisted NASA in selection of suitable locations for the APOLLO lunar landings and the Viking planetary mission, and has made many notable contributions to radar and radio astronomy, ionospheric physics, and to the aeronomy and dynamics of the earth's upper atmosphere. Continually upgraded, ARECIBO remains in many ways the world's most sensitive instrument for radio and radar astronomy and ionospheric radio physics, and is currently in round-the-clock use for research.

B. TECHNICAL HISTORY

In the early 1950s research on tropospheric and ionospheric scatter communication by the Services led eventually to development and fielding of several military communication systems. Extension of the line of thought of this research also led W.E. Gordon of Cornell University to consider the possibility of directly scattering radio waves from the individual electrons in the ionosphere. Because of the extremely small scattering cross-section of a single electron (derived in the 1920s by J. J. Thomson), Gordon quickly came to the conclusion that a large antenna, about 1,000 feet in diameter, would be required for a useful system using this approach.[1] This was larger than could be expected to be practical for a communication system in most locations. However, a single such antenna as part of a radar system appeared to open a new range of possibilities for detailed exploration of the structure and dynamics of the ionosphere. It was not long after Gordon's first publication[2] that an actual detection of the incoherent or Thomson scatter from the ionosphere was achieved by the Bureau of Standards.[3] The radio physics research

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[1] W.E. Gordon, unpublished notes, 1987.

[2] W.E. Gordon, Proc. IRE 46 (1958), p. 1824.

[3] K.L. Bowles, *Physical Review Letters* 1, 1958, pp. 454.

possibilities, and the challenges of finding a suitable location and of designing and building a 1,000-foot antenna strongly intrigued several members of the Cornell faculties of geology, engineering, and physics. Much of this preliminary work at Cornell was funded by ONR's electronics branch through an existing contract.[4]

In roughly the same time period, there were several other large antennas under construction or planned. The Naval Research Laboratory (NRL) had constructed a 200 x 234-foot parabolic section antenna in a ground depression for experiments on moon-bounce communication in the mid-1950s.[5] The success of these experiments encouraged NRL to propose construction of a 600-foot fully steerable dish to be located in a low radio noise environment at Sugar Grove, West Virginia. The largest fully steerable antenna at the time was the 250-foot dish at Jodrell Bank in the United Kingdom. While motivated primarily by exploration of the potential of moon-bounce signals, the NRL plans were to allow part-time access to the 600-foot antenna for radio astronomy research. Approvals for the SUGAR GROVE facility had been obtained by the time Cornell was formulating a proposal, and in late 1958 preliminary work on construction was underway. However, the scope of the project was expanded to include a radar capability under an accelerated schedule, and severe problems were encountered with the construction. The 600-foot dish project was cancelled in the early 1960s.[6]

Plans were also being formulated in the late 1950s by the National Science Foundation (NSF) for several large steerable antennas for its National Radio Astronomy Observatory to be located at Green Bank, West Virginia, not far from Sugar Grove because of the low radio noise expected there.[7] The NSF project also ran into construction problems with the first of these antennas while the Cornell proposal was being considered by ARPA.[8]

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[4] W.E. Gordon, unpublished notes, 1987.

[5] L.A. Gebhard, "Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory," NRL Report P-300, 1979, pp. 114-115.

[6] G. Kistiakowsky, *A Scientist at the White House*, Harvard, 1976, p. 153, recounts discussions in 1959. Cf. also "The Navy's Big Dish," *IEEE Spectrum*, Oct. 1976, p. 38. There were several other antennas built by the Navy at Sugar Grove subsequently, some using parts of the 600-foot project.

[7] NRL had previously obtained a Federal ban on TV and other sources of radio noise in the area.

[8] Milton A. Lomask, *A Minor Miracle--An Informal History of the National Science Foundation*, USGPO, 1975, p. 139ff.

Lincoln Laboratory had also constructed, in the mid 1950s, the large MILLSTONE HILL radar. This L-band facility began ionospheric research exploiting incoherent scatter, shortly after Gordon's publication.[9]

The Cornell group discussed the possibilities of a 1,000-foot dish with ARPA beginning in mid-1958.[10] The approach was to construct the antenna within a limestone "Karst" formation, a bowl-like depression, about 9 miles south of the town of Arecibo, Puerto Rico from which the facility took its name. This location was chosen partly because it was closest to Cornell of all sites considered eligible, and partly because its latitude was favorable for observing the planets.[11] The original proposal to ARPA, made in early 1959, was to construct a parabolic dish which could only look upward in a narrow range of angles, primarily to do ionospheric research and secondarily for "radar astronomy" investigations of the moon and planets, and also radio astronomy.

The proposal was assigned to project DEFENDER, which was concerned with phenomenology of missile flight, part of which would take place through the ionosphere. However, it was several months before ARPA took action on the proposal. In part this seems to have been due to an unfavorable climate caused by the difficulties being experienced at the time by the other big dish construction projects, the Navy's 600-foot steerable dish project at Sugar Grove, and with NSF's project at Green Bank.[12] Partly also the delay seems to have been due to arguments within ARPA over the degree of relevance for DEFENDER of the investigations proposed using the ARECIBO dish.[13] The main justification for ARECIBO under DEFENDER emphasized particularly the lack of knowledge about the structure of the upper ionosphere, above the F-layer, inaccessible to ground-based sounders.

Partly also, the delay was due to the fact that ARPA made a suggestion to Cornell that a spherical dish antenna be considered, which could allow access to a wider range of angles than could a parabolic dish, at the expense of some difficulties with "feeds" conforming to the line focus of a spherical mirror. W. Low of ARPA/IDA put the Cornell

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[9] See, e.g., J.V. Evans, "Millstone Hill Thompson Scatter Results for 1964," Lincoln Laboratory Technical Report 430, 1967.

[10] Discussion with W.E. Gordon, 1990.

[11] There were many other eligible sites, e.g., in Hawaii, Mexico, and Cuba.

[12] Antennas at Sugar Grove and Green Bank are being used by the Navy and NSF's National Radio Astronomy Observatory (NRAO) today. The largest NRAO antenna at Green Bank collapsed in 1989.

[13] Discussion with Dr. C. Cook, 4/90, and Richard J. Barber, *History of ARPA*, 1958-75, p. VI-21.

group in touch with the Air Force Cambridge Research Laboratory, which had been doing research on spherical antennas for use at microwave frequencies.[14] After some further discussion, Cornell adopted the suggestion, which was recognized to primarily benefit the facilities' use for research on the moon and planets, rather than on the ionosphere.

ARPA finally responded positively to the Cornell proposal, first by AO 106 of 7/59 to undertake design and research planning studies and a little later with AO 122 of 12/59 for construction of a "1000-foot ionospheric probe." Apparently Dr. J. Ruina, then director of ARPA, felt that it was most important, at the time, to do good research in areas broadly related to DEFENDER, and that the Cornell proposal was a good example in point.[15] As DEFENDER developed, however, attention became concentrated on missile reentry phenomena below the ionosphere. This helped fuel continuing arguments about relevancy to ARPA mission, within ARPA and DoD, which apparently went on until the project was transferred to NSF in 1969.[16]

Construction of the initial open-wire mesh 1,000-foot dish took about 4 years. Relatively conservative bridge-type wire suspension technology was involved, yet a number of problems needed to be surmounted. The steel mesh was "fitted" into the depression, with provision for multipoint adjustments. Figure 2-1 shows a section through the planned structure, which involved suspending a carriage for the feeds from three concrete towers around the edge, together with an outline of initial specifications. A hole in the dish's center allows the feed-carriage to descend for repair. A control station at the dish's edge steers and turns the carriage. Building efficient line feeds of unprecedented size also proved difficult. A cooled parametric receiver was to be used, and provision was made for transmitting and receiving different polarizations.[17]

In November 1963 the facility was dedicated, about a year later than anticipated. The antenna's smoothness was determined by photogrammetry, and after a few months' adjustments the initially desired level of 1-inch average surface deviation, then considered

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[14] W.E. Gordon, op. cit.

[15] Dr. Ruina's philosophy was expressed in a 1967 Pugwash address, printed in "Impact of New Technology on the Arms Race," MIT, 1971, p. 304. Cf. also Richard J. Barber ibid., p. VI-24 where Ruina is quoted about the approval of his decision on ARECIBO by Dr. H. Brown, then DDR&E.

[16] Richard J. Barber, op. cit. p. VI-25.

[17] The planned capabilities of the facility were advertised in IRE's Transaction on antennas and propagation, "The Design and Capabilities of an Ionospheric Radar Probe," W.E. Gordon and W. Lelande, June 1961, p. 17.

compatible with uncontrollable motions of the feed carriage, was attained.[18] Figure 2-2 shows a photo of the antenna.

In early 1964 the "ARECIBO Ionosphere Observatory" began operations and revealed at once its unique capabilities due to the great resolution and gain of the antenna. A great deal of detail about the structure and dynamics of the ionosphere was quickly obtained. The data excited related activity on the part of plasma physicists, who recognized ARECIBO's possibilities as a precision instrument with which to test their theories, under conditions actually present in the ionosphere. However, "competition" was soon presented by the "topside sounder" satellites, which were actually the first to explore the upper ionosphere. The MILLSTONE HILL group were also very active in ionosphere investigations at this time.[19] As had been planned previously by the Cornell group, precise radar measurements were made of the distances to the moon and planets with results that have helped correct the orbital parameters for these astronomical objects, as well as the fundamental "astronomical unit."[20] Doppler returns gave information on the rotation of Venus and Mercury, and the smoothness and electromagnetic characteristics of the moon surface layers were determined with greater resolution (20 or 30 km) than ever before.[21] In the mid-1960s, systematic studies of lunar radar reflectivity began, which led to a NASA-supported project in the late 1960s to assist selection of a site for the lunar landings.[22] A number of new radio stars were also discovered and catalogued. After Pulsars had been discovered in 1968 in the United Kingdom, ARECIBO located the pulsar in the center of the Milky Way, which was considered to be an example of a "neutron star."

However, not many ARPA projects directly involved ARECIBO. Some of the early discussions, while the proposal was under consideration, involved some of the JASON group and others who were concerned with the structure of ionized

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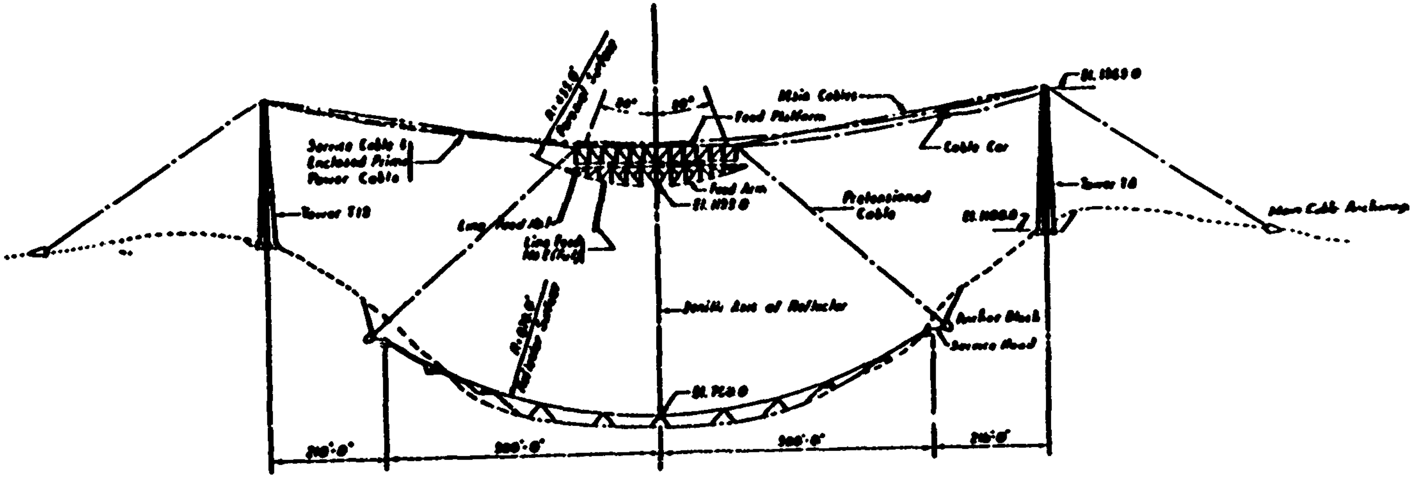
[18] W. E. Gordon, ibid., and "The ARECIBO Telescope 1974," The National Astronomy and Ionosphere Center, Cornell U. Ithaca, New York.

[19] J.V. Evans, op. cit.

[20] W.E. Gordon, IRE 1961, op. cit., and B. Hiatt, "The Great Astronomical Ear," The National Science Foundation MOSAIC (USGPO), Vol. II No. 2, 1980, p. 31. Cf. also "Radar Astronomy, " J. V. Evans et al., Ed., McGraw-Hill, 1968, p. 168.

[21] ARPA Annual Report of 1965 (declassified), p. 2, and Evans, ibid., p. 251.

[22] Discussion with W. Gordon and T. Thompson, 4/90. Cf. "Apollo 16 Landing Site: Summary of Earth-based Remote Sensing Data," NASA publication SP 315, 1972.



ELEVATION.

Outline of General Specifications

1. Elevations refer to U.S. Geological Survey datum for which El 0.00 is Mean Sea Level.
2. All concrete shall be of class "A" having an ultimate compressive strength of 3,000 psi minimum in 28 days.
3. All reinforcement shall be intermediate grade conforming to ASTM designation A 15 and A 308.
4. Except as otherwise noted, all steel for feed arm, track and platform shall conform to the current specification for steel for bridges and buildings, ASTM designation A 373.
5. The following criteria have been used for this preliminary design:
   - (a) Range of temperature change................ 30° F
   - (b) Wind velocity: Operating Conditions........30 MPH
     Ultimate Stability......................... 140 MPH
   - (c) Maximum rainfall intensity.............2"/15 minutes
   - (d) Existing ground contours shown on Cornell Survey Map PT-23
   - (e) Live load on feed structure is limited to maintenance crews and light tools.
   - (f) Impact to be the motion of feed arm of 100 degrees per minute in azimuth and of line feed at 10 degrees per minute in alteration.
   - (g) Normal bearing capacity of foundation tock to be 8 tons per sq. ft.
6. The entire reflector and feed system have been designed to conform to the basic data presented in Cornell Research Reports 395 and 435 and the general specifications outlined in the subcontract of Jan. 1, 1960.
7. All cables, steel structures and the exposed surface of concrete towers shall be given a finished coat of aluminim paint.

Figure 2-1. Plan Section of Antenna and Specifications

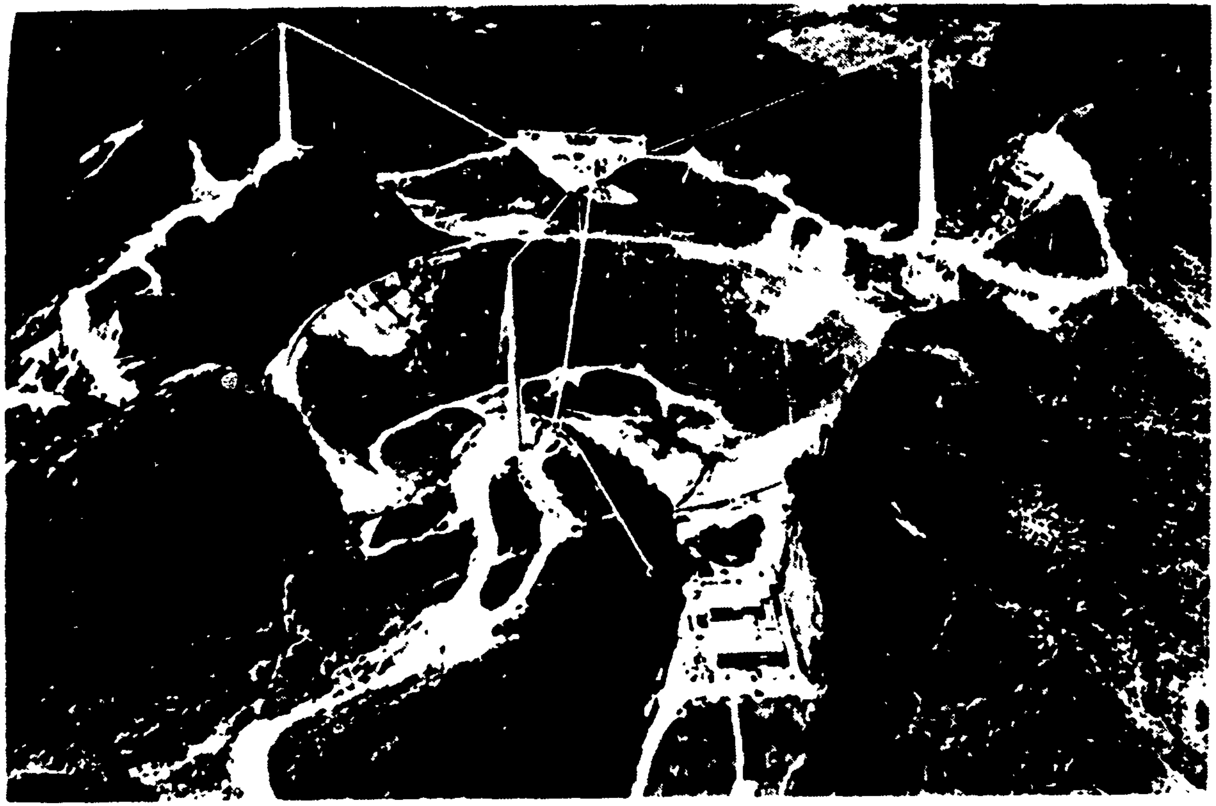


Figure 2-2. The ARECIBO Antenna

missile wakes.[23] There were also some attempts to correlate ARECIBO data with measurements made for the ARPA OTH radar project.[24] After the cancellation of the Navy's 600-foot antenna project, there was some interest in investigating ARECIBO's potential for receiving moon-bounce signals, but this was abandoned for reasons similar to those that had led to the cancellation. However, after the transfer of ARECIBO to NSF, an auxiliary "hf heater" antenna was constructed and a number of ionospheric projects have been conducted that, in retrospect, could have been judged to be relevant for DEFENDER.[25]

In 1980 about 20 percent of the facility's time was occupied with ionospheric and atmospheric work, and about 65 percent on radio and radar astronomy.[26] There have also been some uses of the ARECIBO radar's unique capabilities to infer the deployment of antennas and rotational motions of space probes at great distances.[27] However, in the mid-1960s when DoD was questioning ARPA's justification for ARECIBO, the researchers there apparently did not cooperate much in developing projects then considered relevant to DEFENDER.[28] ARPA successfully fought off these attacks and continued its support of ARECIBO, albeit reduced somewhat, until a formal transfer of responsibility was made to NSF in 1969.

After the transfer to NSF, the ARECIBO dish was reconstructed in the early 1970s with aluminum panels, which achieved an average smoothness of a few millimeters, permitting use at higher frequencies. The history of this upgrade goes back to the mid 1960s, when a smoothing upgrade to ARECIBO appears to have been proposed to NSF by Cornell. The Dicke Advisory Panel to NSF for large radio advisory facilities, noting that the ARECIBO carriage feed had moved less than 1/2" in hurricane Inez, concluded in 1967 that the ARECIBO upgrade was the most cost effective of many radio astronomy facilities then being proposed. NSF did not act, however, giving as reason lack of funds.

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[23] W. Gordon, op. cit.

[24] Some of these were done by Raytheon under AO 982 of 2/67.

[25] Some of these involved ionospheric heating experiments and the investigation of large scale ionospheric "holes" due to missile passage. Cf. MOSAIC, op. cit., p. 31.

[26] MOSAIC, ibid.

[27] E.g., L.B. Spence et. al., "Radar Observations of the IMP-6 Spacecraft at Very Long Range," *Proc. IEEE*, Dec. 1974, p. 1717. Some of this work was done by investigators from Lincoln Laboratory which has been very active in "Space Object Identification," mostly by imaging radars in the microwave range such as HAYSTACK, built with ARPA support in the early 1960s.

[28] Richard J. Barber, op. cit. At the time, there was also a general problem in DoD-University relations because of the Vietnam War.

Apparently in 1969 the Mansfield Amendment forced the issue, the Dicke panel was reconvened and reaffirmed its previous recommendation. NSF did act this time to carry out the upgrade.[29] NASA then provided a new high power transmitter with which ARECIBO was able to get data on the roughness of the surface of Mars, which were used in the selection of a suitable location for the VIKING Mars landing. The extension of useful frequency range at ARECIBO has allowed investigations to be conducted of weak molecular absorptions in the galaxies, which have also been used to confirm intergalactic distance scales. The aeronomic structure of the earths' atmosphere has also been explored using molecular absorptions, and the wavelike dynamics of the upper atmosphere and lower ionosphere have been investigated using the very weak reflections from gradients in refractive index.[30] The facility has also been used in the SETI project which attempts to detect "intelligent" radio emissions from the universe, so far unsuccessfully.[31]

The ARECIBO facility is now in use 24 hours a day for research, with many investigators vying for observing time. It is again being upgraded, incorporating a Gregorian type mirror which will reflect to a point focus and markedly increase the bandwidth, since line feeds of the type used hitherto have a narrow bandwidth. ARECIBO's characteristics have been re-examined recently by radio and radar astronomers who have concluded that it remains, in many ways, the most sensitive instrument available in its range of useful wavelengths. One recent estimate is that ARECIBO is about one order of magnitude more sensitive as a radar, at its shortest wavelength of about 13 cm, than the JPL GOLDSTONE when used as a single dish at its shortest wavelength of 8.5 cm.[32] The Bistatic GOLDSTONE-multiantenna very large array (VLA) combination may prove more sensitive, however.

C. OBSERVATIONS ON SUCCESS

The ARECIBO facility originated in a 1958 proposal from Cornell to ARPA. There was interest in properties of the ionosphere in ARPA's large project DEFENDER, and the facility described in the proposal offered prospects of obtaining data on its structure in a great deal of detail. There were also interests in a variety of rapidly developing areas, some

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[29] Cornell U., op. cit.

[30] MOSAIC, op. cit., p. 36.

[31] Ibid.

[32] Steven J. Ostro, "Planetary Radio Astronomy," *Encyclopedia of Physical Science and Technology*, McGraw-Hill, 1988, Vol. 10, p. 611.

of more military interest than others, and in which ARECIBO could make a possibly unique contribution. There were even political considerations involved, probably because of concerns about Puerto Rico's economy. However, the decisive fact seems to have been that Dr. J. Ruina, director at the time, was in favor of the proposal, following his philosophy of ARPA's supporting good research that is broadly related to areas of military interest.[33] In the short run many objections to this viewpoint could be, and have been, raised in DoD; nevertheless, over the years ARECIBO has produced a large amount of information which is, in fact, useful for the progressively more sophisticated models of the ionosphere and upper atmosphere required for defense-related projects.

ARPA did not respond to the original Cornell proposal with its then characteristic speed. This was due to several factors: the controversy within ARPA over the proposal's relevance to DEFENDER; the difficulties that were being experienced at the time by other ambitious, large antenna projects; and also because of a positive suggestion made by ARPA staff to use a spherical rather than a parabolic dish. This technical suggestion would not make a big difference in ionospheric research, which was ARPA's main stated justification for support, but could help a lot in radio and radar astronomy, and so added to the attractiveness of the facility for a wider range of investigators.

After construction and demonstration of its unique capabilities, ARPA sought to transfer the facility to NSF in the mid-1960s. NSF was not involved from the beginning due partly to an appreciation by Cornell that problems had started to plague that agency's radio astronomy initiative at Green Bank, and partly that the main thrust of their initial proposal was to be on the ionosphere, which wasn't a high priority area for NSF. In fact it was likely, at that time, that NSF would have pointed out that DoD had more ionospheric interests and that Cornell should try going to one of the DoD agencies.

It took a bit more than 4 years for the transfer of ARECIBO to NSF to be effected. This was not unusual, since NSF, largely due to its internal procedures, has had difficulty taking over large projects from other agencies, and when it does the process takes several years.[34] ARPA maintained enough support through this time, recognizing the facility's

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[33] A similar idea underlay ARPA's support of AMOS, under Dr. Ruina, initially intended to partly be for military, partly for open astronomical research. AMOS' history is different than ARECIBO's, however, having been used primarily for military work. See Chapter X, of Vol. I.

[34] Other examples include ONR's STRATOSCOPE II balloon astronomy project, the Air Force's Sacramento Peak Observatory, and the Interdisciplinary Materials Laboratories, discussed in Chapter 20 of Volume [illegible].

importance, to keep it viable until the transfer could be finally effected, notwithstanding a number of problems in justifying these actions to DoD.

ARECIBO, throughout its lifetime, has been continually upgraded in its electronics, computational capabilities, and in its antenna characteristics. It is now used around the clock, mainly by visiting scientists. It is expected that it will continue to be an important and productive national facility and the largest "filled aperture" antenna in the world. Today some of its chief competition comes from fields of antennas or "unfilled apertures," such as the multiantenna VLA, which can be linked with sophisticated processing techniques.

ARPA's outlays for ARECIBO, from project records, were about $9 million for the construction and initial operations, and about $10 million more in support of research through the transfer period to NSF for a total of about $19 million to 1970. NSF support currently has been about $7 million a year, and appears to have totalled more than $110 million to date.[35] The replacement value of the ARECIBO facility was estimated in 1974 as $100 million.[36]

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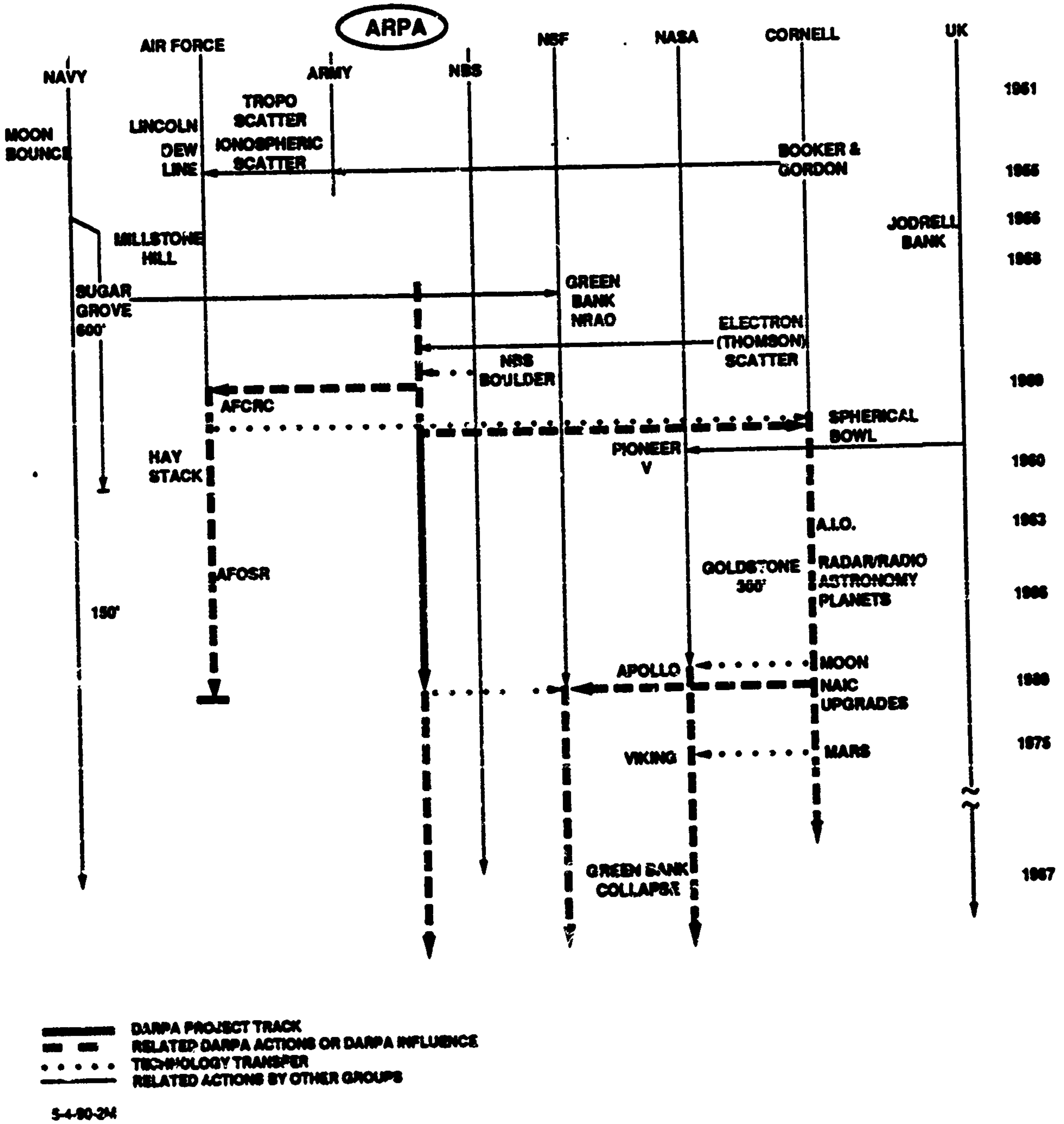
[35] In FY90 dollars. Discussion with Dr. F. Giovane, NSF, 4/90.

[36] Cornell U., op. cit.

ARECIBO


ARPA
NAVY
AIR FORCE
ARMY
NBS
NSF
NASA
CORNELL
UK
1951
MOON BOUNCE
LINCOLN
TROPO SCATTER
IONOSPHERIC SCATTER
DEW LINE
BOOKER & GORDON
1955
1956
JODRELL BANK
MILLSTONE HILL
1958
SUGAR GROVE 600'
GREEN BANK NRAO
ELECTRON (THOMSON) SCATTER
NBS BOULDER
AFCRC
1959
SPHERICAL BOWL
PIONEER V
HAY STACK
1960
A.I.O.
1963
AFOSR
GOLDSTONE 350'
RADAR/RADIO ASTRONOMY PLANETS
1966
150'
APOLLO
MOON
NAIC UPGRADES
1969
VIKING
MARS
1975
GREEN BANK COLLAPSE
1987
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS
5-4-90-2M

III. HIBEX - UPSTAGE

A. BRIEF OVERVIEW

HIBEX (High Booster Experiment) was a 2-year research project to investigate the technology of a very high acceleration, short range anti-ballistic missile interceptor, for hard point defense. The HIBEX missile achieved nearly 400 g peak axial and over 60 g lateral acceleration, reaching a velocity of nearly Ma = 8, in a little over 1-sec burn time, with pitch over from a vertical ejection from a silo to a trajectory of 15 deg elevation. In 2 more years, UPSTAGE, a maneuvering HIBEX second stage, demonstrated over 300 g lateral acceleration and a side-force specific impulse $I_{sp} > 1000$ sec using external burning, jet flow control techniques and a laser gyro for guidance. The HIBEX technology furnished the basis for the Army's LoADS short range interceptor program. UPSTAGE jet maneuvering control technology has been incorporated into the SDI's HEDI missile.

B. TECHNICAL HISTORY

A number of early U.S. studies of Ballistic Missile Defense (BMD) indicated that the problem of active defense of restricted-area "hard points" appeared much more tractable than that of defending larger urban areas, the primary emphasis of the Army's NIKE ZEUS BMD project. A presidential decision in late 1962 led to the cancellation of NIKE ZEUS and the start of the NIKE X R&D program.which involved development of hardened phased-array radars capable of computer-controlled acquisition and tracking of a large number of reentry objects, and a two-stage high acceleration missile, SPRINT, which was to intercept and kill reentry vehicles (RVs) by an explosion of its nuclear warhead at altitudes of about 45,000 ft. SPRINT was launched after "atmospheric filtering" had allowed better discrimination of the threat RV from decoys.[1]

About the time of this Presidential decision, there were also further studies of alternatives to NIKE X, involving a variety of radar and missile systems, with a view to

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[1] ABM project history, Bell Telephone Laboratory, Oct. 1975, p. I-33, ff.

possible future hard point defense.[2] Hardpoint BMD appeared to be easier than urban defense for a number of reasons. The defended target is "harder," and the stakes were lower than urban defense. Technically, the radar ranges could be shorter, search could be confined to a narrow "threat corridor," and atmospheric filtering simplified the problem of sorting out the real threat RVs. However, the time for intercept action was compressed into a narrow "window" (see Fig. 3-1) requiring a very high acceleration missile. Also, the hardened large phased array antennas being constructed by BTL for NIKE X were expensive, and economic hard point defense required that such antennas have lower cost.

Shortly after the NIKE X decision, ARPA's project DEFENDER commenced investigation of several key advanced concepts for hard point defense, including a high acceleration missile in its HIBEX project, together with the HAPDAR (Hard Point Demonstration Array Radar), a low cost hardened phased array radar.[3] Previously, ARPA had investigated other advanced BMD concepts but had not, to this point, undertaken any

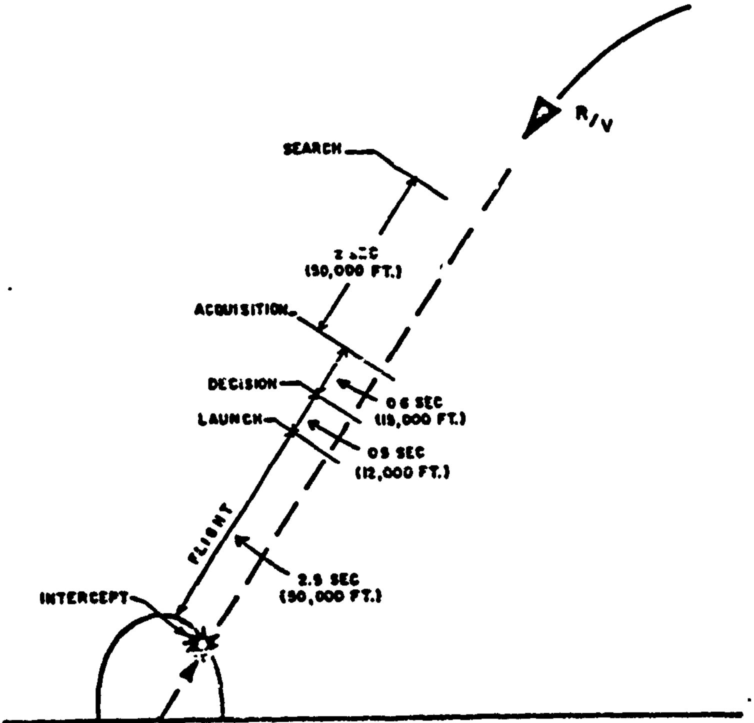

Figure 3-1. Hard Point System "Window" Profile[4]

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[2] Eg., Intercept X, conducted by IDA.

[3] AO 510 of 9/63, HIBEX, and AO 516 of 10/63, HAPDAR.

[4] From "Introduction for HIBEX," by V. Kupelian, Bulletin of the 20th Interagency Solid Propulsion Meeting, July 1964, Vol. III, p. 338 (declassified).

booster development under DEFENDER. Its earlier CENTAUR and SATURN projects had aimed at space flight and in both cases, after early funding critical to getting them started and some brief technical involvement by ARPA, the major part of the technical development of these vehicles was done by other agencies.[5] In the case of HIBEX, in contrast, ARPA was in close control throughout.[6]

Besides exploring the technical boundaries of high acceleration missiles and the associated control problems, ARPA's interest at the time also encompassed the possibilities of non-nuclear kill of RVs, and the feasibility of firing a second interceptor if the first one failed.[7] While the possibilities of using HIBEX alone for intercept were considered, the ARPA concept also included a second stage which might be able to execute the "high g" maneuvers required to "chase" maneuverable RVs, then beginning to be studied.[8]

At the time of these investigations it was known that propellant wakes could absorb and refract electromagnetic waves. Therefore, the ARPA concept envisioned command guidance from the ground during a "coast" phase of HIBEX flight, after propellant burnout. In the actual HIBEX experiments, however, no attempt was made to do any external guidance. Internal, closed-loop guidance was used.

Preliminary studies of HIBEX indicated (see Fig. 3-2) that accelerations of several hundred g's and burnout velocities of about Mach 8 would be required. HIBEX was to be launched vertically, from a small silo, and afterwards would "pitch over" to a direction suitable to accomplish intercept, requiring high "g" also transverse to its axis (Fig. 3-3).

It did not seem possible, based on information from the initial HIBEX studies, to be able to use a scaled vehicle for tests in the usual scheme of engineering research.

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[5] CENTAUR and SATURN are discussed in Chapters IV and V of Volume I.

[6] Discussion with V. Kupelian, 12/87.

[7] Discussion with A. Rubenstein, 11/87.

[8] A. Rubenstein and V. Kupelian, ibid. One such MaRV was ARPA's MARCAS, AO 569 of 4/64.

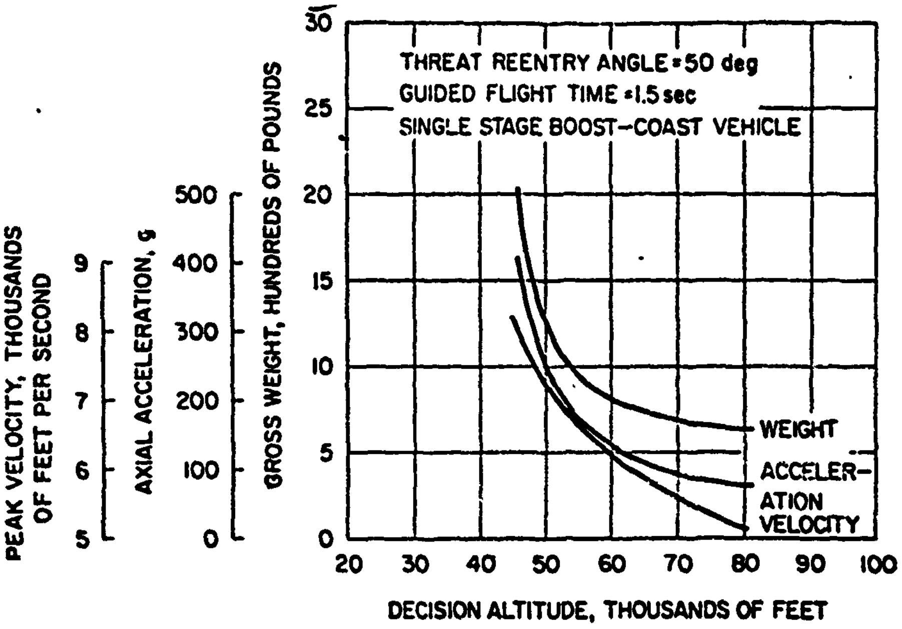

Figure 3-2. Effect of Commitment Altitude on Interceptor Characteristics (From Kupelian, op. cit.)

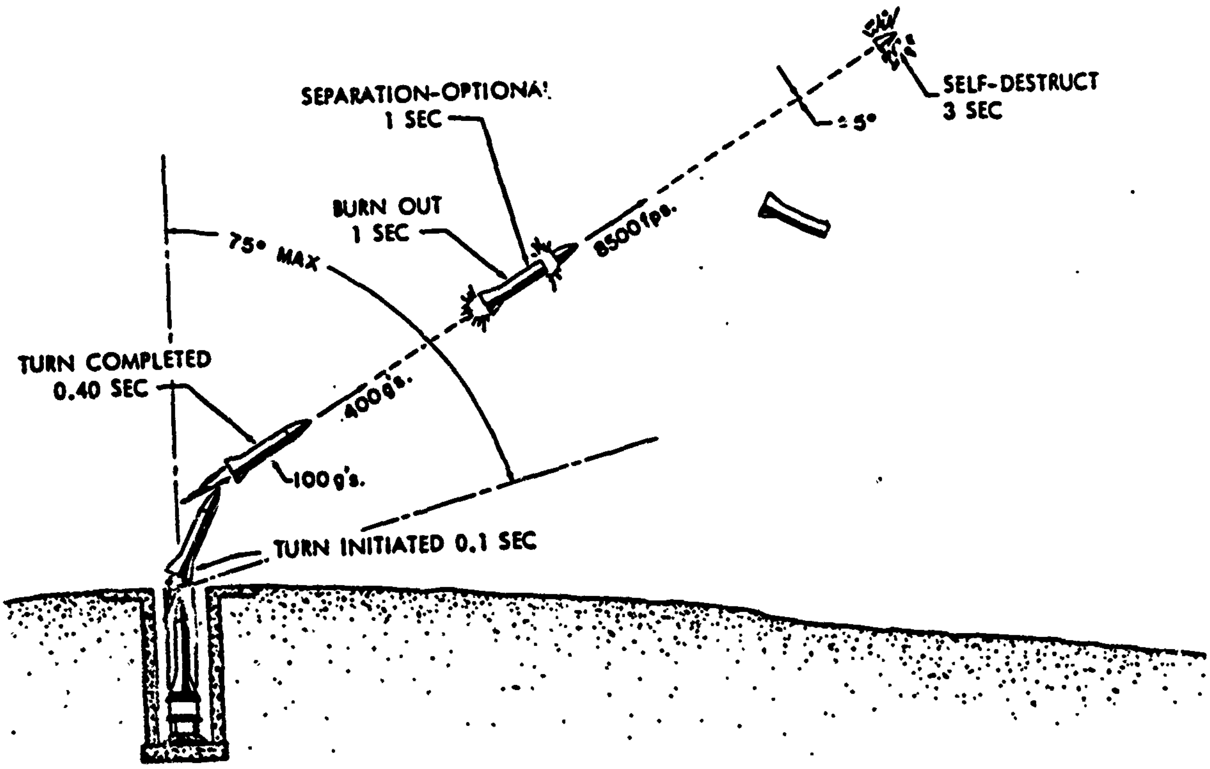

Figure 3-3. HIBEX Experiment Mechanization (from Kupelian, op. cit., p. 387)

Therefore it was decided early-on, to undertake HIBEX as a series of full scale field tests. This was more risky, but if successful the results could be more convincing. The performance desired was higher than SPRINT's first stage (although the two-stage SPRINT achieved a higher terminal velocity and a longer flight); also HIBEX would be a much smaller vehicle. As a research program, the boundaries of performance to failure could be explored in HIBEX without the constraints of practicality imposed in engineering a system for production. In contrast, because a near-term production was expected, SPRINT had these kinds of constraints.

In particular HIBEX required a higher burning rate propellant than was available, and one which could stand several hundred "g's" without undue deformation or fracture. Technology was available to increase the burning rate by addition of small metal fragments, and also for strengthening the propellant "matrix," but tradeoffs were required. Measurement techniques had not been developed for such important quantities as propellant strain in the regime of stress expected. Consequently, a series of static firings was made to test successive approximations to eligible propellants.

At the time of HIBEX, aerodynamic characteristics of vehicles in hypersonic flight with large angles of attack were not well known. Wind tunnel tests were performed to assist in gaining understanding of the forces and moments; but the stability of the actual system was somewhat a matter of guesswork, with fortunately compensating errors made in design parameters.[9]

An outline of early HIBEX requirements is shown in Figure 3-4. Boeing was chosen as prime contractor, with Hercules for propellant development. A large number of measurements were planned for each flight, in accordance with the exploratory nature of the investigation. Besides being in entirely new parameter ranges, the measurement instruments themselves had to withstand very severe environments. The HIBEX flights took place at White Sands Missile Range (WSMR) and took advantage of the telemetry and optical range instruments there. Figure 3-5 shows a cut-through diagram of HIBEX. Strap-down mechanical gyros, the only technology then available, was used for guidance in both stages. The first flight was a test of the booster and did not involve on-board flight guidance. The second and later flights incorporated on-board control and involved tests of thrust vector control in one, and later in two dimensions. Thrust vector control was

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[9] Discussion with V. Kupelian, 12/87.

achieved by injection of liquid Freon, as with SPRINT. The final flights involved maneuvers of 75 deg in pitch and 45 deg in azimuth. In the last (7th) successful flight a second stage incorporated a propellant which was burned externally in order to achieve very high transverse impulse.

HIBEX Requirements

- **Experiment - Full Scale**
- **Vertical Silo**
- **300 lb Second Stage (15 in. x 15 in.)**
- **Burnout Velocity 8000 FPS in 1 second**
- **Elevation 15° to Vertical**
  Azimuth ± 45° } **Controllable**
- **0.5 Second: Available for PreLaunch Commands**
- **Program not to exceed 2 years**
- **Flight and Ground Instrumentation**
- **Existing WSMR Facilities**
- **Data and Test Reports**

Figure 3-4. HIBEX Requirements[10]

The original 2-year schedule for HIBEX slipped by 2-months, but six out of seven flights were successful. An explosion at one of the propellant testing facilities required reimbursement.[11] Such explosions of advanced propellants were not unusual.

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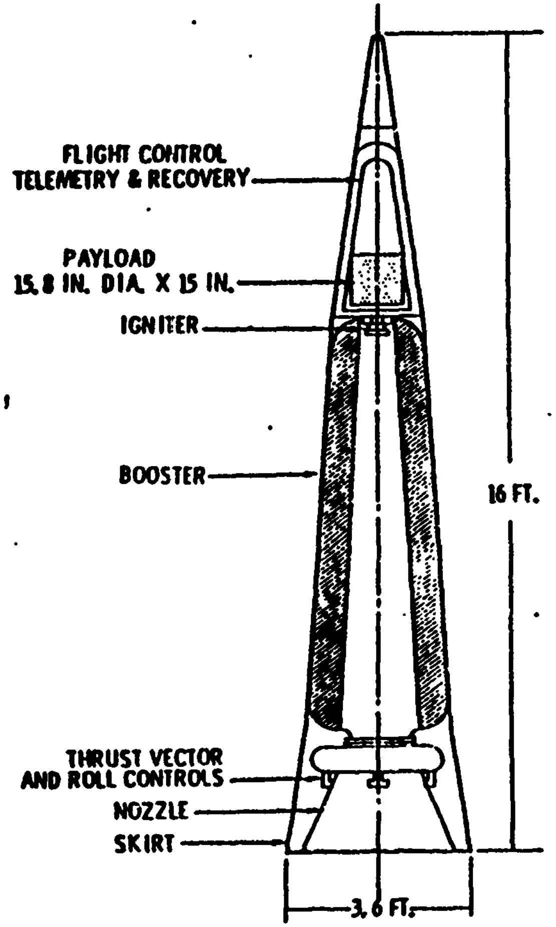
[10] From "HIBEX Booster Development," by E.V. Moore and A.M. Jacobs, *Bulletin of the 20th Interagency Solid Propulsion Meeting*, July 1964, Vol. IV, p. 39, (DECLASSIFIED).

[11] AO 93 of 5/66, HIBEX Explosion Payment, $ .5 million.



BOOST DURATION	1.0 SEC
BOOST THRUST	490,000 LB
PAYLOAD WEIGHT	300 LB
PROPELLANT WEIGHT	1687 LB
B/O VELOCITY (VERTICAL) (LAUNCH WT. = 2577 LBS)	8450 FT/SEC
B/O VELOCITY (15°) (LAUNCH WT. = 2637 LBS)	7290 FT/SEC
MAXIMUM LONG ACCELERATION	377 g
MAXIMUM NORMAL ACCELERATION	60g

HIBEX TEST VEHICLE CONFIGURATION & PERFORMANCE

Figure 3-5. HIBEX Test Vehicle Configuration & Performance (from Moore and Jacobs, op. cit.)

In its flight test HIBEX reached an axial acceleration of about 362 g's, and about 60 g's lateral acceleration. The project results indicated that even higher accelerations were possible.[12] The last two flights originated from silos. Measurements were made also of acoustic over-pressures in the vicinity.

Table 3-1 shows a comparison of HIBEX parameter objectives and achievements. Despite the 2-month extension of schedule, the project was accomplished at low cost with five fewer "shots" then originally contemplated.[13]

Table 3-1. HIBEX Flight Performance*

Item	Objective	Achieved
Boost Burn Time	1.05 Sec.	1.124
Burnout Velocity	8,000 fps	8,408 fps
Weight of Second Stage	300 lb	295-303 lb
Trajectories with Programmed Turns From Vertical To:		
Elevation	15 deg.	15 deg
Azimuth	± 45 deg.	45-deg.
Burnout Velocity Vector Error	± 5 deg	1.8 deg. maximum
Stage Separation	Favorable for Missile Guidance	Favorable for Missile Guidance**S

*Source: Moore and Jacobs, op. cit., p. 22.

A HIBEX symposium was held in 1966, to present its results, and several (classified) articles were published later in the *Journal of Defense Research.*[14]

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[12] HIBEX Final Technical Report, Boeing, March 5, 1966 (DECLASSIFIED), p. 22.

[13] Boeing, ibid., p. 396.

[14] "HIBEX," an experiment in high acceleration boost for BMD, by C.R. Smith, *Journal of Defense Research*, Vol. 2A, 1970, p. 170 (CLASSIFIED).

Toward the end of HIBEX, some external burning propellant experiments were conducted with encouraging results. A study was then made of a maneuvering second stage interceptor, UPSTAGE, which would incorporate external burning for sidewise thrust.[15] PRESTAGE, the immediate follow-on project to HIBEX, was carried out in the 1965-68 time frame, to investigate external burning in a controlled hypersonic flow environment and the corresponding problems of thrust control, axial and lateral.[16] "Disposable" vanes were studied along with lateral jets for thrust vector control. PRESTAGE was carried out by McDonnell-Douglas,[17] and included laboratory and flight test experiments, using available rocket motors.

After PRESTAGE, project UPSTAGE began in 1968, dedicated to investigation of a second stage for intercepting maneuvering RVs. A HIBEX vehicle was used for UPSTAGE's first stage. The UPSTAGE effort covered second stage separation phenomena, control system, thrust vector control generation techniques and mechanisms, guidance, aerodynamics, structure and communications. The UPSTAGE vehicle was designed with "lifting" aerodynamic characteristics. An important new guidance feature incorporated was a laser optical gyro, which required no "spin-up," and which had been developed partly with ARPA funding.[18]

External guidance for UPSTAGE was provided by a command guidance link and tracking by the ZEUS target-tracking radar at WSMR. "Finlet" injections were used to provide transverse thrust. UPSTAGE reached several hundred lateral g's with response times of milliseconds. The UPSTAGE maneuvers were controlled in a simulated MARV chase but no actual interceptions were attempted.[19] The tests were generally successful and indicated the feasibility of the technology along with a need to better understand external burning.

In another follow-on project Radar Homing On-Board Guided Intercept (RHOGI) was investigated.[20]

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[15] AO 595 of 7/64, UPSTAGE.

[16] AO 765 of 8/65, PRESTAGE.

[17] Douglas had also been the NIKE ZEUS SPRINT contractor.

[18] AO 744 of 6/65.

[19] V. Kupelian, ibid.

[20] AO 873 of 3/66.

In 1975 a Presidential decision was made to deploy SAFEGUARD, an advanced version of NIKE X, to defend Minuteman missiles, then not considered a "hardened" system. SAFEGUARD involved SPRINT missiles in silos. After Congress voted to keep U.S. BMD in an R&D status, the Army's subsequent HARDSITE and LoADS programs involved a missile similar to HIBEX in general descriptions of weight and size.[21] V. Kupelian, ARPA's HIBEX project manager, was for a time in the Army's ABMDA, in charge of missile-related work in terminal BMD. So far, LoADS has been formally cancelled, but the Army apparently considers its technology to be "on the shelf."

The SDI R&D program for wide area defense does not involve a short range terminal defense missile. However, SDI includes HEDI (High Endoatmospheric Defense Interceptor), a missile incorporating UPSTAGE jet maneuvering control in endo atmospheric intercept, but at somewhat higher altitudes than HIBEX's range.[22]

C. OBSERVATIONS ON SUCCESS

HIBEX and UPSTAGE were key projects in ARPA's DEFENDER program for hard point defense. In accord with the DEFENDER assignment, these projects explored the boundaries of possible performance of high acceleration missiles for intercept of RVs. HIBEX was widely recognized to have been an impressive R&D achievement. While HIBEX is often compared with the SPRINT system then being built under the Army's BMD program, it must be recognized that SPRINT had the major constraints of a system being engineered for production deployment on a limited time schedule.

UPSTAGE also had a very ambitious objective of demonstrating a capability for chasing MaRV's, a mission not emphasized in the SPRINT system design, and possibly coming close enough for non-nuclear kill. UPSTAGE was successful in demonstrating much of what might be achieved with external burning, but some questions were left for further R&D.[23]

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[21] Thomas M. Perdue, et al., "Low Altitude Defense for MX (U)," *Journal of Defense Research*, 82-3, 1982.

[22] AIAA Assessment of Strategic Defense Initiative Technologies, March 15, 1982, p. 32.

[23] Project UPSTAGE, Progress Report, May 1968, McDonnell Douglas Company (CLASSIFIED). See also "Interaction Control Techniques for Advanced BMD Interceptors," by D.F. Hopkins, et. al., *Journal of Defense Research*, Vol. 9, 1979, p. 274.

Through personnel and information, the HIBEX/UPSTAGE technology as well as other aspects of the ARPA hard point defense program seems to have been effectively transferred to the Army. Treaty restrictions have allowed only R&D on the HARDSITE and LoADS concepts. The Army did build and test a hardened phased array radar; and the success of HIBEX is indicated by the fact that the LoADS interceptor missile has not had a development program, but is described as having gross characteristics similar to HIBEX[24] and is regarded as "off the shelf," readily available technology. The ARPA-developed laser inertial guidance system is regarded as readily available also. SDI does not include a missile like that in LoADS probably because SDI is aimed primarily at area, rather than terminal defense. SDI's HEDI missile for high endoatmospheric intercept however, does incorporate UPSTAGE jet maneuvering technology.

From project records ARPA outlay for HIBEX appears to have been about $25 million and for UPSTAGE (including PRESTAGE) about $26 million.

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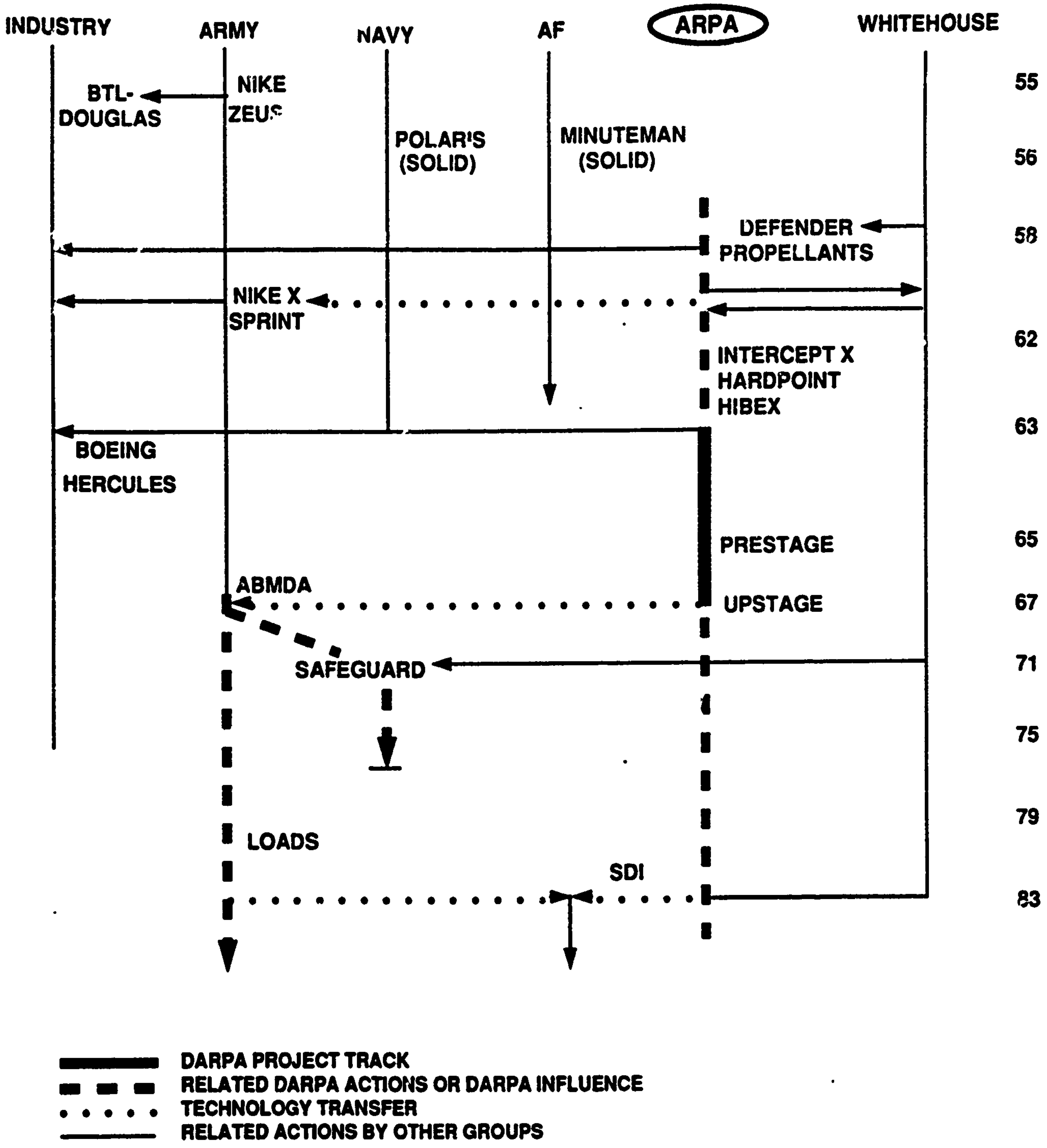
[24] Perdue, op. cit.

HIBEX/UPSTAGE



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IV. PENAIDS

A. BRIEF OVERVIEW

Through project DEFENDER, ARPA made early contributions to the capabilities of ICBMs to penetrate Soviet Ballistic Missile defenses. A direct assignment by DDR&E in 1961 led to a dedicated ARPA effort on advanced offensive technology for assuring penetration by United States ICBMs, which included support of the Pen X study recommending use of MIRVs. In the mid 1960s as part of the ARPA joint Service-ABRES program, ARPA developed several advanced technology options for possible use as penetration aids (PENAIDS), including observables management, jammers, chaff, and reaction-jet controlled manuevering reentry vehicles (MARVs).

B. TECHNICAL HISTORY

In late 1957, shortly after Sputnik, the DoD established the Reentry Body Identification Group (RBIG) to consider whether measures should be taken to assure that U.S. ICBMs could penetrate possible Soviet ballistic missile defenses (BMD).[1] The RBIG concluded that the possibility of BMD should indeed be taken seriously and recommended that research be pursued on countermeasures, which later were called "penetration aids" (PENAIDS).[2] The countermeasures considered by the RBIG included: decoys, chaff, jamming, possible use of missile tankage and other fragments other than the reentry vehicles (RVs) carrying the ICBM warhead; reduction of the RV radar cross-section; the "blackout" that could be produced by a "precursor" nuclear explosion in the upper atmosphere; and using multiple warheads to saturate the defense.[3] The RBIG considerations were remarkably comprehensive; most of the work on PENAIDS in the following years was along one or another of the lines suggested by that group.

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[1] H.F. York, "Multiple Warhead Missiles," *Scientific American*, Vol. 229, No. 5, 1973, p. 71.

[2] There had been previous study by RAND and others of the ICBM penetration problem, and the White House-level Gaither Committee had a panel also led by W.E. Bradley, which considered possibilities of both ballistic missile defense and offense.

[3] D.J. Fink, "Strategic Warfare," *Science & Technology*, Oct. 1968, p. 59.

The Bradley subcommittee of the President's Science Advisory Committee, (PSAC) convened a little later, reviewed the ICBM penetration problem again and pointed out that while decoys or chaff should work to some extent outside the earth's atmosphere, there were many unknowns in the phenomena of RV reentry into the atmosphere. Some of these unknowns, the Bradley group pointed out, were at the quite fundamental level of properties of atoms and molecules existing in the hypersonic shocks and wakes occurring in reentry, and in the even more complex conditions that would be caused by nuclear explosions.

In the burst of post-Sputnik U.S. Government activity in early 1958 leading to the formation of ARPA, one of its first major assignments--and the one then stated to be the top priority--was project DEFENDER, to look into advanced aspects of ballistic missile defense beyond those approaches being developed and produced by the Services; chief among these was the NIKE-ZEUS BMD system being built by the Bell Telephone Laboratories for the Army.[4] It was understood even at these early stages that the BMD and penetration problems were two sides of the same coin, so to speak, and that any approaches to solutions of both required a common scientific understanding of the observable phenomenology of ICBM flight, from launch to reentry. The second priority of the ARPA program had to do with accelerating development of space technology, especially for surveillance satellites, which were required to more certainly determine features of the ICBM threat.[5]

At this time most attention was being given, in both the Air Force and Navy ballistic missile programs, to getting the missiles (and in the Navy also the Polaris submarines) built and deployed. There had been concern for some time in these programs about how to design and construct RVs to assure their survival of the intense heating of reentry. Two broad approaches to the survival problem had been followed, one using blunt-nosed "heat sinks," and the other involving ablation of outer layers of RV material, which might permit use of a more slender RV body. The expectation that nuclear explosions would disturb the reentry environment added the requirement for the RVs to withstand the associated heating and nuclear radiations. It was clear early-on that RV materials and aerodynamic shapes were inter-related and both would have strong effects on reentry observables. Some of the first steps in the ARPA DEFENDER program were toward obtaining good full-scale data

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[4] House Subcommittee on DoD Approriations, 1985 Congress, 2nd Session. Hearing on the Advanced Research Projects Agency, April 25, 1958, testimony of R. Johnson, p. 292.

[5] Ibid.

as soon as possible on reentry phenomena, using the U.S. missile test program just beginning.[6]

The proceedings of early ARPA meetings on project DEFENDER indicate the wide range of current activity, reflecting the RBIG guidance, including: field measurements and the associated radar, infrared and optical instruments needed to make them; fundamental atomic and molecular physics involved in reentry phenomena; nuclear effects; effects of hypervelocity impact of dust, rain and projectiles on RVs; decoy packaging and discrimination; ICBM fuel tank explosion effects; exoatmospheric infrared detection of cold decoys; interceptor flight characteristics; directed radiation weapons; and radar component technologies.[7] Some of the earliest missile flight tests included decoys and chaff.[8]

One of the earliest explicit scientific discussions of an approach to a penetration aid, an RV with low radar cross-section, was given by a scientist from the United Kingdom at an early review for ARPA's Anti Missile Research Advisory Committee (AMRAC) in 1960.[9] Recognizing that much exploratory and research work had to be done in DEFENDER, ARPA held a series of meetings at which such scientific papers were elicited in order to more clearly define the status of understanding. The U.K. scientist pointed out the advantages of a slender conically shaped RV for lowering radar observability, and outlined several other general approaches to reducing radar cross-sections.[10]

Also in the early 1960s, the Air Force's FORECAST I study recommended that conically shaped RVs be used because with a high weight-to-drag ratio (usually termed "Beta"), these could give greater accuracy and, would penetrate further before slowing down than would blunt-nosed RVs.[11] Conical-shaped RVs were in fact developed by the

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[6] E.g., W.R. Hutchins, "ARPA FY 1959 Program," ARPA BMD Technology Program Review, 3-14 Aug. 1959, p. 13, (declassified). In 1960, ARPA noted that U.S. data on our own reentry objects were generally from off-axis broadside observations near Ascension Island. Any terminal defense (e.g., NIKE ZEUS) required looking head-on at RVs. So ARPA funded the DAMP ship in June 1961 to make observations head-on of U.S. RVs launched from Patrick Air Force Base into the Atlantic. Radar, optics, and IR sensors were placed aboard the DAMP ship. Observations included RV oscillations and radiation from reentry objects. Discussion with A. Rubenstein, IDA 7/90.

[7] ARPA 1959 BMD Review, Table of Contents--much of this early ARPA effort was carried out under AOs 5 and 6 of 4/59, with many tasks. AO 39 of 3/59 included a task on Decoy Packaging.

[8] E.g., Summary of KREMS Tests Through 30 June 1979, Lincoln Laboratory, 1979 (CLASSIFIED).

[9] T. Dawson, "Radar Camouflage Aspects of the Blue Streak Re-entry Head Design," *AMRAC Proceedings*, Vol. II, July 1960 (CLASSIFIED).

[10] T. Dawson, ibid., and K. Siegel, et al., in *Journal of Missile Defense Research*, 4, No. 4, p. 379 (CLASSIFIED).

[11] Discussion with BGen. R. Duffy (Ret.), 5/90.

Air Force in the early 1960s to use on follow-ons to Minuteman I missiles.[12] But blunt-nosed RVs continued to be used for some time on the larger ATLAS and TITAN ICBMs.[13] It was soon appreciated that the observables and PENAIDS for the blunt and slender RVs would be quite different.[14] Also, while slender conical shaped RVs would have the advantages of lower shot dispersion and radar cross-sections, these also had severe volume constraints and would be subject to high thermal and aerodynamic loadings during reentry.[15] In turn, these thermal and aerodynamic factors affected RV observables, such as radar fluctuations due to body geometry and motion and the high temperature wakes affected by "seeding" by RV material ablation and evaporation.

It became clear relatively soon that what had been considered simple exoatmospheric PENAIDS, such as chaff, in fact involved complex practical difficulties, such as ejection of long wires in order to obtain a satisfactory distribution of scattering objects in space. It was also clear quite soon that "atmospheric filtering" would likely be the most effective means for BMD to sort out RVs from reentering decoys and other fragments. The implication was that to penetrate terminal BMD one would have to develop decoys with Beta comparable to those of the RVs and with similar wake phenomenology, but under constraints of small weights and volumes this was a difficult task.

In the late 1950s and early 1960s there was growing evidence of a serious Soviet BMD program.[16] In late 1961 Dr. H. Brown, then DDR&E, assigned ARPA the task of providing the Joint Chiefs' Weapons System Evaluation Group (WSEG) the task of providing technical inputs for their study of the capability of U.S. ICBMs to penetrate Soviet BMD, and to develop a comprehensive base of related technology.[17] In early 1962 ARPA commenced a dedicated PENAIDS program.[18]

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[12] First Minuteman RV's were blunt.

[13] Due to their large warheads, the Soviets had less need for accuracy and used blunt-nosed RVs for some time. Cf., ABRES 1962-ASMS 1984, TRW, Inc., 1985, p. 15 and p. 2.

[14] A. Grobecker, "Parametric Considerations for Design of Penetration Aids," IDA TN 61-27, Dec. 1961 (CLASSIFIED).

[15] Apparently a satisfactory solution to these problems was not achieved until the mid 1970s (TRW, op. cit).

[16] Sayre Stevens, "The Soviet BMD Program," in *Ballistic Missile Defense*, Brookings, 1984, p. 182 ff.

[17] Richard J. Barber, *History*, p. V-24, quotes the memo from H. Brown, DDR&E, giving the assignment.

[18] "Second Report of IDA Committee on Penetration Effectiveness of Decoyed ICBMs," IDA TR 62-14 (CLASSIFIED).

At about the same time as the PENAIDS assignment ARPA provided funds for the TRADEX measurements radar and other measurement instruments at Kwajalein where NIKE-ZEUS tests were to be conducted, and also commenced investigation of new BMD concepts. For exploration of one of these new approaches to BMD, called ARPAT, the AMRAD high-resolution measurement radar was constructed at the White Sands Missile Range (WSMR). It was anticipated that using AMRAD and the NIKE-ZEUS radars already at WSMR, together with multistage missiles which would augment reentry velocity to that of ICBMs, would be advantageous for testing RVs and penetration aids, as well as new BMD concepts, for reasons of economy, efficiency, and security. This early ARPA program provided for on-board RV measurements of reentry wake and hypersonic shock layer properties; exploration of nuclear effects; investigation of the properties of RV materials as these were affected by thermomechanics of reentry; radar, IR and optical observables; and active jamming by decoys.[19] Studies were also commenced on the overall "system" and cost effectiveness of the balance between ICBM penetration options and BMD.

In late 1962 DoD commenced the joint Services-ARPA ABRES (Advanced Ballistic Reentry Systems) program, to more directly coordinate under DDR&E all the efforts related to ballistic missile penetration in the exoatmospheric and terminal reentry phases. Apparently some initial funding for ABRES came through ARPA, but in early 1963 management responsibility was given to the Air Force which had the major part of the program, while DoD conducted regular monthly review and coordination meetings.[20] As its part of ABRES, ARPA continued investigations of advanced penetration aids and provided critical measurements using the PRESS sensors at Kwajalein.[21]

In the early 1960s there were increased concerns and sharper technical appreciations of the characteristics of Soviet BMD which U.S. ICBMs would have to penetrate. The Soviets conducted some large nuclear tests and, significantly, also a "live" test of a BMD system under conditions involving nuclear explosions--something never done in the United States programs.[22] The United States NIKE X program also indicated the characteristics of a sophisticated BMD system that might eventually be developed by the Soviets.

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[19] AO's 413, 415, 440, 441.

[20] SAMSO Chronology, USAF Space Command, 1975, p. 123. The ABRES meetings were first chaired by the then ADDR&E for missile defense, D. Fink.

[21] PRESS is discussed in Chapter I of this volume.

[22] Sayre Stevens, op. cit., p. 193.

One of the immediate reactions to these new threat developments and concerns was the Navy's upgrade of the penetration capabilities of the Polaris missile system with multiple reentry vehicles (MRVs).[23] The MRVs all would have the same urban target, but would complicate the Soviet problem of BMD--the assessment was that the Soviet system, like the earlier NIKE ZEUS, would have difficulties handling multiple RVs.[24] Also in the early 1960s, the Air Force FORECAST I study had pointed out the possibility of multiple independently targeted reentry vehicles (MIRVs). A number of relatively independent technology developments, in this same time frame, for satellite deployment and for separation of RVs in ICBM tests, also suggested the MIRV possibility.[25] The decisive push to U.S. MIRV development, however, appears to have been due to other factors: a Strategic Air Command requirement to be able to attack 3,000 Soviet military targets, and the decision by Secretary of Defense McNamara, on economic grounds, to limit the AF ICBM force to 1,000 Minuteman missiles--providing a direct incentive for each Minuteman to have multiple high-accuracy warheads.[26]

To get a clearer picture of the cost-effectiveness of different "mixes" of penetration aids (other than warheads) and MIRVs, the DoD commissioned the Pen X study, a large-scale 6 month effort conducted by IDA and budgeted through ARPA.[27] The Pen X results indicated that MIRVs had several advantages, but that a "mix" of MIRVs with other penetration aids would also be useful under many circumstances.[28] Pen X appears to have influenced subsequent DoD decisions generally favoring the use of MIRVs.[29] Up to this time, most of the activity regarding PENAIDS had been on paper.[30] However, the Air Force, then and later, did not give PENAIDS a high priority.[31]

The large size of the Soviet Galosh BMD missile, exhibited in late 1964, indicated a capability for long-range intercept, with a large nuclear warhead. With this new background, in the mid-1960s ARPA undertook investigation of a number of

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[23] H. York, op. cit., p. 22.

[24] R. Duffy, op. cit.

[25] H. York, op. cit., p. 18.

[26] I. Getting, *All in a Lifetime*, Vantage 1989, p. 479.

[27] A.O. 741 of 6/65.

[28] The PenX Study, IDA R-112 (Summary) August 1, 1965, (CLASSIFIED).

[29] R. Duffy, op. cit., and Richard J. Barber, *History*, p. VII-9.

[30] Fink, op. cit., p. 59, R. Jayne, "The ABM Decision," MIT Thesis, 1975, p. 257, and R. Duffy, op. cit.

[31] Duffy, op. cit., and discussion with MGen. Toomay (Ret.) 4/90.

exatmospheric PENAID approaches. Along the lines of the first early ABRES emphasis on LORVs (low observable RVs) ARPA investigated new radar-absorbing RV materials, "impedance loading," active ECM, and related power supplies.[32] While much of this early LORV effort appeared not to have been not very successful, at least one ECM approach, developed in part through ARPA efforts, seems to have met with some acceptance as a possible PENAID.[33]

Another major ARPA PENAIDS effort in this period was HAPDEC (hard point decoy), a decoy-RV combination which would involve wake and radar cross-section "management" to make discrimination more difficult down to low altitudes where hardpoint terminal defenses would operate.[34] HAPDEC was designed during a time when ARPA started several efforts on hardpoint defensive technology which could be assumed to be eventually "mirror-imaged" by the Soviets. HAPDEC was flight-tested in the ABRES program, but seems not to have been adopted due, in part, to weight and complexity.[35]

In the early and mid-1960s several analyses were done of the possibility of MARVs. Some of these approaches involved guiding flaps, or change of RV body shape. The possibility of MARV attack on hardpoint defensive systems motivated ARPA's HIBEX/UPSTAGE program, having a second-stage UPSTAGE interceptor capable of reaction-jet controlled maneuvers.[36] A little later similar reaction jet technology was applied in the ABRES-ARPA MARCAS (Maneuvering Reentry Control and Ablation Studies) MARV program.[37] A number of successful MARCAS flight tests were conducted at WSMR.[38] However, scaling up the MARCAS jet control technology apparently involved unacceptable weight penalties.[39]

During the mid-1960s work on PENAIDS (both system and technology oriented) was at its peak. At that time both the Navy and Air Force had PENAIDS systems work going on for POLARIS/POSEIDON and Minuteman, as well as the ABRES program.

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[32] AOs 679, 705, 779, 803.

[33] TRW, op. cit.

[34] HAPDEC, AO 920 of 9/66.

[35] TRW, op. cit., p. 15.

[36] HIBEX/UPSTAGE is discussed in Chapter III of this Volume.

[37] AO 929, of 10/66.

[38] *AMRAC Proceedings*, 1968 (CLASSIFIED) contains several papers on MARCAS.

[39] Duffy, op. cit., and TRW, op. cit.

Expenditures amounted to several hundred million dollars per year. ABRES alone was supported at just under $150 million/year.

After transfer of defense-oriented DEFENDER projects to the Army in 1967-8, ARPA's PENAIDS activity was also reduced and characterized in ARPA statements as "mature."[40] Subsequent ARPA activity, related to both PENAIDS and BMD, moved more toward exploration of exoatmospheric optical and IR phenomena, and means of obscuring or detecting these.[41] This ARPA work has contributed to the database for SDI and countermeasure technology for the Air Force's efforts in follow-ons to ABRES, now conducted under the Air Force Advanced Strategic Missiles Systems (ASMS) Program. Related midcourse observations useful for ABRES ASMS, and also for BMD, continue to be made at the ARPA-built AMOS optical and IR telescopes and imaging radars. Similarly useful data continue to be obtained by the ARPA-built sensors at the Army's KREMS (Kwajalein reentry measurement system) site.

C. OBSERVATIONS ON SUCCESS

The early RBIG study gave a comprehensive outline of the areas of research required for PENAIDS and BMD. The subsequent DoD PENAIDS assignment, together with the earlier DEFENDER assignment, put ARPA in the unique position of being a key participant in both the offensive and defensive aspects of BMD. For both aspects, also, ARPA was to be a source of independent and critical technical information for DoD. ARPA's contribution to both aspects may have been greatest through the PRESS measurements of reentry phenomena at Kwajalein. Other aspects of the DEFENDER program, such as investigating nuclear effects, and vulnerability of RVs to non-nuclear attack, also made important contributions to the development of PENAIDS. DoD took a strong direct role in control of the PENAIDS efforts about 1963, with the Pen X study and the institution of ABRES, which ensured coordination and technology transfer, while the Air Force conducted the major part of the program.

ARPA's direct contributions to PENAIDS technology, while real, do not seem to have had a major impact. Apart from MIRVs which apparently had multiple origins, PENAIDS were a susbstantial factor in the U.S. ICBM and SLBM developments.

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[40] P.J. Friel, "Project Defender, Progress and Future," *AMRAC Proceedings*, Vol. XVIII, 1967, p. 87 (CLASSIFIED).

[41] E.g., AO 1846, Plume Physics, and P.J. Friel, op. cit.

PENAIDS were deployed on Minuteman I and II and POLARIS and were developed for Minutmen II and TRIDENT I. The PenX study appeared to have had an effect on the DoD-level decision on MIRVs. While the use of conical RVs seems to have been accepted quite early, mainly on grounds of their accuracy, their low radar cross-section seems also to have been considered a sufficient PENAID against the then estimated Soviet BMD threat. It apparently took a long time, from 1963 to 1976, to arrive at a satisfactory RV nose cone.

Two former long-term participants in ABRES on direct query, while agreeably crediting ARPA with contributions to advanced PENAIDS technology development (which were formally or informally transferred to ABRES) could not recall any major impact of the specific ARPA-supported efforts.[42] These directors also felt that the PENAIDS program had been under-funded, through most of its life and not a major Air Force priority. While initially this may have been due to a low appreciation of the BMD threat, apparently the feeling grew within DoD in the early and mid-1960s that saturation of enemy defenses was the appropriate offense--conservative tactic because unexpected advances in decoy discrimination techniques, which could not be entirely discounted, could rapidly degrade RV penetration capability.[43] Later, the BMD treaty removed much of the impetus for PENAIDS-related efforts.

ARPA expenditures directly for PENAIDS, from project records, appear to have been about $25 million to 1968.

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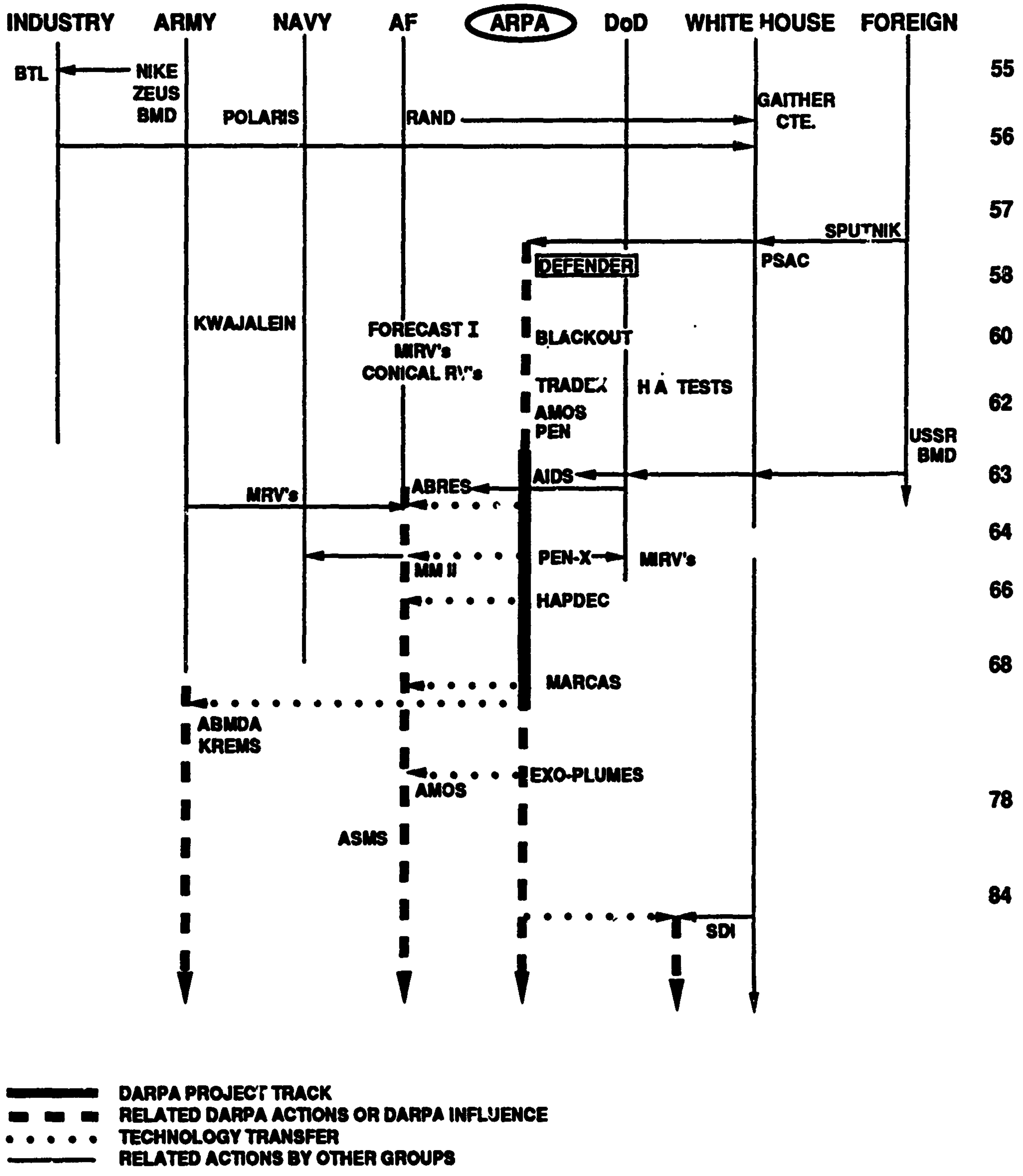
[42] Duffy and Toomay, ibid.

[43] T. Greenwood, *Making the MIRV: A Study of Defense Decision Making*, Ballinger, 1975, Appendix A, p. 163.

PENAIDS



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TACTICAL TECHNOLOGIES

V. ASSAULT BREAKER

A. BRIEF OVERVIEW

Soviet conventional warfare doctrine for Europe historically has called for initial attack forces to break through NATO forward defenses at selected sectors of the NATO defense border, with exploitation by fresh forces moving through the gap in defenses created by the breakthrough. Various forces following the initial attack at the front are essential to Soviet operational concepts. These forces may be configured in one of the following ways: as second echelons to reinforce the breakthrough attempt if it meets high resistance; or as Operational Maneuver Groups to move into NATO's rear and disrupt the support for an orderly defense in depth; or as exploitation and pursuit forces should NATO's defenses crack.[1] To enable NATO's forward defenses to perform their tasks successfully, NATO's counterstrategy has always contemplated the need to disrupt, delay and ultimately halt the movement and attack by these Soviet/Warsaw Pact (WP) "follow-on" forces. The DARPA ASSAULT BREAKER concept combined many interrelated and complementary systems for this purpose.

The ASSAULT BREAKER program accomplished unprecedented integration of radar, missile, and submunition technologies to demonstrate a capability to attack multiple tank targets using terminally guided submunitions released from a standoff "missile bus" controlled by an airborne radar (see Fig. V-3). It also represented a pioneering and ambitious effort by DARPA that successfully nested major programs within larger programs, and combined them in a coordinated way to achieve the overall objective. ASSAULT BREAKER significantly impacted the joint Army-Air Force JSTARS battlefield surveillance radar and the Army's ATACMS missile system, both of which are currently in

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[1] There has been no suggestion that the Soviet force consolidation implicit in the current (1989-90) European force reduction talks has discarded this doctrine. Rather, some of their literature suggests that they may feel better able to implement it under conditions of reduced conventional force postures in Europe, because (in their view) Soviet forces would be better integrated while NATO's would become more fragmented. See United States General Accounting Office, Supplement B, to a report to the Chairmen, Committees on Armed Services, U.S. Senate and House of Representatives, *NATO-WARSAW PACT Conventional Force Balance: Papers for U.S. and Soviet Perspectives Workshops*, Appendices VIII, IX, and X, December 1988.

the early steps of procurement. These programs involve a new degree of inter-Service operational cooperation. NATO established Follow-On Forces Attack (FOFA) as a "critical military area" based in part on the successful early demonstration of the ASSAULT BREAKER concept, and is now planning and developing several weapons-mix "packages" that incorporate ASSAULT BREAKER-type technologies. The program history is summarized in Figure 5-1.

B. TECHNICAL HISTORY

1. Program Origins

In the late 1960s and early 1970s, considerations of approaching NATO/WP nuclear parity led to the Strategic Arms Limitations talks. There were many studies and projects related to needed improvements in conventional arms.[2] A particular problem was the potentially large conventional force asymmetry, which would make it very difficult for NATO to withstand multiechelon WP attacks. It was widely recognized that this problem required some approach allowing effective attack of many mobile targets at once and in a relatively short time period.[3] During the same period, the Vietnam and the Israeli wars had taught several lessons regarding the potency of ground-based air defenses and the potential of "smart" weapons. Also in this period the U.S. Army was developing the concept of Air-Land battle in the extended battlefield[4] requiring precise fire support at longer ranges than had been considered earlier. In the late 1970s, the Army had begun studies of replacement or upgrades of the Lance missile which, with its nuclear capability, was a mainstay of NATO force posture.

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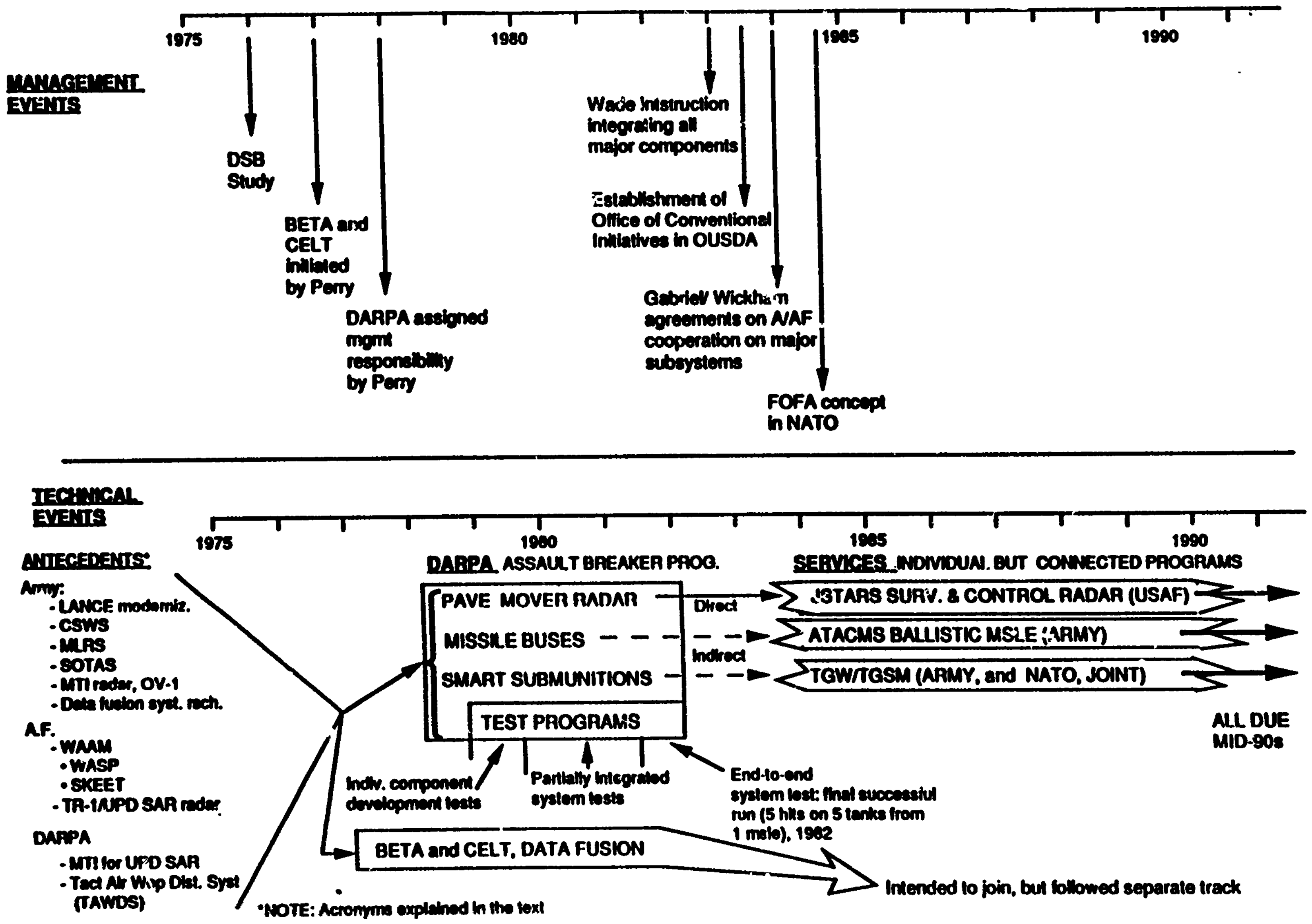
[2] U.S. efforts in these developments go back at least to the early 1960s, see A.C. Enthoven and K.W. Smith, *How Much is Enough*, Harper, 1969, Chap. 1.

[3] A declassified briefing-summary of many of the then current concepts can be found in IDA Paper P-1062, *Methods of Improving the Ability of U.S. Forces to Engage Mobile Targets in a Tactical European Environment*, August 1974. The importance of this report was in pointing out the high leverage of terminally guided submunitions (TGSMs) dispensed from air or ground-launched missiles if they could be made to work, and in demonstrating the importance of a real-time link between standoff radar and time of arrival (TOA) target location systems, and guidance of a missile "bus" to the point where it should release its TGSMs.

[4] The extended air-land battlefield concept was apparently first promulgated in the 1982 version of the Army's FM 100-5.



*NOTE: Acronyms explained in the text

Figure 5-1. Short ASSAULT BREAKER History

In the mid-1970s the Defense Science Board (DSB) reviewed available technologies for possible approaches to the needed improvements of conventional armaments in the European theater.[5] An important input to this study was made by F. Marian from Martin Marietta, who sketched for the DSB the dimensions of a possible Soviet attack on NATO. He showed the potentially high leverage that could be obtained by use of the Martin Marietta concept of a ground launched "Battlefield Interdiction Missile" that could dispense submunitions capable of homing on and attacking several tank targets simultaneously. Some of the work on such a missile had been supported by DARPA.[6] Terminally guided submunitions (TGSMs) that might use infrared or millimeter wave seekers were in various stages of development in the Air Force and Army Missile Command (MICOM) programs. The DSB study also reviewed the technologies for detection and location of targets, such as "time of arrival" electromagnetic intercept systems and, particularly, high resolution synthetic aperture radars and Moving Target Indicator (MTI) radars in aircraft.

The DSB concluded that all these technologies, or achievable modifications of them, could be integrated into a feasible warfighting system. It was anticipated that such a system, operating together with a facility to "fuse" the information about targets, could effectively counter the "second echelons" of the expected Soviet attack configurations. Some of these approaches, the DSB pointed out, would require an unprecedented degree of interdependency of Army and Air Force operations.[7] The DSB panel also noted that no organized attempt had been made up until that time to put together the technologies to demonstrate the kind of approach they felt would be worthwhile, and their report recommended that this should be done. Because of the strong inter-Service interdependency that would be involved, the DSB also felt that some kind of special management scheme was required. It should also be noted that this kind of attack would

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[5] Final Report, DSB 1976 Summer Study on *Conventional Counterforce Against a PACT Attack* ODDR&E, May 26, 1977 (CLASSIFIED).

[6] E.g., ARPA order 2209, of April 1972, A.O. 2238 of July 1972. Apparently there were similar concepts offered by other companies at the time. The Martin Marietta contribution to the DSB considerations was mainly in their impressive portrayal of the overwhelming nature of a potential WP attack against NATO and the need for a massed fast response. Discussion with Dr. J. Luquire, June 1989.

[7] DSB 1976 Summer Study, p. 21.

require an unprecedented degree of coordination and timing in the target acquisition/strike sequence, a process the Director of the Weapons System Evaluation Group (WSEG)[8] at the time, LtGen Glenn Kent, USAF, had called "target engagement." This posed a severe technical challenge, in addition to the many doctrinal challenges inherent in the concept.

The USDR&E, Dr. Perry, responded to the DSB recommendation in 1978 by giving DARPA management responsibility of the project called ASSAULT BREAKER in recognition of its purpose. Dr. Perry established a flag-level steering group and Executive Committee with Secretarial participation to guide the fast-paced program envisaged.

Dr. Perry also set up (in 1977) the Joint Services (and DARPA) BETA project to develop and demonstrate a state-of-the-art, near real-time information fusing facility for operations on an extended battlefield, including ASSAULT BREAKER. BETA was also associated with CELT (Coherent Emitter Location Testbed), initially envisaged by DARPA as part of an overall approach to precise target location in the ASSAULT BREAKER program. CELT would contribute information to BETA, which would "fuse" all available target information to provide target location and identification data for weapon firing and control. However, all these projects were pursued on such compressed time scales that there was no opportunity to put BETA and CELT together with the ASSAULT BREAKER program.[9]

As noted previously, there were antecedents in related DARPA and Service work dating back to the early 1970s.[10] In the mid-1970s DARPA pursued the key concept of modifying the Air Force-developed UPD synthetic aperture radar (SAR) to obtain MTI (moving target indicator) capability. This effort later turned into the joint DARPA-Air Force Tactical Air Weapons Direction System (TAWDS) project. With such a radar, targets could be identified and tracked, and a TGSM-dispensing missile guided to a mobile

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[8] WSEG was a part of the Office of the Joint Chiefs of Staff, organized in the early 1950s to evaluate joint Service weapon system concepts for the JCS. The Institute for Defense Analyses (IDA) provided analytical support to WSEG, through combined IDA/WSEG civilian/military analytical teams. WSEG was thus in a position both to reflect and to influence Service views in complex system design and acquisition matters.

[9] J. Tegnelia, et al., "History of ASSAULT BREAKER and Related Projects," *Journal of Defense Research*, 1984 (CLASSIFIED). CELT and BETA individually had significant impact, the two additional programs are described separately in this volume.

[10] See the DSB summer study report. Also, ARPA orders 2228 of August 1972, and 2479 March 1973 "IR Terminal Guidance," and 2878 of Sept. 1974, "Tactical SAR Experiments."

target. DARPA apparently briefed this concept to Dr. Currie, then DDR&E, and obtained his backing for it.[11]

There had been related earlier efforts that caused the Services some hesitancy in moving ahead rapidly with the DARPA program. The Army had several related ongoing programs going back to the MARS rocket project in the 1960s, abandoned because of the number of missiles required in one-on-one engagements. By the mid 1970s the ongoing Army programs included the Lance modernization already mentioned; the MLRS launcher for firing multiple rockets with unguided anti-materiel warheads; the Corps Support Weapon System, a rocket intended to have TGSMs and related dispensing and seeker technologies, then mainly in exploratory development; the standoff target acquisition system (SOTAS) helicopter radar; the ALARM MTI radar on the OV-1 aircraft and other ELINT systems; and an all source analysis tactical data fusion system. In the same time frame the Air Force had an ongoing wide area anti-armor munitions (WAAM) project, which included the WASP, a small, high velocity, air launched missile, and submunitions such as the AVCO SKEET self-forging fragment munition. For long range battlefield surveillance, the Air Force was developing the high altitude TR-1, a successor to the U-2, which was to carry the UPD-SAR. Each service wanted, to the extent possible, to have an organic capability to undertake their respective missions, with the Army covering the near battlefield and the Air Force doing deep interdiction, a separation of responsibilities dating back to the "Key West" agreement of 1947. There was a degree of accepted interdependence in operations, partly due to lack of capability of the systems. For example, the Air Force's SAR had high resolution, but couldn't detect and track moving targets very well, while SOTAS lacked resolution and range but was designed to track close-in moving targets.

Despite early Service coolness, the new ASSAULT BREAKER program was eventually supported by the Army, to the extent that MICOM became the DARPA agent for the ground-based missile and TGSM work, recognizing its potential for going beyond LANCE modernization. The Air Force Electronic System Division (ESD), the agent for the TAWDS (Tactical Air Warfare Direction System) radar development (eventually renamed PAVE MOVER) also became an enthusiastic participant. For both these programs, substantial "up front" DARPA funding was made available. The DoD approved

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[11] Discussion with J. Luquire, 6/89.

continuation of the Service in-house development programs related to defeating the Soviet second echelon attack, in addition to ASSAULT BREAKER.

There was also provision in the early ASSAULT BREAKER program for an air-launched missile. This, however, met with resistance by the Air Force's Eglin ASD group, which had the WAAM responsibility.[12] The ASD group apparently did not like the idea of an air-launched ballistic missile from tactical aircraft and preferred the idea of a cruise missile which had a loiter capability, or an air-launched straight-in high velocity rocket attack.

Both Services recognized that an attack on the tank top, which has thinner armor, would have a better chance of success with a small munition delivering either a shaped charge (requiring a direct hit) or a self-forging fragment (SFF) (fired from a distance). Both Services, while recognizing the criticality of the anti-armor capability, also wanted a "mix of weapons" to deal with the variety of targets that would be involved in a WP attack.[13]

Despite the importance assigned by DoD to ASSAULT BREAKER, Congress did not fully back the program, initially putting off funding for a year because of skepticism about its management. However, DARPA went ahead, with a tight schedule and apparently using available funds.[14] (A little earlier DARPA had provided for support of effort on the BETA information fusion system.[15] Beginning somewhat earlier, also, the DARPA anti-armor effort was accelerated.[16] The DARPA-AF PAVE MOVER program also began in May of 1978.[17] A terminal-guidance seeker program had also been going on, including investigations of millimeter-wave seekers.[18])

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[12] J. Luquire, see footnote 6. Eglin, however, had the responsibility for setting up the ASSAULT BREAKER missile tests.

[13] See e.g., L.D. Buelow, et al., "Antiarmor Survey and Evaluation," AFCMD/SA, Kirtland Air Force Base, February 1984, p. 3, "Summarizing Conclusions of the WAAM Anti-Armor study of the 1977-1980", and "Technologies for NATO's Follow-on Forces Attack Concept," OTA, 1986, for a list of weapons mixes in different "packages."

[14] DoD Authorization Hearings for FY 1980, Committee on Armed Services, HOR, 96th Congress, 1st Session, Research and Development, part 3, p. 913. A.O. 3628, of May 1978, ASSAULT BREAKER.

[15] A.O.'s 2367 of December 1972 and 3596, March 1978, BETA.

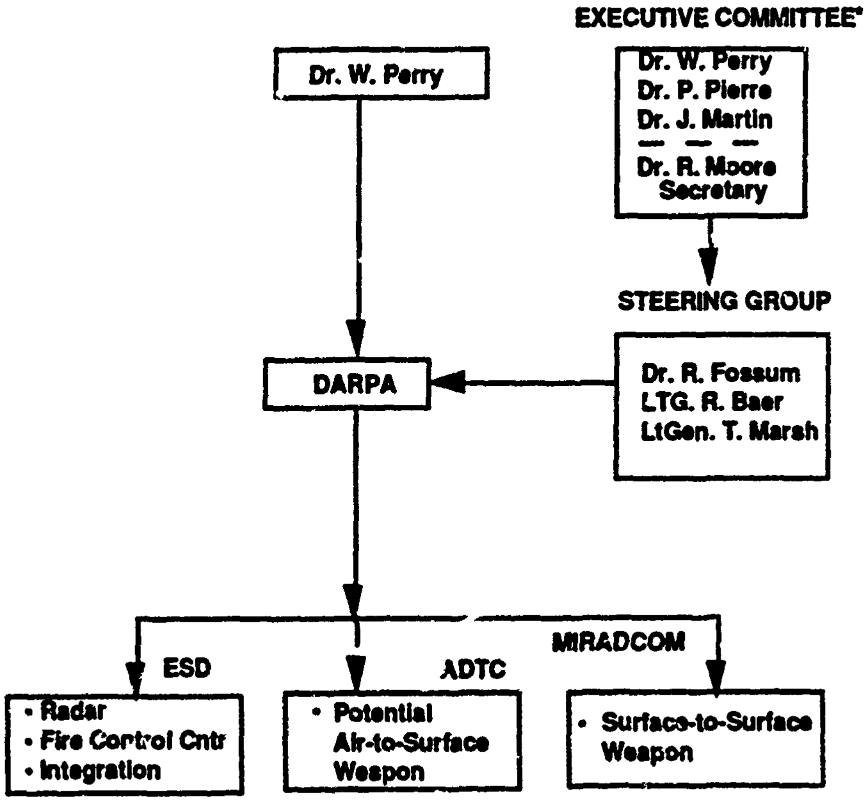
[16] A.O. 3580, Anti-Armor, March 1978.

[17] A.O. 3628, PAVEMOVER, May 1978.

[18] A.O. 3146, March 1975.

2. The DARPA ASSAULT BREAKER Program

Because of the inter-service aspects and many interfaces, the ASSAULT BREAKER program was managed directly by DARPA (and the Steering Group, which was quite active).[19] There was no industrial integrating contractor. The management scheme, devised by explicit decision for the ASSAULT BREAKER program, is shown in Figure 5-2.



*Will include appropriate general officers.

Figure 5-2. Management Scheme for ASSAULT BREAKER Project (Ref. 14)

The ASSAULT BREAKER concept is illustrated in Figure 5-3. The target is detected and located by an airborne radar, operating at some standoff from the front line. This information is passed to an "attack coordination center," also developed and built in the project, to do processing of the radar data and "fusion" of this with information from

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[19] J. Luquire, discussion, 6/89.

other sensors and other sources.[20] Since some of the targets are mobile, a rapid decision about the attack must be made at the coordination center. A ground based ballistic missile was to be guided by its own inertial system until "acquired" and given a guidance update, if needed, by PAVE MOVER. From this update point on, the missile trajectory is to be controlled by PAVE MOVER, in coordinates relative to the aircraft. Such guidance would enable the missile to reach a "basket" near the target area, where submunitions are released to home on the targets. The submunition dispersal pattern could be controlled to some extent to match the target distribution. Working backward from the characteristics of these submunitions determined the dimensions of the "basket" in space and time, and thus the guidance accuracy requirements. For fixed targets, the missile's own inertial system was accurate enough to be relied on. The submunitions had to be able to "recognize" the target, home in on it, and, depending on the munition, either hit the target (TGSM) or fire a penetrating pellet against it (SKEET). Broadly, the ASSAULT BREAKER type of concept had been discussed earlier,[21] but this was the first time it was actually assembled and tried.

The ASSAULT BREAKER program had four phases. The first phase involved a focussed effort on the component technologies--verifying that they really were available and that their performance estimates added up to a feasible overall concept.[22] The second phase involved testing most of the critical component technologies in parallel, and making further developments as necessary. At least two contractors were involved in all the tests and developments. Thus, there were two different approaches, by Hughes and Norden, to the PAVE MOVER radar system and for the related ground processing stations; two "missile bus" contractors, Martin Marietta for the Patriot (T16) and LTV for the Lance (T22) missile; and two contractors, General Dynamics (TGSM) and AVCO (SKEET), for the submunitions.[23] Submunitions components were tested individually, with emphasis on the required dispensing and homing properties to accomplish the "end game."

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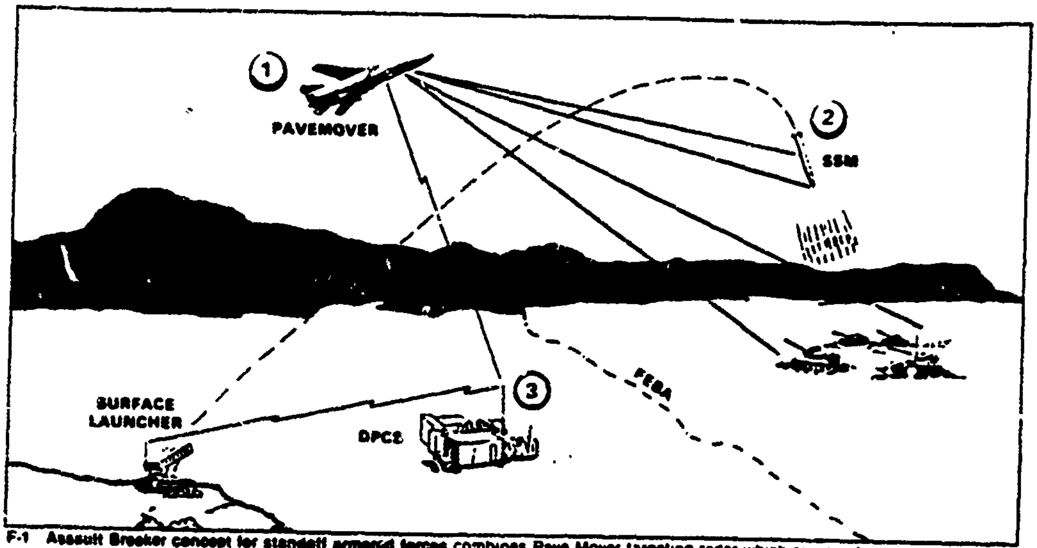
[20] The "fusion" was initially expected to be done in the BETA facility, but actually BETA was not used in any of the ASSAULT BREAKER trials, see Chapter VI.

[21] IDA Paper P-1062, op. cit.

[22] BDM Report, "History of ASSAULT BREAKER," 1985.

[23] Only a few tests of the kill mechanisms were conducted, apparently, partly because of the considerable data available from previous efforts on SKEET and TGSMs.



F-1 Assault Breaker concept for standoff armored forces combines Pave Mover targeting radar which surveys forward battle area, a ground-based data processing station where target engagement is established, radar tracking of the targets, and the launching of missile carriers. When over targets, a carrier dispenses self-contained submunitions to make multiple kills.

Figure 5-3. ASSAULT BREAKER Concept for Standoff Armored Forces Combines Pave Mover Targeting Radar Which Surveys Forward Battle Area, a Ground-based Data Processing Station Where Target Engagement is Established, Radar Tracking of the Targets, and the Launching of Missile Carriers. When Over Targets, a Carrier Dispenses Self-Contained Submunitions to Make Multiple Kills[24]

Submunitions dispensing was tested separately from the actual missile using wind tunnels and high speed tracks, and homing properties were determined in "captive" flight tests using helicopters and fixed facilities elevated above the targets. Much effort was devoted to determining the capability of the submunition seeker systems to discriminate targets, specifically tanks, from infrared backgrounds such as would occur under battlefield conditions. Similarly, armor penetration was tested off-line so that other system testing could be done with inert munitions. Both the General Dynamics TGSM and AVCO SKEET qualified successfully in these trials. In the PAVE MOVER radar program Hughes and Norden both succeeded in developing and demonstrating radars capable of accurately locating and tracking targets, and "interleaving" the SAR and MTI target acquisition modes of the radars as well as their ability to acquire a missile and guide its flight. However, the

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[24] BDM Report, *History of ASSAULT BREAKER*, 1985. This figure is an unclassified excerpt from this classified report.

software for the radars and ground stations apparently proved more extensive and complex than first estimated, causing some delay in the overall program.

In the third phase gradually more complex degrees of system integration were tested. Missile flight tests were conducted, first with inertial guidance only: the T-16 used a Stellar-sight gyro update and the T-22 used an Army-developed optical laser gyro. Later, radar guidance, ground and airborne, was used to steer the missile. Both missiles qualified successfully, achieving the desired accuracies. After this, tests were made including integration of the submunitions with the missile, along with increased complexity in the command signals directing the time, location, and characteristics of submunitions release. Finally, in the last phase of the program, tests of the combined airborne radar-missile-submunitions systems were conducted against some tank targets at White Sands. The final tests (which involved a ground-based radar simulating the PAVE MOVER) in late 1982 had several failures; but in the last test five General Dynamics TGSMs made five direct hits, one on each tank in a pattern of five stationary tanks. The SKEETs, however, did not achieve any hits in these final tests.

A schedule of some of the different phases of ASSAULT BREAKER is shown in Figure 5-4, and the success record in Figure 5-5. The final tests, while successful, unfortunately did not include all features desired, partly for lack of sufficient funding.[25] Nevertheless, it seems generally agreed that the major technological features of an ASSAULT BREAKER capability had been demonstrated by the DARPA program. Proof of concept was established and a decision could have been made to enter full scale engineering development if the Services had adopted ASSAULT BREAKER as a system.

3. Transition

The transition from proof of principle to operating systems has a complicated history, however. OSD set up the follow-on JTACMS (Joint Tactical Missile System) program with the Air Force and Army in 1982-83, while the Air Force and the Army continued separately with the PAVE MOVER and SOTAS radars. Despite this and continued encouragement by Congress for a closely integrated program, the Services did not react quickly. The JTACMS concept required the Army to be operationally dependent

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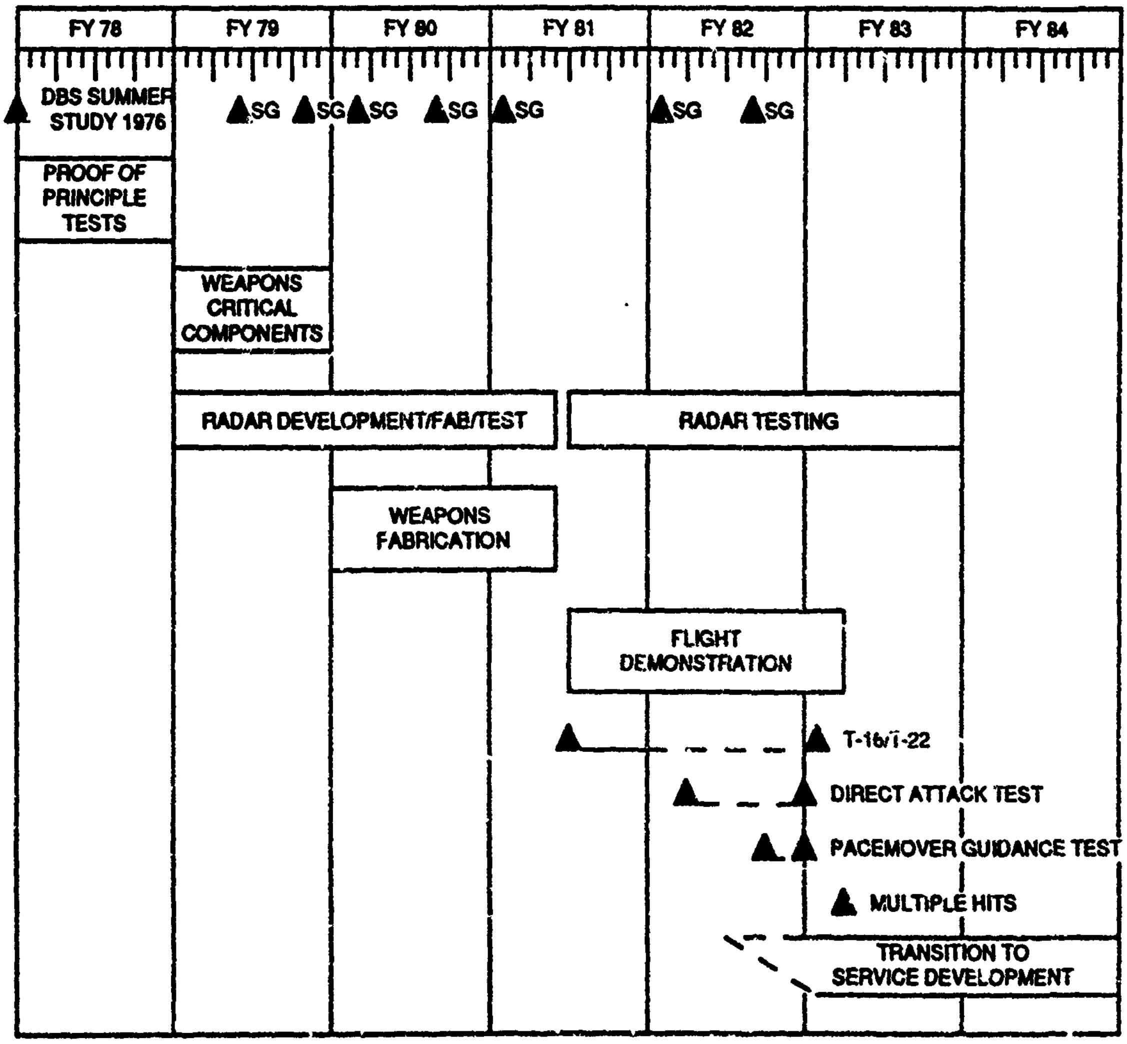
[25] J. Luquire, discussion, 6/89. Most of the government funding, at this step, was from the Services. Also the industrial group involved put up substantial amounts of their own funding for the final tests.



SG — STEERING GROUP MEETINGS

Figure 5-4. ASSAULT BREAKER Schedule
(From BDM Report, *History of Assault Breaker*, 1985)

MISSION FUNCTION	T-16 FLIGHT TEST										FLIGHT NO.			
	1	2	3	4	5	6	7	8	X	9	1	2	3	4
TARGET ACQUISITION (RADAR)				○	○	●	●	●						●
TARGET POSITION TO MISSILE (RADAR)				○	○	●	●	●						●
MISSILE LAUNCH	●	●	●	●	●	●	●	●	●	●	●	●	●	●
PRECISION GUIDANCE (INERTIAL)	○	●	●	●	○	●	○		●	●	●	●	●	●
RADAR TRACK TARGET				○	○	●	●	●						●
RADAR ACQUIRE AND TRACK MISSILE				○	○	●	●	●	●	●				○
RADAR PROVIDE GUIDANCE UPDATE TO MISSILE				○	○	●	●	●	●	●				●
MISSILE TRAJECTORY CORRECTION							●	●	●	●				●
IN FLIGHT DISPENSE		◒	●	●	◒	●	●	●	●	●	●	●	◒	◒
PAYLOAD PATTERN GENERATION		◒	●	●	◒	●	●	●	●	●	○	●	○	◒
PAYLOAD DESCENT FUNCTIONING		○	○	○	●	○				●	○	○	○	◒
PAYLOAD TARGET ACQUISITION AND LOCK-ON			●	○	●	○				●				
TARGET ENGAGEMENT (SINGLE)			○	○	●	○				●				
TARGET ENGAGEMENT (MULTIPLE)					○	○				●				
TARGET ENGAGEMENT (MOVING)														

KEY:
BLANK — NOT TESTED
● — TESTED SUCCESSFULLY
◒ — PARTIAL TEST SUCCESS
○ — TESTED UNSUCCESSFULLY

Figure 5-5. ASSAULT BREAKER Technology Demonstration Score Card (From BDM Report, *History of ASSAULT BREAKER*, 1985) on the Air Force to a greater degree than before, which took a while to work out.[26] After a review by an ad hoc Defense Science Board panel SOTAS was cancelled and PAVE MOVER was transformed into the Joint Surveillance and Target Acquisition Radar System (JSTARS), with the U.S. Air Force as lead Service. A 21 March 1983 memorandum from James P. Wade, Jr., the principal deputy USDR&E, to OSD, the JCS, Service R&D chiefs and relevant CINCs outlined the grouping of JSTARS, JTACMS, Joint Tactical Fusion, Ground Attack Coordination Center and the Tacit Rainbow radar-homing, loitering missile for attacking ground-based air defenses into a constellation of programs designed to attack enemy forces deep behind the close combat zone.[27] Afterward, the Office of Conventional Initiatives was established in OUSDRE to oversee Service follow-through on the integrated program, initially under James M. Tegnelia, who became Director of DARPA's Tactical Technology Office in 1982. In a Memorandum of Agreement of May 22, 1984, Gen. John Wickham, Jr., and Gen. Charles Gabriel, respecively Army and Air Force Chiefs of Staff, agreed, among other things, that the Army would build a ground launched [ballistic] missile system and the Air Force would build an air launched [cruise] missile system under the JTACMS program, and that the Army and the Air Force would support and work together on a single JSTARS platform, to be operated by the Air Force in such a way as to provide dedicated support of ground commander requirements.

Also during the ASSAULT BREAKER period there were a number of NATO studies of the problem of meeting the second and other follow-on echelons of a WP attack deep on the WP side of the battle front, to keep the follow-on forces from overwhelming and breaking through NATO's front-line defense. Objections by some of the Europeans to the concept centered on their concern that attention and resources drawn to follow-on forces attack (FOFA) would detract from NATO's ability to meet the WP attack at the front. There was also some skepticism to the effect that "high technology" approaches to the FOFA problem would fail in battle, and a parallel concern that, if such an approach were adopted by NATO, then Europe would have to "buy U.S." to create the forces.[28] Gen. Bernard Rogers, then SACEUR, was aware of the ASSAULT BREAKER results and was

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[26] Hearings, DoD Authorization for FY 1986, Committee on Armed Services, U.S. Senate, 99th Congress, 1st Session, part 4, Tactical Program, p. 1668.

[27] Discussion in Nov. 1989, with Mr. Loren Larson, Director, Conventional Initiatives, ODR&E.

[28] A list of pertinent NATO (and other) FOFA studies is given in "New Technology for NATO," Congress of the U.S., Office of Technology Assessment, 1987, p. 218. See, also, U.S. Congress, Office of Technology Assessment, *Technologies for NATO's Follow-On-Forces Attack Concept*, Special Report OTA-ISC-312, p. 18.

encouraged by them to persist in his FOFA concept.[29] The concept has since become accepted as one of SHAPE's "critical military areas of warfare" that, along with such areas as air superiority and close combat, are deemed essential to defeating a Soviet attack on NATO.

The major parts of the ASSAULT BREAKER concept have persisted in the Air Force and Army programs to date, although they are not viewed as a single, integrated system. The Army and Air Force do not accept the FOFA concept per se as part of their doctrines, which are centered, respectively, around the air-land battle and deep interdiction. Systems built for these purposes are agreed between the Services and SHAPE to be consistent with the FOFA concept, and the doctrinal issue rests there.

The airborne, multimode radar for surveillance of the deep battlefield continued in the JSTARS program, possibly because RADC had become an internal advocate for the program. There was, early in the program, an argument about which aircraft would carry PAVE MOVER: the high altitude TR-1, a lower altitude aircraft like the Army OV-1 carrying the SAR-MTI battlefield detection system, or a modified transport type aircraft. After the ASSAULT BREAKER tests, the radar contractors felt that it would be desirable to have as much processing power as possible in the aircraft, which pointed to the C-18 (now E-8A) modified Boeing 707 aircraft for JSTARS. Explicit agreements between Generals Wickham and Gabriel on 11 May and 11 June 1984, following their initial agreement in principle, designated the C-18 as the sole JSTARS platform. The C-18 with JSTARS had its first test flight in early 1989.[30] Apparently a new JSTARS radar has been built by Grumman-Melbourne (formerly Norden) with approximately 1.7 million lines of software code, but it has been suffering delays.[31] Perhaps for this reason JSTARS now seems to have evolved mainly into a battlefield surveillance and target acquisition radar, with the more complex missile guidance problem, involving coordinate transformations, put off for the future. The Army has operators in the C-18 and responsibility for the JSTARS ground terminals.

The missile heritage of ASSAULT BREAKER initially involved the joint Army-Air Force effort to arrive at a ground and air-launched missile with maximal commonality, through JTACMS. Congress further directed that the T-16 and T-22 missiles be

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[29] See, e.g., Gen. Bernard Rogers: "Follow-on Forces Attack (FOFA): Myths and Realities," *NATO Review*, V-32, No. 6, Dec. 1984.

[30] *Armed Forces Journal International*, Vol. 126, #7, p. 34, Feb. 1989.

[31] "JSTARS Slips a Year," C^3I Report, March 21, 1988.

investigated for JTACMS, which caused some difficulty in articulating a concept suitable for Air Force operations.[32] The tactical Air Force moved toward a cruise missile with loiter capability for a variety of interdiction missions, and JTACMS became ATACMS, predominantly an Army program involving the T-22 Lance variant used in the ASSAULT BREAKER tests, which is to be launched from the Army's MLRS (Multiple Launch Rocket System) launcher. The first conventional warheads for ATACMS will use the APAM (anti-personnel, anti-materiel) munition, with a TGSM for direct tank attack relegated to a later Block II stage. The TGSM development was slowed by a combination of bureaucratic and technical delays, which involved inter-Service disagreements over jurisdiction and preferred technical approach (IR or mm-wave guidance), and insufficient attention on the part of the technical community to keeping "smart" submunition costs down. As a consequence, the initial implementation will probably use the SKEET or similar self-forging fragment approach, with a true TGSM appearing in the mid-to late 1990s. However, as a general matter, ATACMS seems fully funded as an Army acquisition program.

While the original standoff battle concept involved development and use of the BETA "fusion" system, the ASSAULT BREAKER ground station for tactical missile control and radar data processing was built separately from BETA. However the DoD joint tactical fusion system is in part an outgrowth of BETA and is planned to incorporate the information from JSTARS.

A number of option packages being considered incorporate JSTARS and ATACMS-type technologies in NATO FOFA forces; almost all approaches rely on the Joint Task Force (JTF) concept. These studies have mentioned, in particular, concerns about the survivability of the surveillance aircraft. Germany apparently has serious (largely non-technical) reservations about the ATACMS. They have consistently expressed concerns about proposals and plans for ballistic missiles, which might also be fired deep into Soviet rear areas, for fear of initiating a tactical nuclear war on German territory. France (not in NATO's military command) has also undertaken development of a helicopter radar system similar to SOTAS, named ORCHIDEE, for close-in battlefield surveillance, and the United Kingdom is developing a longer range ASTOR radar surveillance system.

While not directly involved with JSTARS or ATACMS, DARPA efforts continue on such related technologies as HALE (high altitude long endurance) platforms with radars

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[32] Senate Authorization Hearings for 1985, testimony of Gen. Russ, USAF, p. 1815.

and on-board intelligent processing systems; on infrared IR seeker technologies; and on advanced long range cruise missile technologies.

C. OBSERVATIONS ON SUCCESS

The basic concept of ASSAULT BREAKER was apparently discussed in several studies and proposals in the mid-1970s. DARPA and the Services were developing most of the needed technologies, and DARPA was working with the Air Force's ESD (Electronic System Division) to develop the needed surveillance SAR-MTI radar. The DSB Summer Study of 1976 found the essential technologies available and made the recommendation that they be put together and demonstrated. Key inputs to the DSB study on the missile side were made by industry, an IDA/WSEG study of "target engagement," and the DARPA-AF TAWDS work, which indicated that the real-time targeting and missile guidance updates might be feasible. DSB noted that the concept required an unprecedented degree of inter-service cooperation.

Under DoD-arranged extraordinary "Steering" and "Executive Committees," DARPA was given the program management responsibility without assistance of any industrial "integrator." While the DARPA objective was to develop a prototype, not a system to be fielded, there was some disappointment in OSD and DARPA at the end that the Services did not react more quickly to the demonstration that the concept could be made to work, and that they did not fully accept the integrated system concept. However, many Service doctrinal principles were being challenged, so this should not have been surprising.

An extraordinary combination of technologies had to be tested, and some had to be developed in a very compressed time schedule. Of all of them, the most serious major hitch seems to have occurred in the radar development, which has been described by some as perhaps the most complex ever undertaken by the United States. The software development, in particular, seems to have been underestimated. Adding to the complications of the multimode radar's computational system was the need to deal with coordinate systems relative to the aircraft and the missile inertial systems with ground reference. These problems caused about a 1-year slippage in the program, not inappropriate for a highly experimental program; the progressively more complex "integrated" tests had a mixed record.

The original ambitious concept of linking BETA and CELT to ASSAULT BREAKER was abandoned along the way, and these other projects have had independent development histories. BETA and CELT, individually, have impacted related Service programs.[33]

The second technical area where progress was slower than it might have been was in the guided submunition development; this occurred for reasons already described. The final, successful attack of five out of five tanks was a clear demonstration, however, that the essential ASSAULT BREAKER-type technologies could be made to work. The somewhat simplified conditions for this test were probably all that could have been arranged with the funds and in the time schedule followed. The initial feasibility study had probably been carried far enough to warrant initiation of serious Service system development efforts had the Services been of a mind to do so.

From a detached perspective one might say that despite this success, at the present time the Services are following the lines set out *before* ASSAULT BREAKER. By this reasoning, ATACMS can be considered the follow-on Lance II, with a conventional warhead. The Army still has its OV-1 SLAR. The Air Force still has its surveillance ASARS in the TR-1 system underway, with the E-8A for augmentation. And, the Air Force has not adopted any ATACMS ballistic-type air-launched missile, but has returned to its original notions of a standoff cruise missile and a high velocity missile. Nevertheless, ASSAULT BREAKER seems to have led, as the DSB predicted, to a new, if limited, degree of interdependency and cooperation between the Services via the E-8A. NATO has adopted a deep-attack concept (FOFA) and system description that includes many elements of ASSAULT BREAKER, and the U.S. Services consider their deep attack-related systems compatible with the NATO FOFA concepts. The Service delay in responding to ASSAULT BREAKER was due partly to the required adjustment in operational concepts, and partly due to caution about the support requirements for a new and complex system. Their cooperation has yet to be worked out and tested "full up," including a joint command and control system. The ASSAULT BREAKER experience was, however, one of the motivations for DoD to set up a special office for conventional initiatives to encourage and ensure such inter-Service cooperation.

The ASSAULT BREAKER impact, therefore, has been seen in a major legacy of hardware (JSTARS and ATACMS), in significant developments in Service and NATO

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[33] BETA and CELT are topics of separate chapters in this report.

operational cooperation, and in DoD organization. Thus in the FY 1986 Senate Armed Services Committee hearing, LTG Wagner of the Army stated, about JSTARS:[34]

> We signed an agreement with the Air Force. They are going to develop the radar and we are going to develop the ground station. For the first time they have signed an agreement with the Army that will give us dedicated support for the Corps commander. We never had that before. We feel confident we can depend on the Air Force to do that job.

ASSAULT BREAKER's success has affected all discussion, in the United States and abroad, of the possibilities for dealing with WP attacks with smaller size forces[35] than those of the Pact. The resulting concepts and systems could persist as safeguards against sudden massing of Soviet forces in Eastern Europe, should a serious crisis arise after a conventional force reduction agreement there.

DARPA outlays for ASSAULT BREAKER and related previous studies from project records appear to have been about $155 million; for PAVE MOVER and TAWDS, about $50 million. The Services spent, through FY 1984, nearly $200 million on corresponding programs. The anticipated outlays for ATACMS and JSTARS, together, approach $10 billion, exclusive of NATO expenditures.[36]

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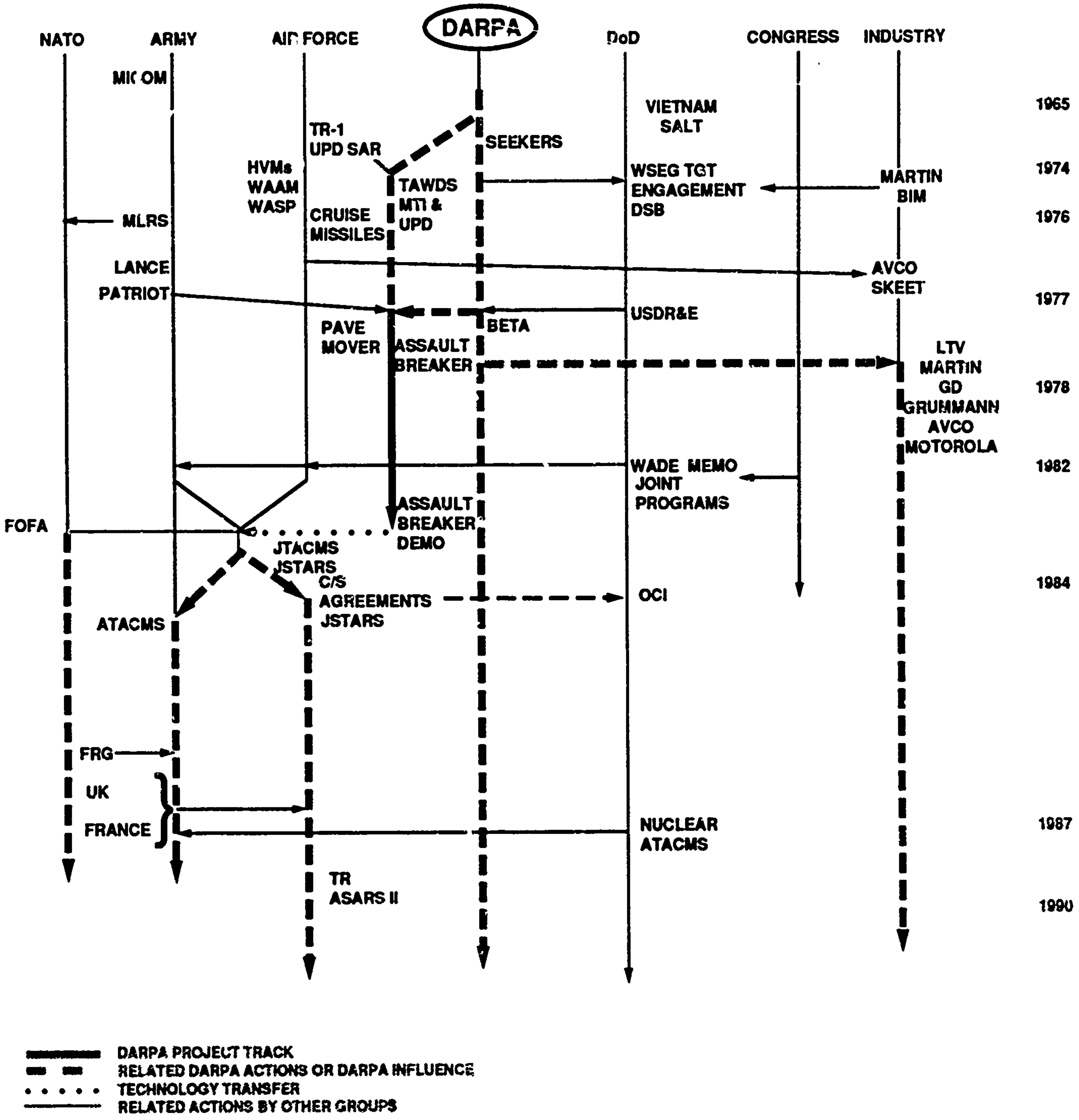
[34] 1986 Senate Armed Services Hearing, p. 1668.

[35] Ibid.

[36] Ibid., p. 1669.

ASSAULT BREAKER



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VI. BETA

A. BRIEF OVERVIEW

The DARPA-Joint Services BETA (Battlefield Exploitation and Target Acquisition) project demonstrated the feasibility of a state of the art, computer-based tactical data fusion system capable of dealing, in near real-time, with the information load of the modern battlefield. A BETA testbed remains in operational use today as LOCE (Limited Operational Capability Europe), a European command asset providing intelligence support to the U.S. Army and Air Force, and to other NATO forces. BETA has also been a testbed to gain experience and a training aid for the Army and Air Force components of the Joint Tactical Fusion System, now under development, and for the planned NATO BICES tactical intelligence fusion system.

B. TECHNICAL HISTORY

In the mid-1970s many new airborne surveillance and reconnaissance capabilities were under development. The joint DARPA/Army/Air Force BETA program originated in the mid-1970s and grew in part out of Service efforts to correlate and exploit all information sources on the future battlefield.[1] The results of these efforts indicated that the target-dense battlefield on the European Theater would generate a flood of data, which could not be adequately evaluated by intelligence analysts in a timely way to assist operational commands. In part, also, the stringent requirements for accurate targeting of precision guided munitions, expected to be used in ASSAULT BREAKER to deal with FOFA, provided a challenge to the capability of computer and display systems which were emerging at about the same time, many from DARPA programs.[2]

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[1] Discussion with Dr. P. Dickinson, 10/89.

[2] L. Bruce James and M. Cox, "Viewing and Targeting Enemy Second Echelon Formations," in *Journal of Defense Research*, Vol. 10 #2, September 1978, p. 79 (classified article). Unclassified excerpts have been made from this and other classified articles cited.

In the mid-1970s also, DARPA's Tactical Technology Office (TTO) funded studies indicating that such a battlefield information correlation "testbed" was feasible, and might be developed into a militarily useful product at an affordable cost. These studies led to a DARPA proposal that a demonstration fusion system be constructed in the European Theater. This proposal, however, was not well received, at first, by the Services.[3] Several WSEG studies and a DSB Summer Study in 1976 pointed out that the Army and Air Force should have a common informational picture of the battlefield to deal with FOFA, and recommended that available technologies be integrated into a testbed for operational evaluation and training.[4] In response, Dr. Perry, then Under Secretary of Defense Research & Engineering (USDR&E), set up the joint Services BETA project in 1977 with ARPA funding and technical direction, with the stated objective of demonstrating feasibility of automated correlation of sensor data for target acquisition and battle management.[5] BETA was, initially, conceptually linked with ASSAULT BREAKER, an essential element to deal with FOFA.

Because of BETA's perceived importance to NATO, Dr. Perry set up a special program management scheme for BETA similar to that of ASSAULT BREAKER. In this approach DARPA managed the program through the Army, and reported to a steering committee, which in turn reported to Dr. Perry. A fast-paced program was set up beginning in early 1978,[6] (see Fig. 6-2) in order that BETA could participate in a large NATO exercise in 1981.

The BETA scenario envisaged was that of an extended battlefield including, perhaps, several hundred thousand "elements of interest" all under surveillance by a number of different sensor systems belonging to the Army and Air Force. It was intended that the BETA fusion center should be able, in near real-time, to filter, correlate, and aggregate all available information from these elements in order to accurately identify, locate, and report on a much smaller number, perhaps thousands, of "high interest" potential targets.[7] BETA was designed to exploit existing sensor systems, and was to combine data from these sensors in such a way as to extract the most information possible

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[3] H. Federhen, *BETA Program: A History*, IDA Memorandum Report M-56, 1984 (CLASSIFIED).

[4] *DSB (1976) Summer Study on Conventional Counterforce Against a Pact Attack*, 1977 (CLASSIFIED).

[5] H. Federhen "BETA," (UNCLASSIFIED), Proceedings of AIAA-NASA-DARPA (CLASSIFIED) Conference on Smart Sensors, November 1978, paper # 29.

[6] AO 3596 of 3/78, BETA.

[7] H. Federhen, "BETA" p. 29-3.

from them without interfering with the primary users of the information. BETA was to disseminate this information in formats that would be tailored to different users in the Army and the Air Force. A variety of sensors could be involved, including imaging systems, radars, and emitter locators, each of which required a different type of processing. Some of the sensors, such as CELT (Coherent Emitter Location Testbed), would be able to generate digital data suitable for direct insertion into BETA's computer processing, and some required human intervention.[8] Based on a study of several battlefield scenarios, an initial selection was made of sensors to provide inputs to the processors in the BETA correlation centers (CORCENs). Later the number of sensors was limited. Each sensor was to have a tailored BETA interface module (BIM) which was to operate, as far as possible, without interfering with the other primary users of the sensor. Each BIM would do some preliminary data filtering and reformatting appropriate for communication to the preliminary data processors in the CORCEN.[9] In these processors, each data message would be checked for errors and further filtered, separated into individual reports, and sent on to the appropriate "user" terminals or to processors in other CORCENs. Figure 6-1 illustrates the flow of events in BETA.[10] Different types of correlation, some with nearly current information and some using previously existing data bases, were to be routinely performed, and some could be done remotely when queried by operators using interactive terminals. Each operator terminal possessed an appreciable fraction of the CORCEN processing capability, and could communicate inquiries, through the CORCEN Control, back to the individual sensors through their command posts.

Because it was to be a testbed, BETA was planned to be constructed using commercially available computer hardware and available military and commercial communications lines, including AUTODIN and voice circuits. However, some BETA elements, notably terminals, turned out to be one of a kind, and in the end the project appeared to have stressed the state of the art of several types of computer hardware and display systems. It was assumed at the outset that available software could be used for BETA communications, data "fusion," and data base management. It was also expected that BETA would be able to accommodate more CORCENs, sensors, and operators

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[8] CELT is discussed in Chapter XXXII of this Volume.

[9] "History of ASSAULT BREAKER," unclassified chapter on BETA in BDM Draft Report, 1985 (CLASSIFIED).

[10] Ibid.

without software changes. However, major software development eventually proved necessary, which caused some truncation of BETA functions and overall program delay.[11]

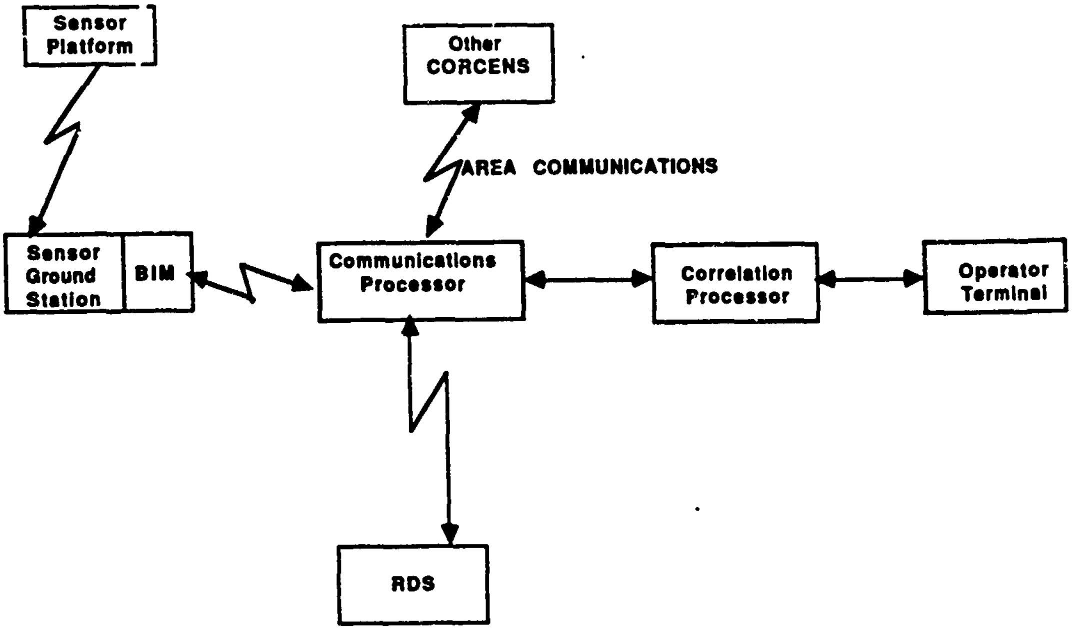

Figure 6-1. Major BETA Components by Function

The first two BETA systems were produced by TRW and in 1981 were given to Army and Air Force tactical operations training units for evaluation. This was timely because in 1980 Congress had mandated that the Army and Air Force should consolidate efforts to automate intelligence fusion, starting what later became the Joint Tactical Fusion Program. Generally, the Services' evaluations were positive, but a number of deficiencies

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[11] BDM, "History of ASSAULT BREAKER." See also J. Tegnelia, et al., "History of ASSAULT BREAKER, and Related Projects," *Journal of Defense Research*, 1984 (classified article) Vol. 16 #4, 1984, p. 277.

were identified, particularly by the Air Force test group. However, these deficiencies had been known to exist beforehand and most could be traced to lack of funding [12]

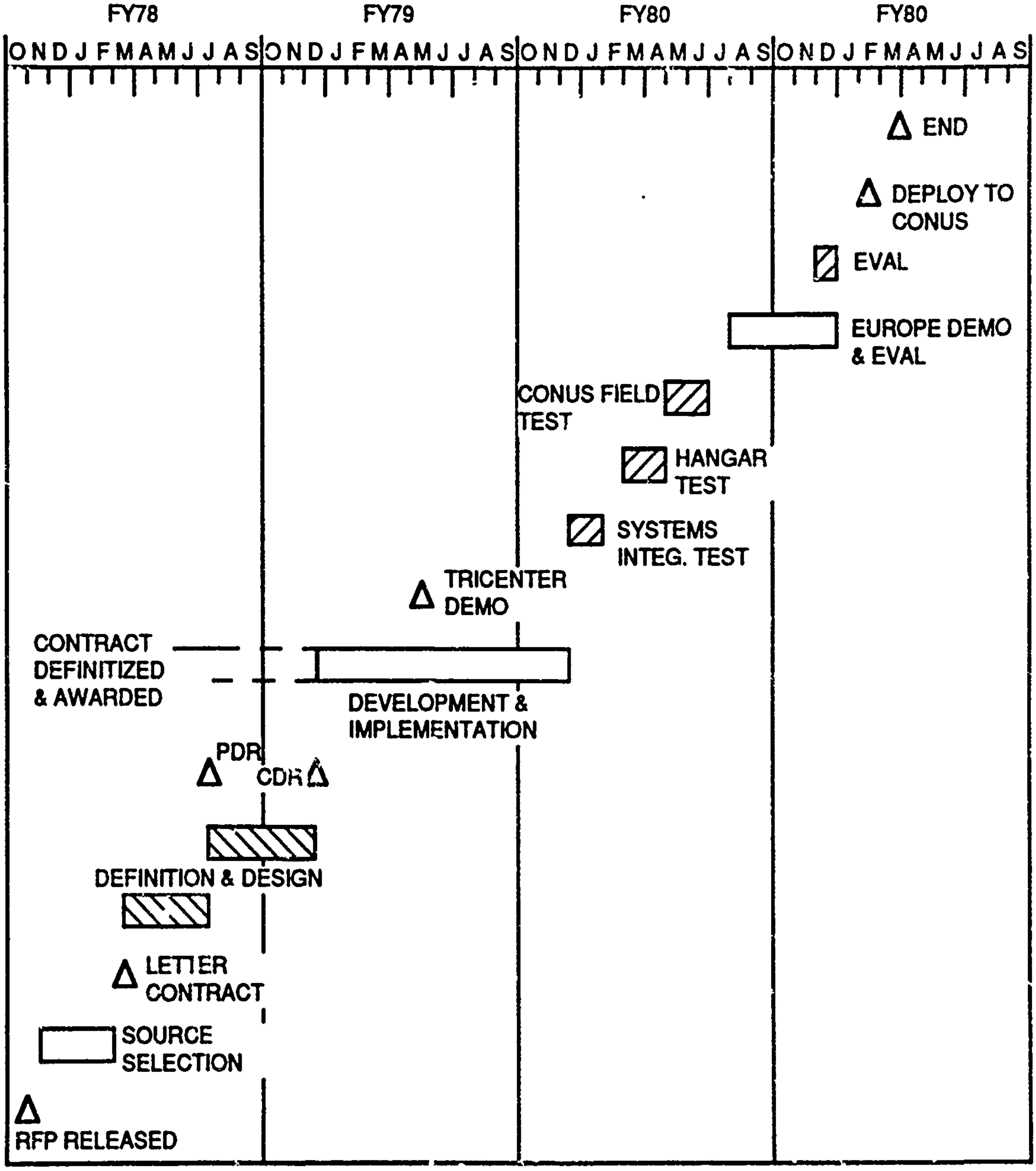

Figure 6-2. BETA Project Schedule

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[12] A somewhat negative GAO report appeared in 1981, while these developmentally oriented evaluations were at an early stage.

These two BETA systems, apparently, were used by the Army and Air Force through 1987 as test beds for their respective ASAS and ENSCE projects in the Joint Tactical Fusion Program.[13] A third BETA system was constructed at TRW out of available parts used for software tests. This system was to have been sent to Europe for further evaluation and operational training in 1981 NATO exercises. However, because a "dry run" demonstration before the steering committee was only partly successful, and expectations had been built up in NATO, the BETA program was extended for 4 months, and BETA was not available for the NATO exercise. With this additional effort, however, a successful demonstration was held before Service and NATO representatives in 1981, using input tapes containing data from the missed NATO exercise.[14] This BETA was eventually placed in Europe with the set-up shown in Figure 6-3. The European BETA underwent two further extensive evaluations in 1984, by the Army and Air Force.[15] A number of problems were identified in these evaluations: the European BETA system found difficulties with multilevel security, particularly with NATO interfaces: the Air Force evaluation found delays in responding to queries: and "lockup" of the system occurred under certain circumstances. In response, BETA operations in Europe were further limited, but overall "availability" remained relatively high. Today the European BETA apparently interfaces with only a few sensors, rather than the larger number planned, and uses only a fraction of its computer capabilities.[16]

Nevertheless, this BETA system, now renamed Limited Operational Capability-Europe (LOCE) and operated mainly by the Air Force, provides the only automated data fusion system capability now available in Europe. LOCE appears to be often used as a communications facility rather than for information fusion. It also functions as a training device for the U.S. Joint Tactical Fusion Program and as a testbed for design of the planned follow-on NATO Battlefield Information Collection and Exploitation System (BICES).[17] In 1985 testimony, LTG Wagner of the Army stated:[18]

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[13] *Assessment of Tactical Data Systems*, IDA Report R-326, p. 244 (CLASSIFIED).

[14] These tapes apparently involved some exercise data and some data from Army simulations.

[15] J. Tegnelia, op. cit. gives some results of these evaluations which were, on the whole, satisfactory.

[16] Discussion with P. Dickinson, 10/89.

[17] "Intelligence Fusion System Planning Project: Lessons Learned From Development and Fielding of TLAC, BETA, and ITEP," JPL, 1984 (CLASSIFIED).

[18] DoD Authorization Hearing for FY 1986, Committee on Armed Forces, U.S. Senate, 99th Congress, 1st Session, Part 4, Tactical Programs, p. 1787-8.

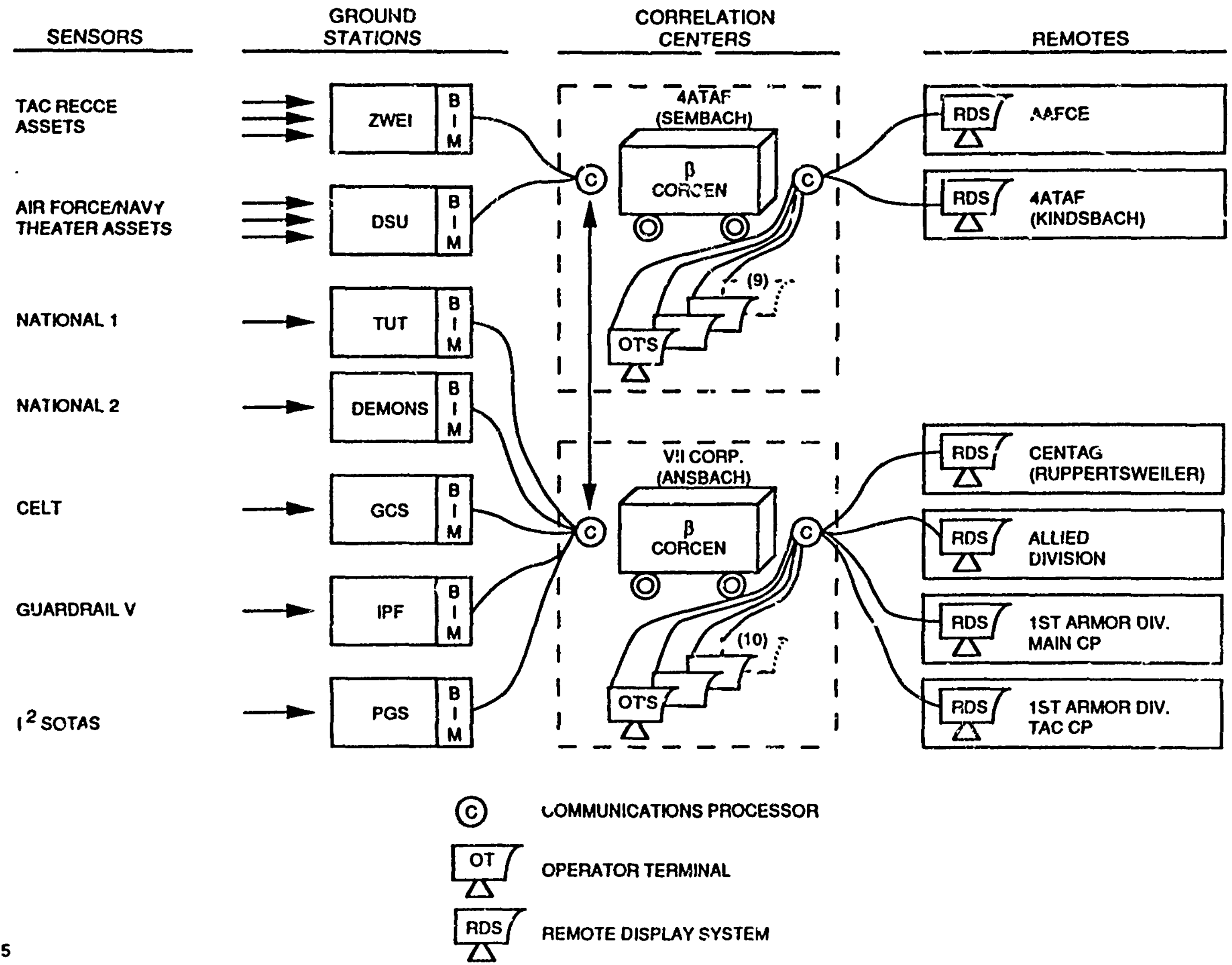

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Figure 6-3. Planned EVCOM BETA System (BDM)

> I would like to emphasize that LOCE is a European Command asset and, as such, provides intelligence support to Army users as well as Air Force users in that theater. Although LOCE is significantly less capable than the Army All Source Analysis System (ASAS) and the Air Force Enemy Situation Correlation Element (ENSCE), the fusion systems now under development within the Joint Tactical Fusion Program, it is performing a valuable service in support of our forces in Europe, while providing useful feedback to the development process for ASAS/ENSCE. Except for LOCE, the Army has no true fusion system.

ASAS and ENSCE, the Army and Air Force elements of the Joint Tactical Fusion (JTF) Program are current developmental programs which were set up by Congressional directive in 1980. These JTF developments have used BETA systems as testbeds and for training, and profited from BETA experience in Europe, but have differences in design due to their operation at "system high" security levels. The Services' JTF programs have experienced technical problems, mostly software, cost over-runs, and lack of test specifications to meet DoD approval.[19] ASAS is developing in evolutionary modules and, while under procurement by the Army as of early 1990 for limited capability configurations, is not expected to be available in time to match the IOC of JSTARS, with which it was hoped to work. One ASAS module has served the Korean U.S. Army's Command as a fusion facility. ENSCE funding apparently has been withdrawn by the Air Force as of early 1990.[20]

BETA's most extensive influence may have been on the NATO BICES which is now being developed to interface with the C^3I systems of all NATO countries. BICES specifications have been worked out using the LOCE BETA testbed. Development of BICES was begun with a consortium of approximately 200 engineers from European companies in 1985 and is funded by NATO. BICES is initially planned to be a testbed, like BETA, but will be more complex, interfacing with several NATO countries' C^3I systems and more closely tailored to NATO requirements.[21] JTF will have to interface with BICES, and LOCE is regarded as the JTF support element for that purpose.

C. OBSERVATIONS ON SUCCESS

BETA was a DARPA initiative toward a demonstration "fusion" center for the European theater. This proposal, apparently, was not well received initially by the Army or

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[19] See cy., ASAS, "From Confusion to Fusion," by James Rawles, *Defense Electronics*, Oct. 1989, p. 105H; and OT&E report for FY 1988, DoD, p. 104.

[20] *Jane's, DMS Market Intelligence Report*, 1990, "Joint Tactical Fusion Program."

[21] *Jane's, DMS Market Intelligence Report*, 1989, for "BICES." L. Bruce James, JDR.

Air Force.[22] However, the urgency of the FOFA problem overtook events. After DARPA had conducted studies indicating BETA feasibility, the DSB recommended a go-ahead and DDR&E set up a joint program in which DARPA had funding and technical responsibilities. Apparently there was no development with the same scope, in the Service programs, at that time.

According to a JPL 1984 review of lessons learned pertinent to the JTF program, the BETA project underestimated the computer and software capability required, was late, delivered less capability than originally estimated, and ran over budget.[23] Its scope was apparently changed in midstream to accommodate NATO users, which caused problems in multilevel security.[24] The original BETA motif, however, was to serve NATO, which would seem to have made such problems inevitable. In its operational tests firm specifications were not set early enough. Although tight coupling to users was prescribed from the beginning, users were apparently not consulted nor adequately instructed in order to operate the equipment with confidence. Also, BETA provided a "quantum jump" in information capability to analysts, which has required some time for the intelligence system to digest.[25]

BETA has performed its function successfully as a research testbed, introducing the Services and NATO to a new level of intelligence capability, and assisting in the working out of specifications for systems such as BICES, the planned NATO tactical data fusion system. BETA remains also a useful, if limited, operational capability in the European command area.

BETA's influence on the development of the U.S. Joint Tactical Fusion Program has been real but appears to have been limited, due largely to multilevel security problems. ASAS and ENSCE, the Army and Air Force elements of the Joint Tactical Fusion program, partly grew out of previous Service intelligence fusion efforts. These programs seem also to have had significant software problems.[26] ENSCE, in fact, seems to have been deferred

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[22] H. Federhen, "BETA," 1978.

[23] "Intelligence Fusion System Planning Project," JPL, 1984.

[24] Federhen, ibid. and JPL, ibid.

[25] JPL, ibid.

[26] Rawles, "From Confusion to Fusion," 1989.

indefinitely by the Air Force, and while ASAS is in procurement, its IOC has slipped to 1993.[27]

While criticized by some as "over ambitious," in his 1984 review article J. Tegnelia characterizes BETA and ASSAULT BREAKER as research programs which were successful technologically and well worth pursuing in view of their technolcgical impact. He pointed out, however, that such technological success does not necessarily lead to implementation, due in part to follow-on management difficulties. Recognizing this, DDR&E established the Office of Conventional Initiatives. This management action can also be credited, in part, to BETA and ASSAULT BREAKER.

From project records, DARPA outlays for BETA seem to have been about $9 million. Total DoD funding was $56 million. Present BICES plans for development funding have been estimated at about one-half billion in 1998. ASAS and ENSCE costs are difficult to estimate but various reports indicate these will be considerably higher than $2 billion.[28]

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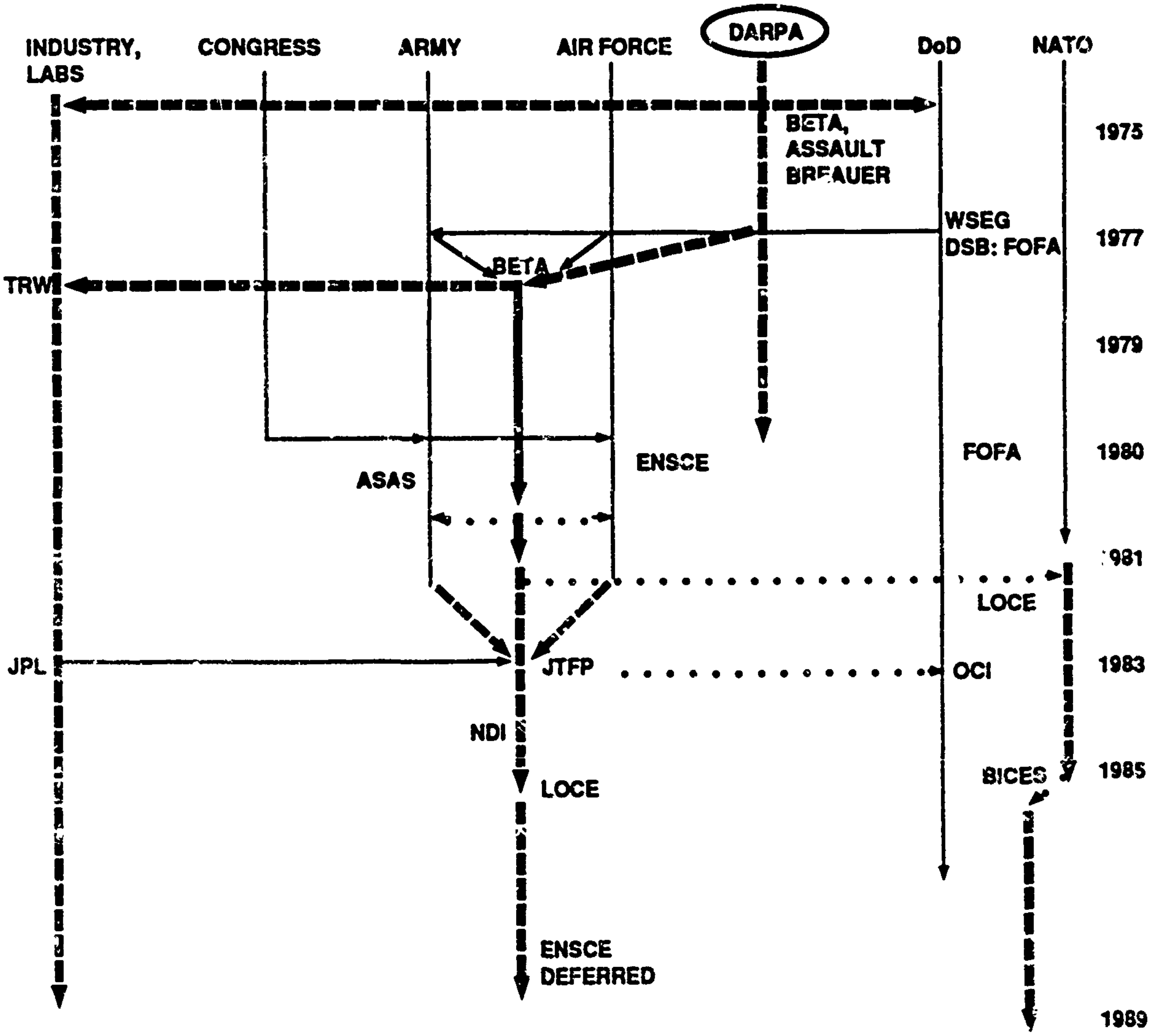
[27] *Jane's DMS Market Intelligence Report 1990*, "Joint Tactical Fusion Program," p. 4.

[28] *Government Computer News*, Vol. V-7, June 10, 1988, "2.6 billion Systems to Merge Secret Battlefield Information," and "House Action Joint Tactical Fusion," *Aerospace Daily*, August 24, 1989, Vol. 151, # 37.

BETA



━━━ DARPA PROJECT TRACK
▬ ▬ ▬ RELATED DARPA ACTIONS OR DARPA INFLUENCE
• • • • • TECHNOLOGY TRANSFER
——— RELATED ACTIONS BY OTHER GROUPS

5-8-90-1M
REVISED
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VII. CELT

A. BRIEF OVERVIEW

The joint Service-DARPA CELT (Coherent Emitter Location Testbed) was the first automatic, near real-time system for precision location of communications emitters. CELT successfully demonstrated its capability in NATO exercises in 1978-80. CELT technology has influenced the design of Air Force PLSS-ELS systems and the Army improved airborne GUARDRAIL system.

B. TECHNICAL HISTORY

The origins of CELT go back to the 1960s, when efforts were made to use airborne systems to locate enemy communications emitters during the Vietnam War, and to even earlier efforts in ECCM.[1] In the early 1970s the expectation was that the European battlefield would involve distances from location systems to targets far greater than those in Vietnam, and would require rapid formation of much sharper beams than those possible on single-aircraft intercept systems. In the mid-1970s, the Air Force RADC and DARPA's Tactical Technology Office (TTO) began a joint effort toward an Emitter Location System (ELS) which used long baseline multiple time difference of arrival (TDOA) and differential doppler (DD) approaches to locate communications emitters.[2] The RADC group involved in ELS was also responsible for development of the Precision Location Strike System (PLSS), dedicated to location of pulsed emitters, to which ELS was to add a communications emitter location capability.[3] Communications emissions, however, were characteristically narrowband in frequency spectra, generally without the sharp time

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[1] See e.g., "Genesis and Evolution of TOA Concepts," Harry Davis, (classified article) in *Journal of Defense Research*, Vol. 5B, #1, Spring 1973, p. 1. Unclassified excerpts have been made from this and other classified references.

[2] Cf., "Techniques to Precisely Locate Non-Pulsed Emitter," L.O. Taylor, et al., *Journal of Defense Research*, Vol. 5B, #4, 1973, p. 350 (CLASSIFIED).

[3] AO 3126 of 12/75 CELT.

reference points provided by pulsed radar-type emissions, so that cross correlations of intercepts over sufficiently long signal samples were required.[4]

The CELT concept involved communications-navigation links between several aircraft similar to that for the PLSS (Fig. 7-1), which also was to include an ELS system. ELS required precise navigation data and used for this purpose ground-based distance measurement equipment (DME) and inertial systems in the aircraft, together with accurate frequency reference data. Digitized encrypted data from the aircraft were transmitted in a high-speed data link to a ground processing station such as BETA, where the major part of the processing was to be done, together with other command, control, and intelligence functions. Figure 7-2 illustrates the flow of events in CELT.

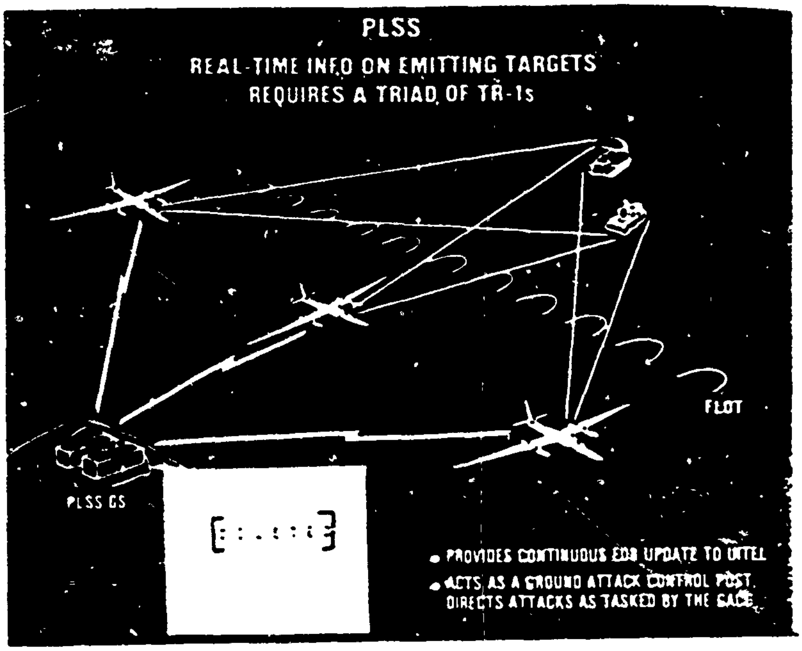

Figure 7-1. PLSS Real-Time Information on Emitting Targets (From Hearing before Senate Committee on Armed Services, 1st Session, March 1984, p. 1735)

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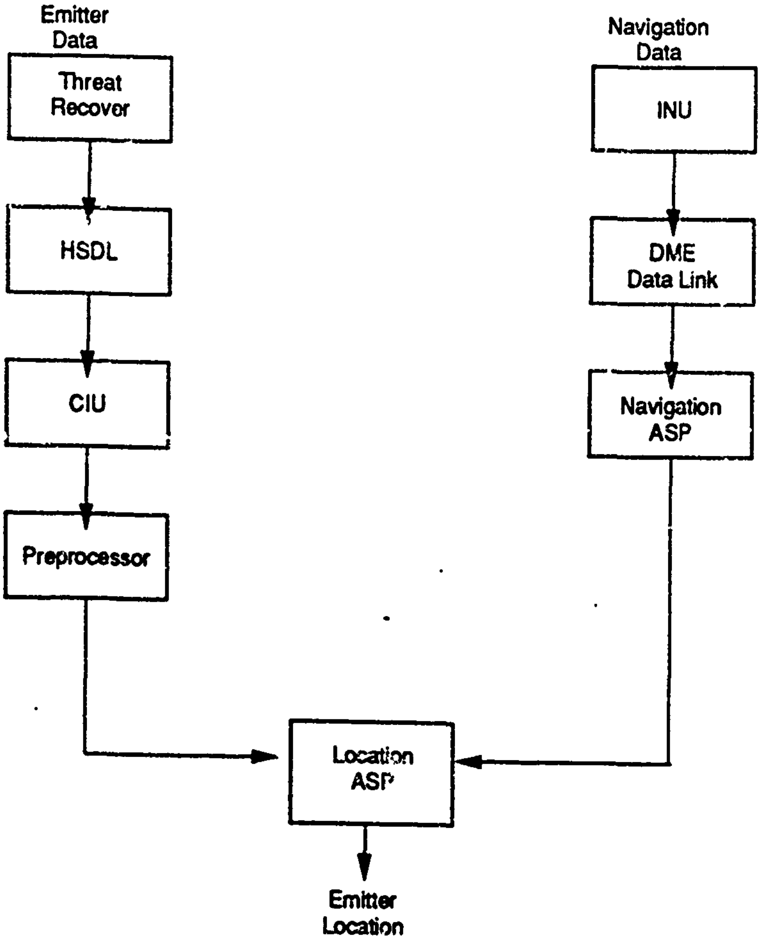
[4] See e.g., "COMTOA: Precision Location of Continuous Emitters," by S. Stein, *Journal of Defense Research*, 5B, #2, Summer 1973, p. 146, (CLASSIFIED article). This and other earlier work had been funded by RADC.



HSDL: High Speed Data Link (encrypted)
DME: Distance Measurement Equipment,
CIU: Communications Interface Unit (ground station),
INU: Inertial Navigation Unit (in aircraft),
ASP: Advanced Signal Processor.

Figure 7-2. Real-Time Data Flow

The Army soon joined DARPA and the Air Force in efforts to develop a mini-ELS system for use on small RPVs, also being developed in the early 1970s, and several flight tests were made of different versions of the ELS.[5] While these early systems did not possess a real-time location capability, the test results indicated the feasibility of accurate location of any type of electromagnetic emitter, narrow or broadband.

In 1978, spurred by the increased appreciation of the threat of massive Soviet "follow-on forces attack" (FOFA), DARPA's TTO undertook initiatives toward precision location data fusion, and multiple target attack, in the BETA and ASSAULT BREAKER

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[5] RPV's are discussed in Chapter XXVIII, of Volume I.

programs.[6] The ELS project (renamed CELT) was now aimed at developing a new generation of technology for the real-time, automatic location and classification of the many communications emitters expected on the European battlefield, with the accuracy required for targeting by standoff weapons.[7] Due to the urgency associated with the FOFA problem, CELT had an accelerated schedule, in order to be able to participate in the NATO REFORGER exercises to take place in late (calendar) 1980. Since CELT was envisaged to provide a key digital, real-time input to the BETA tactical fusion system, (also under development by TTO to meet the same NATO exercise schedule) special efforts were made to configure a BETA interface for CELT.

CELT's schedule had three phases.[8] The first phase, in the 1979-80 time period, involved system design, construction and integration. The second phase took place in the Spring of 1980 and featured evaluations and demonstrations of the CELT air and ground systems, and check-out of the interface with the BETA testbed then at the Army's Fort Huachuca. A "CELT enhancement system" developed independently by IBM (the prime contractor) was added to CELT in this phase. This enhancement system provided "templates" that related the individual emitters located by CELT to the larger "force elements" through which they could assist in assessing the attack and assigning target priorities.

In its final phase CELT was sent to the European Theater in the early fall of 1980 and participated in NATO's REFORGER exercise that year. While it was possible to analyze only part of the data from CELT in this exercise, apparently a large number of emitters were located and many high value targets identified, along with a significant fraction of the related force elements. Unfortunately, BETA was not available to participate in this exercise and link with the CELT input.[9]

After its REFORGER involvement, further quasioperational tests of CELT were conducted in the European Theater in the early 1980s.[10] While quite successful overall,

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[6] ASSAULT BREAKER and BETA are discussed respectively in Chapter V and VI of Volume II.

[7] "Coherent Emitter Location Testbed," RADC TR-81-246, Vols. I-III, December 1981. Unclassified chapter in Final Report, IBM Corp., by J.R. Stovall (CLASSIFIED).

[8] John N. Entzminger, et al., "Emitter Location and Identification Technology for Precision Strike," *Journal of Defense Research*, 78-2, p. 65 This classified article also describes the early history of TDOA systems.

[9] Later, taped recording of CELT and other inputs were used to test BETA. See Chapter VI. on BETA, in this volume.

[10] Stovall, op. cit.

and providing a new level of information on battlefield activity and targeting, these and the previous tests of CELT indicated several problems, one of the most important of which was due to outside electromagnetic interference affecting data links which had been "borrowed" from available Army DME (Distance Measurement Equipment) radiolocation systems.

CELT technology also was to have been included in the tactical Air Force's PLSS-ELS system. However, PLSS was cancelled in 1986--costs were cited as the reason--after production of one complete system which was installed in TR 1 aircraft.[11] CELT technology has also been incorporated into one of the planned improvements in the Army's GUARDRAIL system, the IBM CHAALS (communications high accuracy airborne location system), to provide a high-precision emitter location option when multiple aircraft are involved.[12]

C. OBSERVATIONS ON SUCCESS

The development of CELT had origins in the Vietnam War era. DARPA involvement in CELT began as a joint effort with the Air Force RADC to augment the Air Force's PLSS system capability by locating nonpulsed emitters. An acceleration of the project was motivated by the urgency expressed by the DoD to deal with the emitter location problem of a European FOFA battlefield environment, with its corresponding requirement for rapid and accurate location of a large number of potential targets and identification of enemy formations.

CELT was initially envisaged by DARPA as part of an overall approach to the FOFA problem, together with BETA and ASSAULT BREAKER. However, all these projects had short time schedules because of the urgency of the FOFA problem, and all the pieces were never put together. Despite this, the DARPA CELT, BETA, and ASSAULT BREAKER projects have had, individually, considerable impact.

CELT achieved its major goal of a successful trial under NATO exercise conditions, and its technology was incorporated in the IBM CHAALS, which has been included in plans for the Army's improved GUARDRAIL system. CELT also contributed to the Air Force's PLSS-ELS, which was cancelled by the Air Force in 1986 for stated reasons of economy after one test system was constructed.

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[11] *Jane's DMS Info Service*, 1989, "PLSS," op. cit.

[12] Ibid.

CELT expenditures by DARPA were about $11 million. PLSS expenditures to the time of cancellation were apparently about $500 million.[13] Expenditures for the Army's GUARDRAIL systems, including aircraft, have been about $350 million through FY 90.[14]

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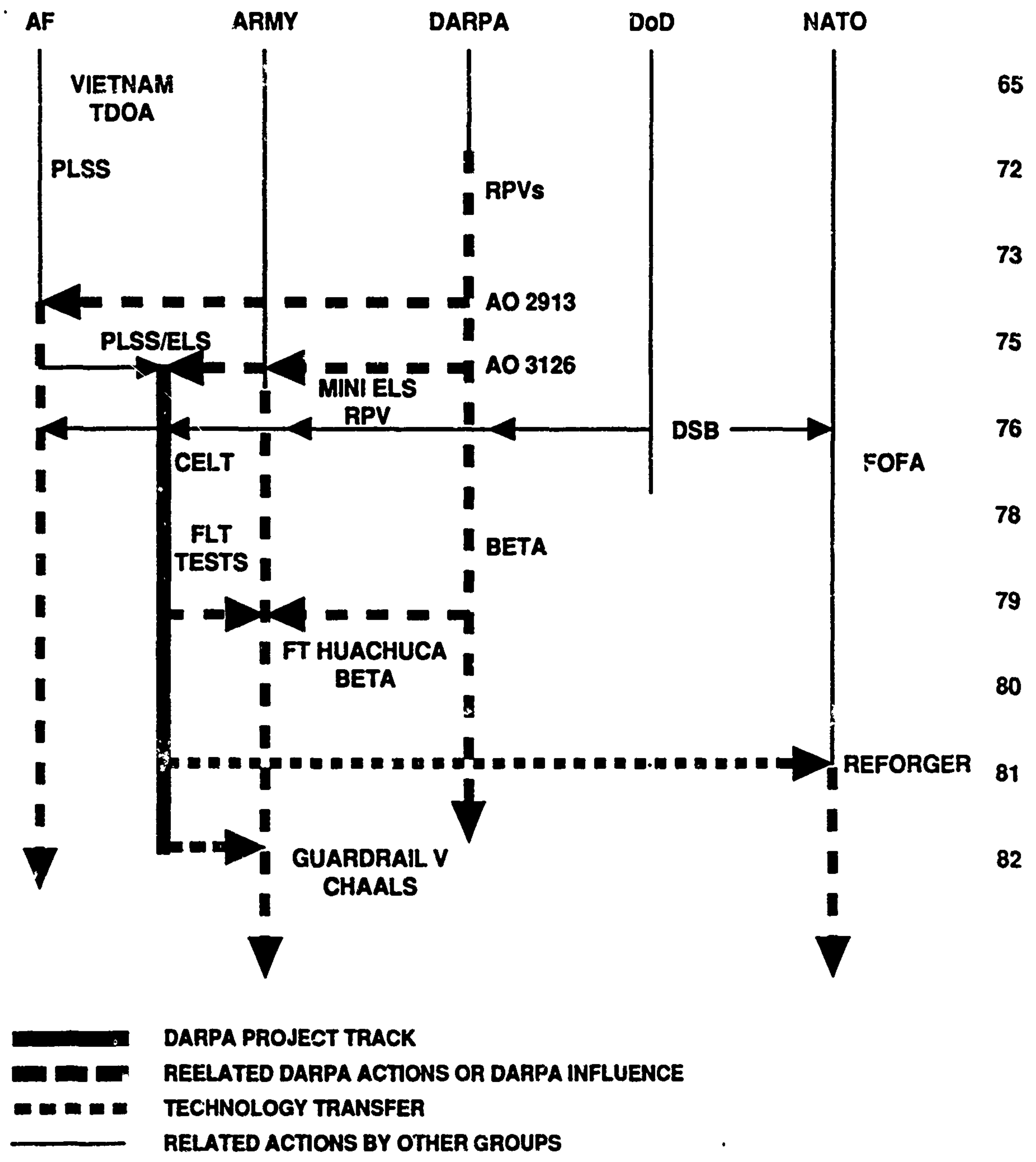
[13] Ibid.

[14] Expenditures to 1984 were mentioned in Hearing before the Committee on Armed Services, U.S. Senate, 98th Congress, 1st Session, March 1984, p. 1735. From FY 84 on, see *Jane's* ibid.

CELT


AF
ARMY
DARPA
DoD
NATO
VIETNAM
TDOA
65
PLSS
RPVs
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73
AO 2913
PLSS/ELS
AO 3126
75
MINI ELS
RPV
DSB
76
CELT
FOFA
78
FLT
TESTS
BETA
79
FT HUACHUCA
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REFORGER
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GUARDRAIL V
CHAALS
82
DARPA PROJECT TRACK
REELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS

6-4-90-1M

VIII. ARMOR/ANTI-ARMOR

A. BRIEF OVERVIEW

DARPA has had a long history of work on the problems of penetrating hardened vehicles with projectiles. In ARPA's early DEFENDER program, research on kill of ICBM RVs by hypervelocity pellets contributed to robust RV designs. From the 1960s and into the mid-1980s DARPA pursued a variety of programs in the areas of armor and penetration research. Under Project AGILE lightweight armor was developed and used on helicopters in Vietnam. Initial work was begun on several advanced concepts for armor penetration, including kinetic energy and chemical energy projectiles, and electromagnetic approaches to projectile acceleration. Through the 1970s some of these efforts were focused on the HIMAG/HSVT-L light armored vehicle programs, which incorporated an automatic cannon firing an advanced kinetic energy round.[1] A workshop sponsored by DARPA in 1973 for the express purpose of creating "a renaissance in conventional weapons technology" had several significant outputs. One was an analytical theory, based on some of the earlier work on RV survivability, high modeling velocity material penetration mechanics, which provided a systematic basis for the DARPA program, in contrast to what had been previously a largely empirical design process. In particular this theory demonstrated the value of ceramic materials for lighter weight armor. This approach suggested, when combined with other data, that Soviet armor design was much more advanced than the United States had thought, and it assisted the DoD in its decision regarding a larger caliber of gun for the M-1 tank. DARPA efforts during the late 1970s and into the early 1980s continued through several modest programs on penetrators (shaped charges, rod penetrators) armor, and rail guns.

During the latter period, growing concerns about the implications of Soviet tank and armored fighting vehicle modernization culminated in a Summer Study by the Defense Science Board in 1985. The Board concluded that the United States faced a problem in the

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[1] Chapter XXVII, Volume 1 of this study.

area that was "approaching a matter of national urgency."[2] Subsequently, with an assignment by the Secretary of Defense via the Undersecretary of Defense (Research and Engineering), DARPA made a major new commitment, with an initial funding level of $62 million in 1986 to the armor/antiarmor area. This new program fundamentally broadened and redirected DARPA's research in both penetration technologies and armor. The new program's management was shared by DARPA, the Army, and the USMC. Innovations made by this program included: involvement of the Department of Energy laboratories and of industry as major players; establishment of a Red Team activity to pose threat challenges to the program; and competitive shootoffs in specific technical areas as alternative approaches were developed. The joint DARPA, Army, Marine Corps armor/anti-armor program has involved financial commitments of nearly $400 million, of which approximately one-third was for armor, one-third for anti-armor, and the remaining one-third for activities that could contribute to both efforts. The program involved a 5-year DARPA commitment through Fiscal 1990, and has led to important advances in chemical energy and kinetic energy munitions, armor design, and electromagnetic gun technology.

B. TECHNICAL HISTORY

1. History up to 1980

DARPA has had a continuing interest in problems of penetration mechanics since its inception. The interest was pursued in a variety of related programs which ultimately converged in the armor/anti-armor program. Initially, the ARPA effort was aimed at achieving non-nuclear, impact kill of reentry vehicles under project DEFENDER. Under this effort, explosively driven pellets at speeds greater than 5 km/sec delivered more than 15 megajoules in lethality demonstrations.[3] While these early investigations were mainly for new terminal anti-missile defense systems,[4] related efforts were undertaken to select

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[2] Defense Science Board, "Armor/Anti-Armor Competition," October 1985, (CLASSIFIED) p. v, 1983 Summer Study. Statement unclassified, quoted in the record of a meeting on "Worldwide Developments in Armor/Anti-Armor" held by Technology Training Corp., Washington D.C., Jan. 23-24, 1989.

[3] Statement of Dr. R. Sproull, ARPA director, before House Defense Appropriation Subcommittee for FY 1965. A.O. 6, of 5/58, included tasks for a broad study of such kill mechanisms, as did A.O. 39. The concepts then investigated included long rod penetrators. A.O.s 70 and 71 were for hypervelocity impact investigation at NRL and BRL.

[4] A.O. 90 of 5/59. NASA and the Air Force also had some related work, going back to the mid 1950s, concerned with hypervelocity impact of meteorites on space vehicles. See, e.g., Proceedings of the 2nd Hypervelocity and Impact Efforts Symposium, Dec. 1957, at NRL.

materials and designs for reentry vehicles (RVs), and to estimate hypervelocity impact effect on survivability of RVs.[5] Some of this ARPA work continued until the DEFENDER project was transferred to the Army in 1967 and the related penetration aid program was transferred to the Air Force. The analytical work on the physics of penetration under this program later became an important basis for DARPA's anti-armor work in the mid-1970s.

In the early 1960s, under project AGILE, an ARPA-funded effort was devoted to developing lightweight armor for personnel and helicopters.[6] About this time ARPA began to support related work by Wilkins and others at the AEC's Livermore Laboratory on approaches to lightweight armor involving ceramics.[7] Together with standoff multiple aluminum armor arrays to make bullets tumble, ceramic armor configurations for aircrew vests were produced that were able to stop the tumbling projectiles.[8] The results of this work were used extensively in Vietnam to protect helicopter pilots from small arms fire.

In the late 1960s "Chobham Armour" was developed in the United Kingdom and was used in new UK tanks beginning in the early 1970s. This armor was provided to the U.S. Army's Ballistic Research Laboratory under a M.O.U. A little later, a derivative "special armor" was developed by the U.S. Army's laboratories and is now used in the M1 tank.[9]

In 1972, ARPA undertook a joint program with the Army to develop a high velocity rapid fire 75-mm automatic cannon firing an advanced "kinetic energy" penetrator. This gun was incorporated into the High Maneuverability Gun (HIMAG) and the High Survivability Vehicle Technology (Light) (HSTV/L) test beds, in a program aimed at exploring the possible advantages of agility on the battlefield. These efforts led to a demonstration armored fighting vehicle system incorporating the 75-mm, high-rate of fire gun. While this vehicle was not adopted for Service use, it contributed to Army and especially Marine Corps Light Armored Vehicle technology.[10] Other DARPA work in the

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[5] A.O. 149, "Hypervelocity Kill Mechanisms."

[6] Discussion with R. Moore, 4/6/90. A.O.s 294 and 359 for nonmetallic composite armor, both in 1962.

[7] A.O. 469 of 4/63. A later A.O. 980 of 1/67 was explicitly for a "Lightweight Armor Research Program." Some of the results are summarized in "Lightweight Armor Research Program," by M.L. Wilkins, et al., *Journal of Defense Research*, Volume 1B, #4, 1969, p. 321, (classified article).

[8] A.O. 2554 of 7/73, "Armor Arrays."

[9] R. Eichelberger, "The Evolution of Tank Armor," *Journal of Defense Research*, 79-1, 1979, p. 116 (CLASSIFIED).

[10] This program, the HIMAG/HSTV/L, is described in Chapter XXVII of Vol. 1 of this history.

late 1970s and early 1980s on tactical armor penetration included designs for a prototype Tank-Launched Guided Projectile; the Tank-Breaker anti-tank guided missile;[11] and the Assault Breaker system for attacking armored follow-on (second attack echelon) forces.[12]

In coordination with these efforts, in 1974 K. Kresa and Robert Moore, the Director and Deputy Director, respectively, of the ARPA Tactical Technology Office, arranged a workshop on tactical systems and technology at the Naval Undersea Systems Center. According to Moore, this workshop specifically aimed to create "a renaissance in conventional weapons technology and research," an area that had been viewed as stagnating in the arsenal system.[13] The objectives of this workshop were (1) to heighten industry involvement in tactical systems technology development, (2) to generate new tactical technology ideas, and (3) to go back to fundamentals to find a more efficient way to design new armor and penetrators. Available methods for such design were based on empirical rules or involved complex but limited and often expensive computer codes.

Several areas of new ARPA-supported work were stimulated by this workshop. One such area was the development of a simplified analytical theory of penetration by C. Donaldson of the Aeronautical Research Associates of Princeton (ARAP), which could also be embodied in an inexpensive computer code, relating the physical properties of the armor and projectile material to the penetration phenomenology. This theory was an extension of earlier work by Donaldson on effect of hypervelocity impact of rain droplets on survivability of RVs. Moore notes that he explicitly brought Donaldson under contract because of this earlier work and Moore's strong feeling that such an analytical approach made the mechanics of penetration more understandable and was necessary to counter the "empiricism" of the Army research. "People had forgotten the fundamental physics work that had been done on problems of penetration," Moore said.[14] Donaldson's theory characterized the armor material by two, and in many cases one, integral dissipative parameter that could be determined by experiments. ARAP carried out such experiments in the mid-1970s for a number of materials and experimental armor configurations.[15] This

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[11] Ibid., Chapter XXVI.

[12] Chapter V of Volume II of this study.

[13] Discussion with R. Moore, 4/6/90.

[14] Ibid.

[15] The ARAP theory and some experiemental results are presented in: R. Contiliano and Coleman Donaldson, "The Development of a Theory for the Design of Lightweight Armor," AFFDL TR-77-144, Aeronautical Research Associates of Princeton, Princeton, N.J., Nov. 1977. Some of the ARAP work on lightweight armor was also supported by the Air Force.

ARAP work suggested a more economical and efficient approach to armor and penetrator designs, notably for lightweight, confined ceramic armor and had considerable impact on the ARPA program at the time. However, it met initially with considerable skepticism from those involved in the Army and the Energy Research and Development Agency (ERDA, subsequently the Department of Energy) laboratories.

In the late 1970s the ARAP analytical models were applied at the request of R. Moore, then Assistant DDR&E for land warfare, to assist in deciding the required caliber of gun for the M-1. The issue was whether the United States' 105-mm gun with an advanced kinetic energy munition or either of the 120-mm guns available from the UK or the FRG should be used, in the M-1.[16] A related investigation of the open literature, instigated by Moore, revealed that the Soviets had developed a similar approach to the armor penetration problem.[17] This, plus the gun characteristics attributed to the recently fielded (mid-1970s) Soviet T72 tank, indicated that the U.S. tanks might be more vulnerable than previously thought, and probably should have a larger gun than previously planned; both were matters of deep concern to DARPA, the Secretary of the Army, and the Secretary of Defense.

Another outcome of the 1974 workshop was the initiation by DARPA of an effort toward improving shaped charge rounds.[18] The use of new liner materials and shaped charge geometries apparently demonstrated important new levels of capability. Later R&D developments along these lines were applied in TANK BREAKER and torpedo warheads.[19] The ERDA national laboratories took a prominent part in this effort. A correlated materials program was initiated in the late 1970s, working toward low cost armor and improved penetrator materials.[20]

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[16] Discussions with R. Moore, 12/89 and 4/6/90. Moore emphasizes that he had earlier discerned Soviet involvement in ceramics for armor based on their avid interest in Wilken's research. He used this information to develop a revised "threat" against which to evaluate the M-1 gun requirement using ARAP's models. The result, which he presented to Dr. Currie, the DDR&E, was that nothing under a 120-mm gun would be adequate.

[17] See e.g., *Soviet Kinetic Energy Penetrators*, Joseph E. Backofen and Larry W. Williams, Batelle Report, 1979, p.22.

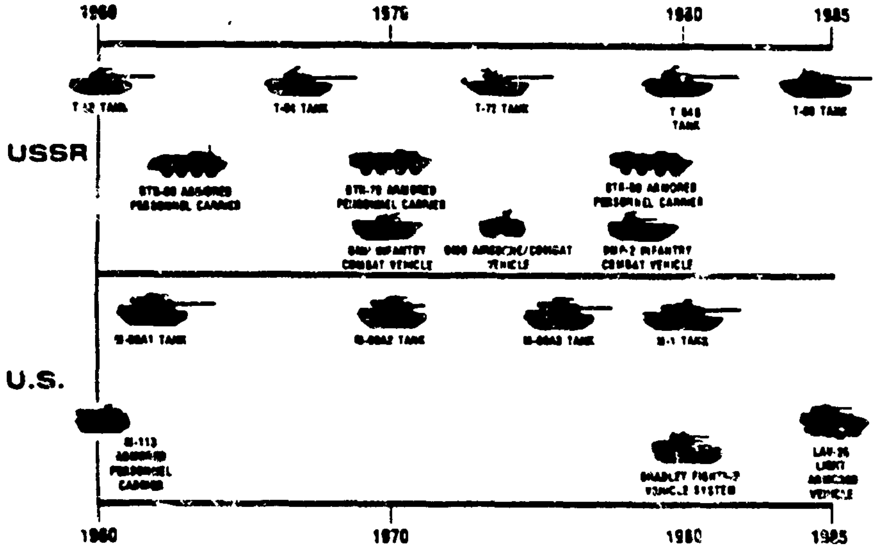
[18] Discussion with R. Moore, 4/6/90.

[19] Ibid., and AOs 4161 and 4470.

[20] Cf., e.g., AOs 3964 for light weight armor and AO 3979 for particulate reinforced aluminum.

2. History of the 1980s

In the early 1980s concerns continued to be raised about the lead that the Soviet Union was believed to have again gained over the United States in armor design and tanks with their larger (125-mm) guns. It was also known that the Soviet Union was fielding improved tanks and armored fighting vehicles at a higher rate than the U. S. (Fig. 8-1). Some of the Soviet tanks, in particular the T-80, were believed to have new armors at least as strong as those in the new U. S. M-1 tank. Moreover, the T-80's gun was a larger caliber than that of the long-barrelled guns used in most United States M-60 tanks, and was larger than that planned at the time for the M-1. Soviet tanks were also being outfitted with reactive armor appliques that would make it even more difficult for shaped-charge, chemical-energy warheads to damage or destroy the tanks.[21]



Tanks showns are both new models and major modifications. Other systems are new models only.

Figure 8-1. New and Modified U.S. and USSR Armored Systems by IOC Date, 1960-1985. From: The FY 1987 Department of Defense Program for Research and Development; Statement by the Under Secretary of Defense, Research and Engineering, to the 99th Congress Second Session, 1986, p. IV-4.

Reflecting these concerns, in 1982 DARPA began an extended Armor/Anti-Armor Research and Technology Program, and the Services also accelerated a number of

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[21] The concept of reactive armor had been investigated for a long time but apparently not funded before the 1970s. Cf., Eichelberger, ibid., p. 117.

substantial anti-armor programs. During this same period, NATO was adopting Follow-on Forces Attack concept and the United States was further refining Air-Land Battle doctrine. These doctrines called for holding Soviet armored force advances at the forward edge of the battle area (FEBA) while their second and third echelons, essential for breakthrough, would be severely damaged or destroyed through interdiction. However, doing this meant introducing "new technologies producing more accurate and lethal weapons systems expanding the possible scope of such action and making new options available."[22] (DARPA's ASSAULT BREAKER program was one of the efforts intended for this purpose.)

By the mid 1980s, the Under Secretary of Defense (Research and Engineering), Donald Hicks, was also concerned, by the mid-1980s, about the slower rate of U.S. armored forces' modernization compared with that of the Soviet Union. All these growing concerns, which were emphasized by then in an exchange of correspondence at the highest levels of government in the United States and the United Kingdom, led the USDRE to assign the problem to the Defense Science Board, which examined it in a 1985 Summer Study.[23] The DSB report confirmed that there was reason to be concerned, saying that the U.S. lag behind the Soviets in the area was "approaching a matter of national urgency." Recommendations made by the DSB to remedy the situation included: advancing armor/anti-armor technology and systems, and changing how DoD conducted R&D, planning and acquisition of systems in this area. However, some feel the DSB ignored the earlier successful DARPA work.[24]

The Under Secretary said, in his February 1986 annual report to Congress: "The Soviet modernization [of armored forces] directly challenges past U.S. qualitative superiority in ground combat forces." The Under Secretary's report further argued that: "Rapid introduction of more effective weapon systems and munitions using emerging

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[22] Michael Moodie, "The Dreadful Fury," Praeger, New York, 1989, p. 31.

[23] *The FY 1987 Department of Defense Program for Research and Development*, Department of Defense, (UNCLASSIFIED), February 18, 1986, p. IV-3. See, also, footnote 2 of this Chapter.

[24] Discussion with R. Moore, 4/6/90. The DSB report Appendix on modeling recommended that both simplified, semi-empirical, and complex computer hydrocode approaches be followed in the DoD Armor-AntiArmor program. This appendix noted that the former had been the path largely followed by industry, and the latter by the Government and DOE laboratories. It also noted that the industrial efforts had been often in competition with those of the government laboratories. DSB, ibid., Appendix D (UNCLASSIFIED). Apparently this happened in the case of ARAP which while first to meet new materials specifications in the early 1980s, nevertheless lost the competition to Livermore. Discussion with C. Donaldson, 5/90.

technologies will be necessary to regain the past U.S. qualitative advantage."[25] The Under Secretary agreed with the DSB recommendations that the Secretary of Defense should assign DARPA the responsibility to undertake a new coordinated program to remedy the situation.[26]

3. Structure of the New Joint Armor/Anti-Armor Program[27]

In a new joint armor/antiarmor program DARPA hoped to further implement the idea, which had been in the background of the 1974 tactical technology workshop, of increasing industry participation in an area that had been almost the exclusive province of the government laboratory system. DARPA's top management also regarded it as important, in the interest of early application of results, to involve the Services in the expanded program as early as possible.[28] DARPA designed a program, developed a Memorandum of Understanding (MOU) with the Services, and proceeded expeditiously to bring industry into the program outline in Figure 8-2.[29]

An MOU with the Army and Marine Corps committed all parties to a joint armor/anti-armor technology program of major financial proportions through 1990; nearly $400 million was to be spent in the time period (Table 1). The available data suggest that the DARPA contribution amounts to between a quarter and a half of the amount in the joint program.[30] [There are additional relevant Service and DARPA technology programs, notincluded in this program, that increase the total contribution of each to the overall problem solution.[31]] The three parties further agreed that the program might be extended

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[25] *The FY 1987 Department of Defense Program for Research and Development*, p. xiii.

[26] There had been some criticism of excessive proliferation and lack of coordination of the substantial Service efforts in the area, totalling nearly $1 billion in FY 81-83. For example, cf. "Anti-Armor Survey and Evaluation, Feb. 1984," DAS-TR-84-3, HQ AFSC, 1987.

[27] Based on unclassified extracts from *DoD 1989 Antiarmor Munitions Master Plan*, September 1989 (CLASSIFIED).

[28] Discussion with R. Moore, 4/16/90. One effect of the early multiagency nature of the program was the rearrangement of the work among various performers as new contracts were let. In the process some of those who had contributed to DARPA's earlier efforts were not included in the new program.

[29] At the early stages of the program, however, technical goals were not clearly delineated. Discussion with R. Gogolewski, 3/90.

[30] E.g., A.O.s 5868 and 5882 of 6/86. 5937 of 7/86 total nearly 80 million; there were many other A.O.s.

[31] Loder, R. K., (AMC), Unclassified data from "DOD Armor and Antiarmor Technology Base Program," *Journal of Defense Research*, Special Issue on Armor/Antiarmor, SECRET/NOFORN, in publication, 1990.

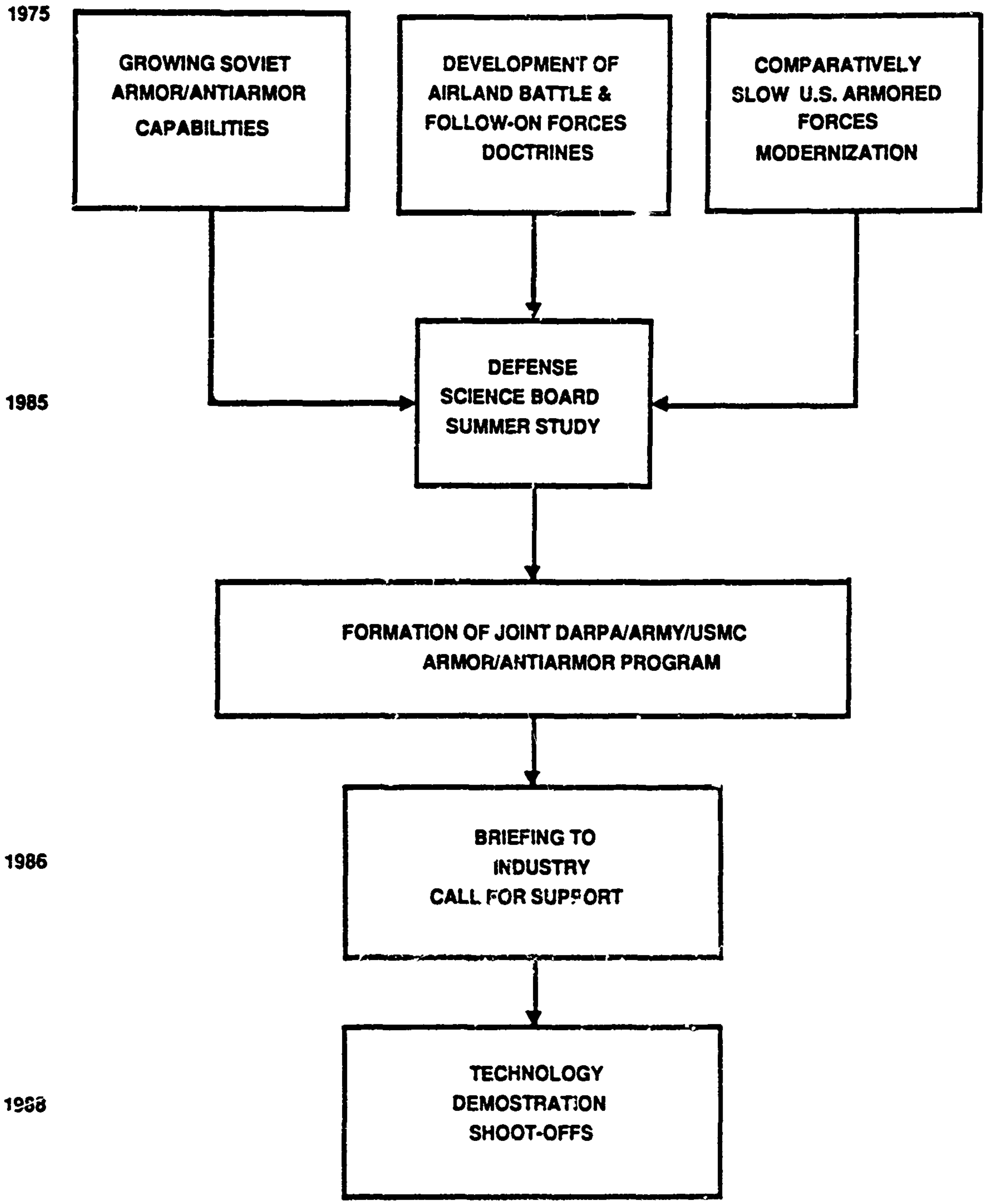

Figure 8-2. Evolution of the Joint Armor/Anti-Armor Program

through 1992 after an OSD assessment of its status and progress as of 1990. It was also decided at DARPA's urging, subsequent to the MOU, that Los Alamos National Laboratory (LANL) would act as Independent Technical Advisor, doing some of the work and letting contracts to other performers.

Table 8-1. Joint Armor Anti-Armor Program Budget (In $ Millions)

Project	FY86	FY87	FY88	FY89	FY90
CE WH	4.9	10.3	9.3	12.7	11.0
KE WH	2.2	8.9	8.1	17.2	15.0
Armor	3.6	8.3	12.1	10.6	16.0
Veh Surv	3.5	4.5	8.0	8.5	14.0
Int & Trns	1.2	1.6	1.2	3.4	10.0
Red Des	1.0	3.1	11.4	13.0	5.9
ATAC	3.0	16.2	10.2	15.8	15.0
SPT	0.3	4.2	0.0	0.0	0.0
• Tech Base	12.0	9.6	8.6	4.7	3.7
NUNN	0.0	0.0	15.0	12.0	10.0
Total	31.7	66.5	83.9	97.9	100.6

Under the MOU, direction of the armor/anti-armor program was assigned to an Executive Committee consisting of representatives of the Army, the Marine Corps, OSD, and DARPA; the Committee is co-chaired by DARPA and the Army. This group provides program direction to DARPA, which is implemented through contracts with industry, the Department of Energy, and universities. The DARPA Tactical Technology Office has had the lead in prosecuting the program, and a Joint Program Office at DARPA, with strong Army and Marine Corps participation, has managed it. The management process has been important to the transfer of results to the Services and will be explained here.

A major objective of the DARPA/Army/Marine Corps program has been to build a capability in industry to analyze, design, and test armor/anti-armor mechanisms and systems. In a specific research area, work is carried out by all participants toward a common goal--for example, the design of a lightweight armor system capable of defeating a given set of kinetic energy and shaped-charge penetrators. At the end of each cycle of competition, the designs are evaluated in a shoot-off, and a contract could be awarded to adapt the winning concept to a specific application. Following each shoot-off, a new cycle of competition is initiated using updated threat or evaluation criteria.

The organization of the program is shown in Figure 8-3. An important program feature is the independent Red Design Bureau, headed by Battelle Mechanical Technologies, Columbus Laboratories, which produces suitable simulators of Soviet equipment for use in the shoot-offs. The Advanced Technology Assessment Center (ATAC), located at the Los Alamos National Laboratory, plans and conducts the shoot-offs and also takes part in the competitive evaluations.

The Joint Program Office (JPO) provides administration and day-to-day oversight of the program. This office includes personnel from DARPA, the Army, and the Marine Corps. The Executive Steering Committee provides "strategic" guidance to the program. This group is assisted by the Intelligence Steering Committee and the Independent Assessment Group. The Independent Assessment Group is made up of representatives of the Army and Marine Corps test and evaluation community, and provides an independent assessment of new technologies and selected test procedures to the Executive Steering Committee.

4. Areas of Investigation Under the New Program[32]

The penetration investigations were divided into chemical energy and kinetic energy approaches to defeating tank armor. The armor program is aimed at improvements in protection for both heavy tanks and light armored vehicles. Other parts of the program were aimed at defeating incoming attack before actual contact with the vehicles, and have been intended eventually to incorporate pioneering technological results in weapons and platforms.

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[32] The program achievements listed in the following sections are taken from Siegrist, D., BDM Corp., unclassified briefing charts on the accomplishments to date (as of 1989) of the armor/anti-armor joint program, unless otherwise noted.

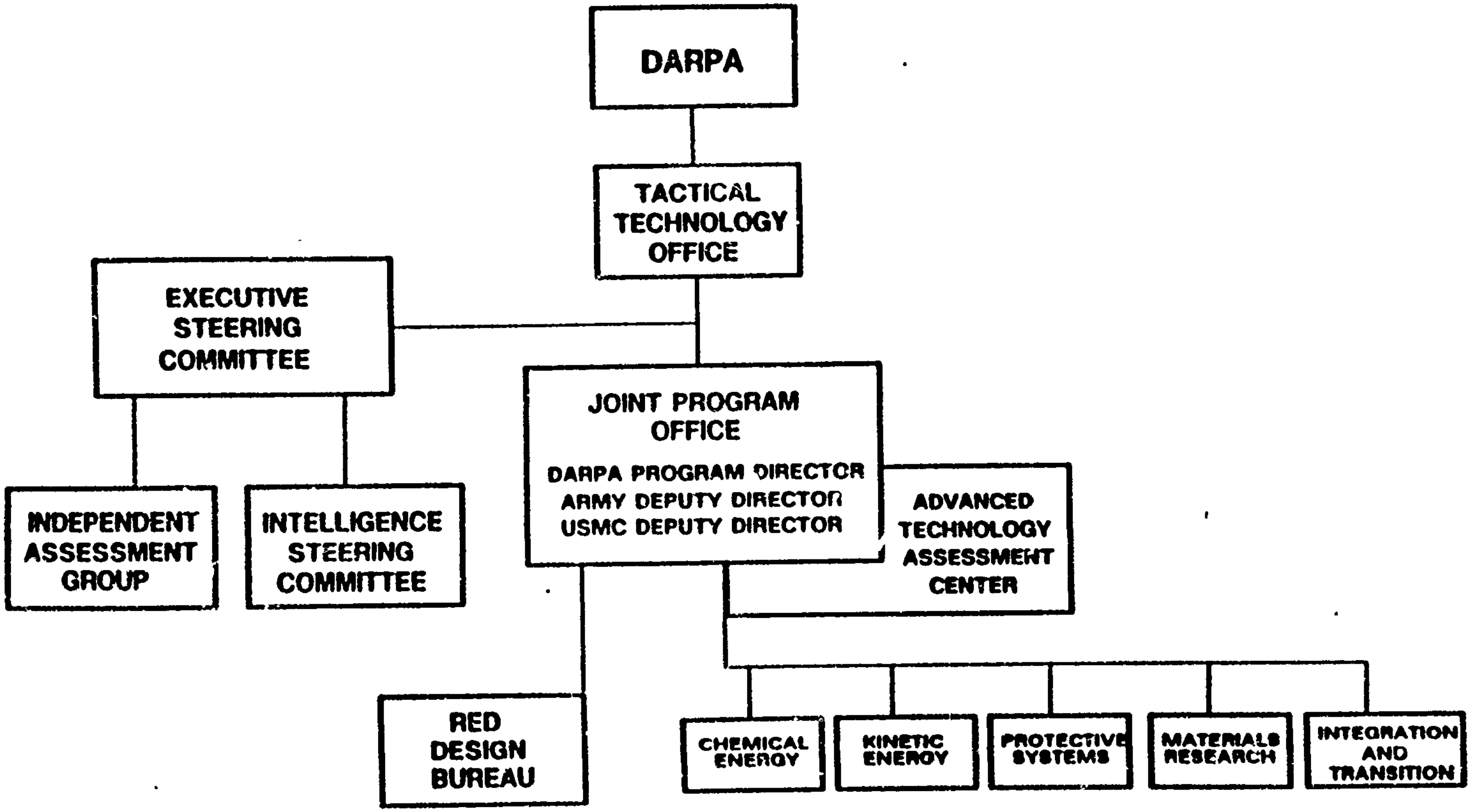

Figure 8-3. Armor/Anti-Armor Program Organization

a. Chemical Energy[33]

Two of the questions posed to the teams concerned with chemical energy weapons for Phase I of the program were:

- Can a 10-pound HEAT warhead greater than 81 mm but less than 150 mm in diameter of any design defeat projected FST II armor in direct attack, or is a tailored trajectory necessary? If it cannot, what is the minimum diameter and weight?
- Can an effective top-attack submunition be retrofitted to existing delivery systems that will defeat projected applique armor on the T-72 and T-80?

The results obtained in response to the first question established the warhead parameters and tradeoffs for ATGM systems, and are being applied to systems such as the AAWS-M and AAWS-H. The second question concerns tradeoffs for short overflight shaped charges and explosively formed penetrators. The competing systems were evaluated in a shoot-off that began in May 1988. In addition, a large body of data is available from test firings done by each of the contractor teams. Storage of this information in an automated central data base for future reference is underway.

The three industrial teams competing in the chemical energy warhead area have different areas of emphasis, as shown in Table 8-2. A fourth area consists of several industrial efforts to address unconventional, high-payoff chemical energy warhead approaches in Phase II of the program. In addition, a technology support team headed by Lawrence Livermore National Laboratory (LLNL) has performed work of general interest to the industrial teams, such as the development of advanced explosives and improved liner materials, and investigations of some novel shaped-charge concepts. This team serves a basic research function for support of the overall effort; it does not compete with the industrial teams.

In 1988, warhead technologies for both direct and indirect fire weapons were successfully demonstrated against interim threat targets. However, at the end of Phase I developments, new intelligence information for the year 2000 + led to newly defined threat targets, starting new cycle in the armor-antiarmor historical pattern. Targets reflecting substantially higher levels of difficulty were used in the May 1988 shoot-offs. While these higher threat levels made the problem more difficult than had been anticipated, several

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[33] DoD 1989 *Antiarmor Munitions Master Plan* (CLASSIFIED).

shaped-charge and explosively formed penetrator-based warhead designs were successful, although larger warhead diameters were required. The industrial competitive shoot-off led to a focus on technology gaps in warhead systems for the next armor/anti-armor cycle. These are being addressed by the program through design iterations for which testing began in the second quarter of FY89, as an extension of Phase I efforts. It is planned that warhead technologies demonstrated thus far be transferred through specific programs for warhead upgrades.

Table 8-2. CE Program Structure (From Ref. 33)

		AAWS-M (4"-5")	Heavy (6"-7")	Top Attack Submunitions	Direct Fire Projectile
Competitive Industrial Teams	UNCONVENTIONAL	● →	→ ○	●	●
	Team 1	●	●		○
	Team 2	○ ←	← ●	●	
	Team 3	○ ←	← ●	●	
Advanced Technology Support Team	LLNL and Others	●	●	●	●

● = Major Emphasis ○ = Secondary Emphasis

Phase II of the chemical energy warhead program, which began during FY89, has the aim of enhancing the robustness of the maturing technologies, development of near-term warhead solutions, and cultivation of unconventional far-term, high-payoff chemical energy warhead technologies. By FY90 and FY91, it is expected that additional warhead technologies with potential application not only to the above mentioned systems, but also to HELLFIRE, FOG-M and AAWS-M, will be demonstrated and readied for FSD.

b. Kinetic Energy[34]

The major thrusts of the kinetic energy penetrator program are the following: to increase total penetration through the use of segmented rods, new materials, and novel penetrator concepts; to increase projectile velocities, particularly for longer ranges; and to improve projectile accuracy, either through reduced ballistic dispersion or through the use of guided rounds.

Because of uncertainties regarding the penetration mechanics and target interaction of novel penetrator concepts, the initial efforts in the kinetic energy penetrators program are parametric investigations to compile a database of various impactor materials attacking a variety of target types over a wide range of velocities (Table 8-3), in order to provide the background for the formulation and experimental evaluation of advanced penetrator concepts.

Table 8-3. Projectile/Target Matrix of Hypervelocity Impact Investigations

	Targets				
Projectiles	RHA	Ceramic	Spaced	Reactive	Scaled International Range Targets
Rods of Different Materials	x	x	x	x	
Segmented Rods	x	x	x	x	x
Sheathed Rods	x	x	x	x	x
Jackhammer Rod	x	x	x	x	
Tubular	x	x		x	
Ceramics	x	x		x	
"Grease Gun"	x	x			

The X-Rod program has been initiated in the Joint Program to demonstrate kinetic energy munitions suitable for firing from a 120-mm tank cannon and capable of defeating projected Soviet tank frontal armors at extended ranges. These concepts involve

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[34] Ibid.

propulsion outside the gun tube (for example, rocket or ramjet-assisted) and some form of guidance or accuracy enhancement. Competitive industrial teams have been formed and Phase I component development work is well underway. A shoot-off was planned for FY91, after which development for the 120-mm application could begin, followed by 105-mm development.

Additional work in the area of anti-armor gun systems is also being pursued in a related program, the Electromagnetic Gun Technology Demonstration program, designed to demonstrate maturity of launcher and projectile technologies for weapon development.[35] Projectile velocity upward of 5 km/sec are being sought. A portion of this program is funded by the DARPA JPO; funding is also provided by the Balanced Technology Initiative and the Strategic Defense Initiative. Three distinct technology approaches have been pursued: an electromagnetic railgun, an electromagnetic coilgun, and an electrothermal gun. Projectile development for this effort focuses on high velocity and draws on results obtained in the kinetic energy projectile parametric examination described above. Demonstration hardware is planned for a maximum energy output of 9 megajoules. An anti-armor system based on any of the three approaches is estimated to require an energy output in the neighborhood of 18 to 25 megajoules.

c. Armor

The results of the armor program are expected to be incorporated into improvements of existing tank and armored combat vehicle designs, and into new vehicle designs such as the Army's new Armored Family of Vehicles. Two industrial teams are competing in each area. The four contractors were evaluated initially at a shootoff in late 1988. Cooperation with other NATO countries is also being established as part of this program.

Both the light and the heavy armor programs enhance protection levels through innovative geometries, next generation armor appliques, and advanced ceramics. Materials, advanced manufacturing techniques, and improved approaches to design of materials through improved computer models of the material-penetrator interactions are all part of this program.

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[35] E.g., A.O. 5882 of 6/86.

C. OBSERVATIONS ON SUCCESS

ARPA's early, non-nuclear impact kill experiments resulted in robust designs of RV nose cones and indicated feasibility of mechanisms that form part of the database for the SDI program. The ARPA AGILE work on light armor led to applications for personnel and helicopter protection in Vietnam.

Moreover, DARPA's early work from the DEFENDER and AGILE programs pointed toward the directions for solving a number of fundamental questions about penetration mechanics. Near the end of the Vietnam War DARPA involved industry in this area, changing it from an almost exclusive government laboratory preserve. A new, simplified approach to armor penetration mechanics emerged, derived from the earlier work on RVs. This approach provided a theoretical basis for a systematic efficient and economic sense of experiments that demonstrated the value of lighter weight confined ceramic armors.

This work, together with other data, pointed to the possibility that the Soviet Union was already using such armors, placing them ahead of the United States in tank design; the work impacted later lightweight armor designs and assisted DoD decisions favoring an increase in gun caliber for the M-1 tank. An attempt to integrate many of these advances with other technology in HIMAG/HSTV/L was overtaken by threat advances in heavy armor. However, another result of this DARPA initiative was the involvement of the Los Alamos and Livermore Laboratories in efforts to improve shaped-charge warheads.

Converging concerns in the United States and NATO about a growing Soviet lead in armor capability were reinforced by the DARPA-supported work on penetration mechanics, and by the observation of more frequent Soviet fielding of new tank and infantry combat vehicle designs. The implication of a growing U.S./NATO disadvantage in armored systems and forces was confirmed and reinforced in a DSB study undertaken as a consequence of the concerns. This, together with a lack of focus among Service programs in the area, led the Secretary of Defense to ask DARPA to undertake a new joint armor/anti-armor program. The DARPA program, with responsibility for conducting a coordinated program, represents a relatively new approach to ensuring Service adoption of DARPA program outputs. Since it is still on-going it is impossible to assess this program's impact. Preliminary indications are that parts of the new program are making substantial contributions to addressing the concerns raised by the Defense Science Board.

Developing new analytical tools and creating the Red Design Bureau at Battelle are widely acclaimed successes of the new program. The recent Program-sponsored projects at Department of Energy laboratories that are developing complex, multidimensional computer models are seen as substantially advancing the armor design process.[36] Additionally, the new program modified existing special diagnostic capabilities resident in Department of Energy laboratories to improve the design process for kinetic and chemical energy warheads. The Red Design Bureau's efforts to forecast potential Soviet armor design advances, and then to build prototypes of those designs, have gone a long way toward implementing the Defense Science Board's recommendation to define future Soviet threats in more imaginative ways.

There have also been a number of specific technical successes in the recent program, including many advances in shaped charge design that greatly enhance their penetrating power, even against reactive armor; advances in kinetic energy rounds including validation of segmented-rod penetration theory; boosted kinetic energy rounds of greatly enhanced performance, and demonstration of a 3.4 km/sec tactical bullet; and progress in the areas of armors, electromagnetic guns and antiarmor mine warfare.[37] While these accomplishments may be regarded by some as evolutionary, the results have increased U.S. capability both to penetrate armor and to afford protection against penetration. For example, armor material concepts developed in the new armor/antiarmor program were the competitive winners for the Block II armored vehicle upgrade program, and several chemical energy warhead designs have been accepted for application by the U.S. Army Missile Command (MICOM).

DARPA leadership of the recent program has also led to the introduction of a number of valuable management features. The initial DARPA hope of involving industry in the technology-base aspects of this national problem in an important way has been realized. The use of Los Alamos in an integration-oriented role is helping to tie the entire program together. The time to transfer useful results to the Services appears to have been reduced by virtue of Service participation in the joint program and the Joint Program Office. The use of competitive shootoffs between new capabilities in specific technical areas as they were developed has increased the chances that the results will be sturdy to new threat developments.

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[36] Rurik K. Loder, op. cit.

[37] Siegrist, D., BDM Corp., unclassified briefing charts on the accomplishments to date of the armor/antiarmor joint program.

Some DARPA participants have expressed disappointment that more couldn't be done in the new program. In particular, the time from conception of an idea to contract to results has tended to be longer than desired. Also, some of the desired technical parts of the recent program--work in integrating all of the results in demonstration vehicles, reminiscent of HIMAG/HSTVL, for example--have been given up. Some believe that technical impetus may have been lost because some participants in the earlier efforts were not involved in the new program, and that some earlier contributions seem to have been ignored at the new program's inception.

Overall, in managing this program DARPA has fulfilled one of its important roles, that of facilitating a rapid approach to an important national problem where our technical capability was lagging. To do this, DARPA drew on a long background of involvement in relevant technology matters. A final score sheet will obviously have to await the completion of the program and the outcomes of the Service utilization of the results.

DARPA outlays in the armor-antiarmor area, from available records, were about $100 million up to 1985. The subsequent program budget has been somewhat larger. The technology from this DARPA effort has impacted a wide variety of defense systems involving armor, guns, warheads, and penetrators, programs totalling several billion dollars.

SURVEILLANCE

IX. IR SURVEILLANCE: TEAL RUBY/HICAMP

A. BRIEF OVERVIEW

ARPA had early involvement in satellite infrared (IR) surveillance technology and, later, in development of IR imaging for the Vietnam war. In 1975 DARPA began to push the state of the art in IR focal plane array staring imager technology, and commenced the Teal Ruby program to construct a satellite capable of near real-time IR detection of strategic and tactical aircraft. Under Teal Ruby very large space qualified focal plane arrays were successfully produced at a fraction of previous costs per image pixel, along with larger long life cryocoolers, and large lightweight optics. To assist design of Teal Ruby processing algorithms. HICAMP, an aircraft-based background measurement program produced the major IR data base now available for satellite systems for aircraft detection. After a number of management problems, cost over runs, and delays, the planned Teal Ruby launch via the space Shuttle was postponed and later cancelled by Congress. The Teal Ruby satellite is now in storage.

B. TECHNICAL HISTORY

1. Background

From its earliest days ARPA was involved in infrared surveillance technology. As part of its broad space assignment ARPA briefly took over responsibility for the Air Force (AF) MIDAS, infrared satellite program for ICBM detection and early warning. ARPA changed the Air Force 1171 surveillance satellite program to make MIDAS a separate satellite.[1] Some in ARPA/IDA also had further concerns about the MIDAS IR system but, these had little effect on MIDAS which was then well along toward launch.[2] When MIDAS was found to have excessive false alarms it was cancelled, and DoD gave ARPA an 18 month assignment to determine whether there were fundamental problems which

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[1] Richard J. Barber *History of the Advanced Research Project Agency*. 1958-75, 1976, p. IV-11 and 12.

[2] H. York, the first ARPA Chief Scientist, states that "the Air Force (satellite) programs were approved essentially as they stood." in *Making Weapons, Talking Peace*, Basic Books 1987, p. 145.

would not allow any IR missile warning system to work. ARPA responded with project TABSTONE, which made many high accuracy measurements of of missile propellant radiation, atmospheric transmission, and of the background seen from high altitude sensors.[3] TABSTONE was completed in 18 months as assigned, and its results raised DoD confidence that satellite IR surveillance of ICBM launches could indeed be practical. Subsequently the Air Force undertook several satellite R&D programs toward an IR ICBM surveillance system, culminating in the launch of the satellite early warning system (DSP) in the early 1970s.

Under project DEFENDER ARPA also supported IR measurements of ICBM reentry in project PRESS, and in project AMOS constructed an IR telescope for precision IR imaging of space objects and stellar backgrounds for measurement of IR transmission by the atmosphere.[4] AMOS was also a testbed for some later infrared detection arrays.

The Vietnam War provided a major impetus for development and production of infrared imaging systems, in the late 1960s and early 1970s. ARPA funded many of the developments in this period, along with the Services. By the early 1970s it was clear that there was a fast-growing demand for IR imaging systems for use in the field, but the costs of these systems were high. A concerted DoD effort, with Army lead, was set up in 1973 toward a "common module" approach to construction of infrared sensor systems, in order to bring costs down and facilitate production.[5] Part of the basis of the common module effort was an assumption that something of a plateau had been reached in the early to mid 1970s in several key ingredient technologies, detectors including 1-D (1-dimensional) arrays of up to 180 detectors, cryogenic coolers and custom integrated circuits.[6]

This plateau assumption was useful for "freezing" some of the technology for the mass-production efforts that followed, but the large funding base also allowed several developments to continue, including construction of early 2D focal plane arrays (FPA) with around 10^3 detectors, with charge coupled device readout systems in the back of the FPA.[7]

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[3] TABSTONE is described in Chapter VII of Volume I of this report.

[4] AMOS is described in Chapter X of Volume I and PRESS in Chapter I of this volume.

[5] ARPA funded one of the earliest attempts toward simplification of IR imaging sensor design, at Honeywell. Discussion with R. Ennulat 4/88.

[6] *Common Module--Overview and Perspective,* by W.A. Craven, Jr., Proc. IRIS Infrared Imaging, Specialty Group Meeting, 1986, Vol. 1, p. 9.

[7] *Common Module FLIR Impact on Technology Development*, by J. Stephens, Proc. IRIS Imaging Specialty Group Meeting, 1986, p. 32, and chapter on Improved Surveillance, by J. Fraser, in *Army Control Specification*, Eds. K. T. Spies, et al., Pergamon, 1986, p. 179.

2. TEAL RUBY

Around 1975 Dr. George Heilmeier, then Director of DARPA, was anxious to push the state of the art in IR focal plane array technology. The recent success of the common module program, outlined above had shown that techniques were to allow the use of IR focal plane technology in a wide variety of military programs. Furthermore, the advent of CCDs in the early 1970s implied the possibility of very large focal plane arrays, with two to three orders of magnitude increase in the number of pixels over the current state of the art. Aside from the focal plane array issue, DARPA was interested in other key technologies such as large lightweight optics, mechanical cryocoolers, active satellite structure control, and data processing. This effort was intended to support missile surveillance, theater surveillance and targeting, air vehicle detection, (AVD) and other surveillance interests. To push the technology, the detection of air vehicles from space appeared to be the most challenging, yet within the bounds of reality and cost. Furthermore, the AVD issue was at the forefront within the Defense community (as well as Congress) because of the development by the Soviets of a long range bomber capability (Backfire). Thus, although IR focal plane arrays were initially the driving issue, contracts were awarded to Lockheed and Rockwell to develop a demonstration satellite for IR AVD: Teal Ruby. Competition continued through Program Decision Review (PDR) at which point Rockwell was awarded the contract for the final phases of the program. Although funding and direction was provided by DARPA,[8] contract management and spacecraft development was provided by Air Force Space Division under the Space Test Program. This type of management arrangement had worked earlier for less complex systems, but for Teal Ruby it led to difficulties, which will be discussed below.

The Teal Ruby program was begun in 1975 to place into orbit a satellite capable of detecting strategic and tactical aircraft in several infrared wavebands. The program objectives were:[9]

1. to demonstrate the feasibility of AVD from space with an IR mosaic sensor;
2. to demonstrate the producibility and assess the performance of IR focal plane arrays and associated technologies in space; and

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[8] ARPA Order 3058 of 6/75 provided most of the early funding.

[9] M. Schlessinger, *Infrared Handbook of Air Vehicle Detection*, Volume 6, *The Teal Ruby Experiment*, ed. Hans G. Wolfhard, The Institute for Defense Analyses. IDA Paper P-1813, September 1985 (SECRET). Unclassified excerpts have been made from this classified article.

3. to generate and establish a background and target database of radiometric and other data that will support the development and test of future operational AVD sensors and space surveillance systems.

Although aircraft detection was the primary objective, Teal Ruby was also to perform experiments relevant to missile launch detection, naval targets such as ships and submarines, ground targets such as mobile missile launchers, and other non-AVD problems. Thus, Teal Ruby was to demonstrate the potential of IR surveillance to many different interest groups.

Development of a space-based IR AVD system required more than focal plane arrays. Waveband selection was by no means a foregone conclusion; thus, multiple filters were required on Teal Ruby in order to optimize an operational system. The original concept was to use a single array with an acousto-optical filter. However, data handling issues caused that idea to be discarded in favor of dividing the focal plane into 13 filter zones; each zone had within 12 32 x 96 IRCCD chips, and the array would be read off a zone at a time. Filter selection focussed on two detection concepts: the detection of the contrast between the aerodynamically heated airframe of the target and the earth's background, and the detection of the target aircraft engine plume. Initially, the plume was thought to be the key signature feature.

Much effort was expended within the Teal Ruby program on the physics of the "blue spike" and "red spike" spectral features in the 4.3 µm CO_2 emission region, which were the "leakage" (i.e., spread) around the central atmospheric absorption region of the emissions from the hot CO_2 in the engine exhaust. Much data was collected, generally at short range, which proved to be very deceptive for inferring signal strength at operational ranges, reminiscent of TABSTONE. Data collected at longer range by B. Sanford of AFGL, (Air Force Geophysical Laboratory) along with subsequent analysis by ERIM (under R. Legault), Aerospace (under F. Simmons), IDA (under Hans Wolfhard), and Hughes Aircraft, led to the conclusion that the plume emissions would not be dependable for AVD detection. This conclusion was programmatically helpful to Teal Ruby in that more zones could be given over to hardbody detection bands, and very narrow, very expensive blue spike filters were no longer required; some of the spectral zones were changed, and included spectral bands to support the Talon Gold[10] program and other

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[10] Talon Gold was a classified program for an experimental space-based laser pointing and tracking system for missile defense

special missions. However, it could be argued that the 13 zones already frozen into the design were probably superfluous.

The detection of air vehicles against the earth's background requires a substantial amount of clutter suppression. Hence, detection algorithms had to be developed and evaluated. It was also decided early on that Teal Ruby should be designed to demonstrate as much a real-time, operational detection capability as was possible. Therefore, provisions were made for on board processing, which had never been attempted before. Detection algorithms all revolved around MTI (Moving Target Indication) schemes, which generally require a low degree of platform jitter, and significant on-board storage and processing. This work was pioneered by M. Schlessinger of The Aerospace Corporation and Dr. E. Winter of Technical Research Associates.

The telescope was comprised of four elements, with an f/3.3 20 inch aperture: total weight was 61 lbs, excluding focal plane hardware. To achieve that low weight, graphite-filled epoxy was selected as the structural material. At the time, graphite epoxy had been used primarily in some experimental aircraft, and in the manufacture of tennis racquets. One technical issue that arose was that graphite epoxy is hygroscopic, and must retain a certain amount of moisture to maintain structural stability. In earth-bound applications a film coating traps the moisture; in space, however, moisture would continue to evaporate, causing condensation problems on the cooled optics. This difficulty was discovered late in the program, and was fixed by the insertion of a transmissive zinc selenite window that isolated the structure from the cold optics.

The development of low temperature (15 K), long life (1 year mission duration) cryogenic systems to cool very large focal plane arrays was a significant technical achievement of the program. The monolithic silicon arrays required low temperature uniformly across the entire assembly. To minimize sensor jitter solid cryogens were specified; the arrays were cooled with subliming neon. Furthermore, the optics had to be cooled to 70 K. This was achieved by coupling subliming solid methane to the rear optical elements.

The IR focal plane array production line for Teal Ruby remains the largest ever in this country. Over 150 IRCCDs were required for the mission, and had to meet stressing specifications of uniformity, responsivity, noise, spectral response, etc. Thus, hundreds of arrays had to be tested in order to select the optimal set. This was a learning process that occurred primarily under the direction of LTC. H. Stears of DARPA; for almost two years the program stood virtually still while sorting out the issue of whether or not the tester (provided by Rockwell gratis) was giving erroneous results or the detectors themselves were bad.

Once this was resolved, a dedicated test facility that largely automated the process was constructed with success; over 500,000 detectors were processed in 6 months time, once the system became operational. Furthermore, massive amounts of ground calibrations were conducted, achieving absolute accuracies to a few percent. An on-board blackbody source was provided, and an unprecedented amount of ground command of bias voltages, gain states, etc. was to occur as detector performance changed with time. Ground truth sites were selected later in the program. The scope of this achievement is easy to underestimate today, but the LANDSAT sensor was in comparison rudimentary.

Aside from the goal of producing very large, space-qualified arrays, there was the objective of obtaining low detector channel costs. At the time, the single pixel cost for 2-D IR surveillance system (including drive electronics), as estimated by DARPA, was \$20,000.[11] The DARPA goal was \$0.10; Teal Ruby achieved \$2.00 per qualified, calibrated pixel.

3. HICAMP

After the down-select to Rockwell, a contract was awarded to Lockheed to collect data from an aircraft-based sensor of targets and earth backgrounds. This program was called the Calibrated Aircraft Measurement Program (CAMP), which flew a two dimensional IR array, and later evolved into HI-CAMP, with higher radiometric accuracy, greater spectral coverage, and higher spatial resolution. HICAMP as a program is only now winding down, and represents the single most comprehensive IR AVD database collected. The purpose of the program was to get the community's feet wet with data. Furthermore, there was a desire to put to rest the plume detection vs. hardbody detection issue. The original intent was to use Teal Ruby "reject" detector arrays, but that was discarded in favor of a dedicated focal plane array. HICAMP data, in the absence of Teal Ruby, has become the major IR AVD database in this country for designing and testing detection algorithms, selecting spectral passbands, and sizing tactical, and air or missile defence systems that operate in the relevant spectral regions.

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[11] Normalized to total fielded unit cost, the per pixel cost for 1-D, common module systems was about \$80. Cf. *Common Modules, A Success Story*, by Walter E. Morrow, Proc. IRIS Imaging Specialty Group Meeting, 1986, p. 25.

The development of detection algorithms required detailed knowledge of background clutter. It was found from the HICAMP data, as well as other, more limited programs, that statistical measures of clutter, such as power spectral density, could lead to erroneous conclusions about the false alarm rates. Indeed, there is still debate as to what measures best characterize the clutter background. Furthermore, although Teal Ruby had planned an extensive set of target measurement experiments, the 1 year mission lifetime implied that a considerable amount of time would be available for collecting background data. Although never implemented, there was also a design feature that allowed the uplinking of new detection algorithms, which would occur as data became available. Finally, the HICAMP database did not exist for denied areas such as the Soviet Union, or for weather conditions that precluded the U2 from flying. Thus, Teal Ruby if it had been successfully launched would have added a large variety of background measurements to the experimental program.

4. PROGRAM MANAGEMENT

Significant time delays and cost overruns occurred in the program; the blame could be shared among the contractor, DARPA, and AFSD.[12] DARPA had imposed initially a highly unrealistic schedule, wherein many new technologies would be integrated and the whole would come to fruition within 21 months. DARPA had also loosely defined program requirements and given inadequate specifications in an arena where many aspects of the technology were very immature. Unrealistic "success-oriented" cost estimates were accepted, without independent evaluation. There were other issues associated with procurement management, and configuration control. For its part, AFSD provided inadequate manpower; the project office consisted of 3.5 persons in 1980. There was a lack of continuity, with five program managers in five years. The early support by Aerospace Corp. was essentially similar. This led to an acceptance of the overly optimistic DARPA procurement strategy. system requirements, and schedule. Senior management seemed unaware of the nature and scope of the program, which led to inadequate responses to the cost growth, such as arbitrary spending caps. Rockwell in turn, had inadequately estimated the cost of the program, failed to properly audit and track subcontracts, and had problems with the system engineering and program management. Finally, inflation had a

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[12] See Edwin W. Schneider, *The Life and Times of Teal Ruby*, presentation to DARPA Space Symposium, Oct. 4, 1983. Schneider was the Director of DARPA's West Coast Liasion Office, and reports the reentry of the Aerospace Corporation study to assess and rebaseline the Teal Ruby program.

major impact; fully one third of the $30M in program growth that had occurred by the end of 1981 was due to that cause.

Program management was clearly a major issue for Teal Ruby. DARPA provided the money, and was primarily interested in development of the techbase (e.g., focal plane arrays, cryocoolers, lightweight optics, etc.). Air Force Space Division (AFSD) was responsible for contract management and spacecraft development, and was primarily interested in assuring that the system worked; the program was initially treated as a "small" program by AFSD, but was eventually elevated to "major" program status by LtGen McCartney. As might be expected, friction occurred, to the point where the program came close to cancellation several times by mutual consent. In some cases this was averted by the intervention of DDR&E, who considered the program important for addressing the perceived Backfire threat as well as driving the technology. Col. A. Wisdom of AFSD and Lt. Col. H. Stears of DARPA eventually reached a modus vivendi. They tried to obtain a Memorandum of Agreement (MOA) between AFSD and DARPA, but the Air Force would not sign; fiscal flexibility was the issue. Without an MOA, Wisdom and Stears reached a personal agreement, which kept DARPA out of decisions involving less than $100K, placed a DARPA person in the AFSD SPO, and established programmatic goals. Lines of communication opened up significantly. Furthermore, DARPA and AFSD, acting jointly, were able to get Rockwell to renegotiate the contract (now 10 years old) into a fixed-price contract with incentives for on-orbit performance, of a type used in a number of DoD satellite contracts beginning with ARPA's VELA HOTEL.[13]

Teal Ruby came under attack within DARPA. DARPA overall funding had been low throughout the 1970s, compared to the preceding decade, and Teal Ruby was seen by many within DARPA as taking a disproportionate share of the pie. As discussed above, significant cost overruns had occurred. In response, Lt. Col. Stears and L. Lynn, Deputy Director of DARPA, stopped the program for 5 months at the management level to reevaluate. An Aerospace Corp. study was commissioned by DARPA to compare Teal Ruby with other first-time satellite development programs like DSP and GPS.[14] The study concluded that Teal Ruby was within what normally occurred in such Air Force programs, and furthermore estimated that the program could expect that between 1 to 1.5 years of time

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[13] VELA HOTEL is described in Chapter 11, of Volume I, of this report.

[14] See Schneider, op. cit.

outside the schedule would be required to meet unexpected problems. The study also identified potential problem areas. With this in mind, DARPA and the Air Force reformulated the program schedule, with management blocks set aside to meet contingencies, and got the corporate Air Force to agree to the consequent cost and schedule increase. No further overruns occurred. It is important to realize that Teal Ruby was the most complex spacecraft ever constructed by AFSD, in terms of number of parts and subsystems; the fact that it programmatically fell within the norms of other first-time systems might be seen as something of an achievement. In contrast to these other systems, however, the delays in the Teal Ruby program were fatal due to the Challenger launch accident and subsequent events.

Teal Ruby was set for launch when the Challenger disaster occurred. By the time shuttle flights resumed, circumstances and personnel had changed dramatically. Teal Ruby had been transitioned by DARPA to the Air Force for completion. The money for the sensor had been in the Air Force cruise missile line, which was cancelled. The Air Force had money for the spacecraft, but was told by Congress to hold up spending on the other components of the mission until they had seen justification for the program. Congressional attitude at that point was generally positive. However, AFSD issued a contract to Rockwell to allow completion; this step was construed by Congress as a violation of its direction. Congress then cancelled the entire program. The strong support for the program provided by, among others, Lt. Gen. Randolph, had evaporated. Air Force AVD was now focussed on space based radar. Furthermore, the Backfire bomber was seen now as primarily a Soviet Naval Aviation asset, and hence less important to the Air Force threat scenarios. DARPA was anxious to transition the entire IR AVD program to the Air Force, which seemed uninterested. In addition, there was some quarreling within DARPA between the Strategic and the Tactical Technology Offices as to who should control future IR AVD programs. The argument with Congress proved to be the slamming of the door on the program. The Teal Ruby satellite is currently in storage, and remains flyable. The qualification sensor has been tested, and found to be fully operational after 10 years of storage. Cannibalization of Teal Ruby is expected to begin at any time.

As a demonstration program, Teal Ruby has yet to prove itself. After a period of delay, substantial cost over-runs and management problems, a satellite and mission operations center was built, qualified, and calibrated, experiments were designed, and a large amount of testing and analysis was performed to plan and carry out the mission. Teal Ruby was designed as a Space Shuttle payload, and was scheduled and ready to go when the Challenger exploded 5 months before scheduled Teal Ruby launch. The subsequent long wait, budgetary squabbles among DARPA, Air Force HQ, and Congress, and a limited interest in IR AVD within the Air Force due to the push for space based radar systems, prevented Teal Ruby from flying.

The Teal Ruby program represents different things to different people. To critics of infrared air vehicle detection (AVD) the program represents a massive failure that resulted from the hubris within the IR community. To some Teal Ruby is a case history that illustrates why DARPA should not get involved in "big" programs. While there are understandable reasons for holding such views, Teal Ruby has had considerable impact as a technology base program. It demonstrated clearly the feasibility of a number of technologies necessary to the use of infrared for both air vehicle detection and surveillance, and furthermore nurtured a community and a technology that has gone on to support the tactical use of IR, the Strategic Defense Initiative, the Air Defense Initiative, and a variety of other programs.

C. OBSERVATIONS ON SUCCESS

The Teal Ruby program, in spite of the fact that it never flew, can claim a number of technical achievements:

1. IR focal plane array technology. The production number, size, testing procedure, and achieved cost reduction of the arrays remains a singular success.
2. Lightweight optics.
3. Long-life cryocooling for large LFA's.
4. Development of detection algorithms for IR surveillance and their implementation in on-board signal processing.
5. A quantum leap in the understanding of IR target and background signatures.
6. Planning of a ground segment that allowed unprecedented control of the sensor, real-time demonstration of AVD, and reduction of data for later analysis.

Perhaps the greatest achievement of Teal Ruby was in the nurturing of a community and a technology that later has gone on to play a vital role in the Strategic Defense Initiative, the tactical electro-optic community, civilian efforts such as LANDSAT, and a variety of other programs. The absence of Teal Ruby data has proven to be a major handicap to programs in all these a [illegible] with current proposals for satellite-based IR target and background measurement programs a common thread throughout the national security arena.

Teal Ruby was a high risk, high investment development program, but was not managed as such from the beginning. The DARPA-sponsored Aerospace review presented by Edwin Schneider listed the following more basic lessons learned:[15]

(a) Be very selective in initiating high risk, high investment, demonstration programs. Because of the cost liability, the number of these programs should be minimized.

(b) Develop an internal program plan that outlines the program objectives and matches realistic technical goals to the schedule.

(c) Obtain competitive proposals.

(d) Conduct an independent cost analysis.

(e) Develop a formal program plan with the agent that identifies the major tasks, risk areas, program review cycles, organizational responsibilities and interfaces, critical milestones, and the funding baseline prior to program initiation.

(f) Obtain an independent analysis of the plan.

(g) If the program requires non-DARPA resources to be successfully completed, obtain a written commitment for these resources prior to initiation.

(h) Obtain the personal commitment of the agent's commander to fully support and monitor the program.

(i) Ensure that the agent "mainstreams" the program (i.e., subjects it to the same review procedures as the agent's programs).

(j) Incentivize the contract such that end item performance is of equal importance as the cost and schedule goals.

(k) The contract should include Mil-Std requirements and specifications for hardware and software developments; provisions for spares; redundant test equipment; separation of funding clauses if more than one source of funds is used; formal cost reporting; strong quality assurance/control requirements; and at least three end items: a development model, qualification model, and final model.

(l) The problem should be structured so that cost and schedule contingencies are included for both the agent and DARPA; formal program review/evaluation

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[15] Op. cit., p. 84.

points are identified; go/no go criteria or re-evaluation criteria are designated for each evaluation point; and inflation is accounted for in the budget.

The presentation then listed some additional, perhaps less obvious "lessons for DARPA."[16]

(a) Stay involved and as close to the program as possible. Use monthly letter exchanges with the agent and biweekly visits.

(b) Get in the program's major decision loop. Utilize in-plant or in-program office representation.

(c) Use outside experts to augment the contractor's or agent's efforts in high risk areas. Ensure that the prior or related experience is transferred.

(d) Ensure the contractor's top management is involved in the program.

(e) Work all program issues/problems through the agent, not directly with the contractor.

These observations came from the perspective of the Aerospace Corporation review, and the DARPA Liaison Officer then responsible for the Technology Program. Some of these may be viewed as "overkill," or not applicable to other programs, or even, just hindsight not appreciative of the imperatives of the program. However, they do show the important issues of program management and program and program definition that were raised by Teal Ruby.

Teal Ruby was initiated by Director George Heilmeier, who was a strong advocate of a large-scale demonstration program for a space-based large focal phase array sensing system. There were others who favored a more incremental approach.[17] Heilmeier recounts that he purposely was "pushing technology into demonstration as application, when others were reluctant; I saw this as the true mission of DARPA."[18]

In this regard Heilmeier was in accord with the DDR&E, Dr. Currie, who states that his primary motivation for appointing Heilmeier as Director was to "revitalize" the agency by "hitting hard on basic research projects and big projects that could make a difference."[19]

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[16] Ibid.

[17] Discussion with R. Zirkind, 11/88.

[18] Ibid.

[19] Ibid.

Currie explicitly contracted this perspective from his view that "DARPA was spread too thinly doing things it shouldn't have been doing." Instead, he felt DARPA needed to "pursue a more active program that took some risks."[20] In retrospect, Heilmeier says that Teal Ruby should have been cancelled, but cites management problems, particularly with the main contractor, as the main reason.[21]

Teal Ruby and the associated infrared sensing and surveillance technology work clearly moved the state-of-the-art much more rapidly than would have been the case without such a program.

Teal Ruby was started with a $24M contract (with an initial letter contract for $21M), with a delivery date for the sensor system of 21 months and an additional 13 months for it to be integrated in the P80 spacecraft and tested before launch--a total of 33 months (Rockwell had a separate contract with the Air Force for P80-1 spacecraft).[22] By mid 1982 the accumulated over-run was $100M (with schedule slippage of 40 months). In "rebaselining" the program in 1982, additional cost for the Teal Ruby sensor was set at $230M with an additional $220M, required from the Air Force for the P80-1 spacecraft, the land support, and mission planning and data analysis.[23] A program initially scooped at $24 million, over 33 months, grew into one that cost over $575 million and spanned nearly fifteen years and still did not result in a launch.

The legacy of the Teal Ruby therefore is dichotomous: (1) it is a prime example of a large, high-risk demonstration program, that did not yield the end-result intended (a space-based infrared sensing/surveillance system) and cost an enormous amount of resources; and (2) a progenitor of fundamental advances in infrared sensing technology and measurements with the resulting of understanding infrared phenomena that have contributed directly to subsequent surveillance and sensing systems. The lessons-learned, as listed in Schneider's retrospective, clearly show that programs of such scope and risk must be entered into, and continually managed, with much greater attention to their scope and uncertainty. Teal Ruby, in conjunction with the other technology thrusts initiated in DARPA at the time, clearly overloaded DARPA's existing management capabilities and experience. It took several years and intensive effort to bring the program under control.

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[20] Ibid.

[21] Ibid.

[22] Schneider, op. cit., p. 71.

[23] Ibid., p. 83.

The program presents important lesson regarding the strategy of moving forward multiple key technologies demonstration approach. Perhaps the greatest lesson is to clearly understand and consider the risks up-front and to approximately scope the effort in advance. Teal Ruby as a major technology/demonstration program was managed initially as if it were an incremental, business-as-usual activity. This had damaging, nearly catastrophic, effects on the program.

AVIATION TECHNOLOGY

X. STEALTH

A. BRIEF OVERVIEW

DARPA from time to time undertook programs to reduce the observability of missiles, aircraft, and sensors. These included approaches to reducing the observability of re-entry vehicles (RVs) to complicate ABM defense; the QT-2 quiet observation aircraft program for night observation of Viet Cong activity in Vietnam;[1] an approach to a quiet helicopter; observability reduction parts of the RPV program that DARPA pursued from the early 1970s on; and incorporation of Low Probability of Intercept (LPI) characteristics in the PAVE MOVER radar for ASSAULT BREAKER.

In 1975, as the result of an interaction between DARPA and the staff of the DDR&E, DARPA focused more explicitly on concepts for low observability in aircraft.[2] After a period of discussions among the DARPA Director, his staff, the DDR&E, the USAF Deputy Chief of Staff for R&D, and the USAF Chief of Staff, it was agreed that a program to demonstrate the technology would be undertaken jointly by DARPA and the USAF. At this point the clear operational implications of the technology led to designation of special access requirements for DARPA and Service efforts in the low observables area. A number of Service programs subsequently emerged. The decision by the Services to undertake such programs was aided by DARPA's demonstration of technical feasibility. DARPA continued to cooperate with the Services in furtherance of the technology development.

B. EARLY HISTORY

The need to avoid detection of aircraft on missions over enemy territory dates from the time aircraft were first used in such missions, and the problem became especially severe when the Soviets proliferated and continually improved their air defense systems in the post-1950 period.

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[1] The QT-2 program is described in detail in Chapter XVI of Vol. 1 of this history.

[2] See Chapter V. of this Volume for a detailed description of ASSAULT BREAKER.

When visual and acoustic detection were the only means available, night flying could help reduce targeting by air defenses significantly. The "soda straw" of the searchlight and the coarse direction finding of the acoustic array, together with the inherent difficulty of hitting an aircraft with the unguided antiaircraft shells of World War I and World War II, were not adequate to the task. Interceptor pilots could rely on ambient light and visible exhaust trails for night engagements, but in general attrition of night attackers was significantly lower than that of daytime flyers. This, together with the bombing accuracy issue, figured in the World War II arguments between the RAF and the U.S. Army Air Corps about whether to do night bombing with essentially defenseless aircraft or daytime bombing with heavily armed aircraft that could exact attrition from the enemy. The invention of radar for aircraft detection and tracking and artillery direction changed the nature of the arguments, and led to a need for aircraft to have reduced observables in this additional dimension. The problem was made still more complex as electro-optical detection and guidance systems in the infrared bands were added to the inventory in the post-World War II era.

World War II saw the beginning of stealthy use of aircraft for surveillance and reconnaissance. The British Mosquito bomber proved to be especially capable of penetrating the defenses of the time period in Europe at low altitude.[3] As the war was ending, the United States fielded the long-range P-61 "Black Widow," designed and built by Northrop to cover long ranges at night against the Japanese.[4] This aircraft was followed (in 1954) by the U-2 and subsequently the SR-71 (early 1960s). Both were designed for intrusion into enemy airspace for surveillance and reconnaissance using parts of the flight envelope--high altitude, for both, and high speed for the SR-71--that were difficult or impossible for the defenses of the day to reach. The SR-71 was the first modern aircraft to incorporate low radar cross-section (RCS) technology integrated with the design for performance, from the start. Hostile defenses eventually caught up with the U-2, but the Mach-3 SR-71 successfully avoided them throughout its operational life.[5]

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[3] Jane's *All the World's Aircraft*, 1943-1950 issues

[4] Knaack, M. S., *Encyclopedia of US Air Force Aircraft and Missile Systems*, Vol. 1, Post-World War II Fighters, 1945-73 Washington, D.C. Office of Air Force History, 1978.

[5] Sweetman, B., *Stealth Aircraft*, Osceola, Wis., Motorbooks International, 1986.

C. DARPA EFFORTS

DARPA (or ARPA, as it was known until 1972) showed periodic interest in reducing aircraft observables almost from the time the agency was organized. In ARPA's earliest days, in 1959, when the Institute for Defense Analyses (IDA) provided the ARPA technical staff, there was a proposal from the University of Michigan to investigate the possibility of designing aircraft and space vehicles from the beginning with electromagnetic scattering properties as well as aerodynamic qualities in mind.[6] This proposal, by Keeve M. Siegel, a consultant to ARPA and IDA, involved the combination of shaping with radar absorbing materials (RAM). Apparently this proposal received an unfavorable review in ARPA, according to the brief IDA records. There are no details of the proposal, but the negative review seemed based on the fact that there was related technology work at the time at several companies. Eventually, work on the idea in the specific proposal was supported by the Air Force laboratories at Wright Field.[7]

According to the historical records, mainly the ARPA orders, there were then three or four sporadic ARPA efforts in the low-observables area.

Very early-on there were efforts toward low-observable re-entry bodies (RVs). The possibilities in this direction had been "sounded" before ARPA's existence, by the DoD's "Re-entry Body Identification Group."[8] These involved shaping, radar-absorbing materials, and impedance loading body schemes.[9] The goals were to make RVs look like smaller decoys, and to reduce "glint" used by homing vehicles.[10] The U.S. was not alone in this--there was a good deal of interest in the shape and performance of the UK's RV to go on the "Blue Knight" missile that was tested at the Australian range at Woomera.[11] ARPA actively participated in the radar measurements made there through 1965.

The problem of RV observability is complicated by the plasma effects at hypersonic speeds in the atmosphere. Some work was done to reduce the plasma electron content below "critical" for various radar frequencies. Some of this work continued after the

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[6] IDA's TE-33, 6/59, IDA archives (CLASSIFIED).

[7] Discussion with R. Legault of IDA, 11/24/89.

[8] Herbert F York, "Military Technology and National Security," *Scientific American*, V. 221, p. 12, Aug. 17, 1969.

[9] AO 39 Task 14 of 5/59. "Threat Parameters and Observables," AO #197 of 1/61, Task 7, "Penaids Survey," AO 254 of 8/61, Task 3 on LORV's, AO 558 of 4/64. "RV Thin Film Radar Absorbing Materials," AO 803 of 11/65, "Impendance Loading."

[10] AO 873, Task 6 of 10/60, "Glint Measurement and Suppression Techniques."

[11] AO 114 of 11/59, and IDA TE 197 of 1/59 (CLASSIFIED), and AO 709 of 3/65, SPARTA.

transfer of DEFENDER to the Army in 1967.[12] Also, under Project WIZARD the Air Force was measuring components of RV cross-section with the idea of transferring the appropriate parts of the results to air defense system design. The critical question was whether the resulting vehicles, with shape optimized for radar cross-section (RCS) reduction, would fly with reasonable performance for the mission. The necessary technologies were not yet available, and the project did not progress.[13]

The next ARPA low-observables effort of record began in project AGILE. For example, the proposal made by Lockheed for the QT-2 "quiet airplane" originally included work to reduce its radar cross-section by using radar absorbing materials. Perhaps because the QT-2 was to fly low in an environment where the enemy was not expected to have radar, and it achieved its major objective of being acoustically quiet, radar absorbing materials were apparently not applied. When, a little later, ARPA supported investigations of a "quiet helicopter," a somewhat similar pattern was favored--but in this case the radar scattering reduction seems to have been looked into more seriously.[14]

After Vietnam, ARPA began development of mini-RPVs. The second phase of the RPV design was dedicated to increasing these vehicles' survivability mainly by reducing observables. There were several tests of these RPVs' observability.[15] Also, in the late 1970s DARPA incorporated Low Probability of Intercept characteristics in the PAVE MOVER surveillance, target acquisition, and weapon guidance radar of the ASSAULT BREAKER program. This approach was presented by the USAF as "Airborne Low-Visibility Moving Target Acquisition Systems" after the PAVE MOVER technology was transferred to the Air Force when DARPA completed its ASSAULT BREAKER efforts.[16]

The genesis of the DARPA effort in low observables that led to current stealth programs was in the sequel to a 1974 request by Dr. Malcolm Currie, the DDR&E during the 1972-1976 period, to Dr. Stephen Lukasik, then ARPA Director, to consider new program ideas. The idea of building low-observable systems was discussed with Robert Moore, then Deputy Director of DARPA's Tactical Technology Office (TTO), by Charles

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[12] AO 1009 Task 2 of 6/67 "Electron Properties," and AO 1080, "Antenna Radar Cross Section," of 8/67.

[13] R. Legault, op. cit.

[14] AO 1321-2 and 3, Quiet Helicopter, 8/68 and discussion with R. Zirkind, 3/88.

[15] See Chapter XXVIII, in Volume I for history of RPVs. AO #2528 of 10/73, and Hearing before House Committee on Armed Services, 94th Congress, 1st Session, March-April 1975, p. 3973.

[16] Department of Defense Annual Report, Fiscal Year 1979, Harold Brown, Secretary of Defense, p. 264.

Meyers, then Director of Air Warfare Programs in ODDR&E, who raised the notion of "Harvey," an invisible aircraft (named after the invisible, quasi-human 6-foot tall rabbit "companion" of the lead character in a popular play of the time).[17] Subsequently, when George Heilmeier became Director of DARPA in 1975, Meyers also discussed with him the idea of designing an aircraft that would be invisible to the most common means of detection; the purpose would be to achieve surprise in air warfare.[18] Moore applied the term "stealth" to the aircraft that was one of the ideas discussed over the period, and the term remained associated with the entire area of low-observables technology.

Moore and Currie agreed that DARPA would undertake a program to explore what some technical approaches could achieve. When Heilmeier assumed responsibility for the total DARPA program on becoming Director, he felt it would be desirable for DARPA and the USAF to share the funding for the demonstration phase of the program. This was agreed after extensive discussion and negotiation involving the Deputy Chief of Staff for R&D and the Chief of Staff of the USAF. There was a competition among several contractors, and one was chosen to proceed, but ideas developed by others as well persisted in later programs.

In his extensive testimony before the House Defense Appropriations Committee for FY 1976 and 76T, Dr. George Heilmeier, then DARPA director, referring to still another program, stated:[19]

> Improving the ability of strategic aircraft and their offensive weapon systems to reach assigned targets has a direct payoff in the cost/effectiveness of the strategic bomber force. Emphasis is being placed on reducing the detectability of aircraft. As a first step the feasibility of a low radar cross-section strategic penetrator was investigated based on a conceptual flying-wing design. The ability to penetrate can be improved by extreme shaping of the flying wing design, application of thrust vector control/reaction control technology; modified engine inlet designs, and techniques for wing leading edge RCS suppression. Investigations including the analysis of range test data are underway in the evaluation of these approaches.

It became clear around this time that the stealth concepts would be promising, and that they should be closely held for operational reasons. The decision was therefore made to put the programs in the special access category. From this point on the Service

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[17] Interview with Robert Moore, January 10, 1990.

[18] Interview with George Heilmeier, March 28, 1990.

[19] Dr. George Heilmeier, testimony before the House Defense Appropriations Committee for FY 1976 and 75T (p. 4968).

programs, all of which have special access requirements, predominate. The DARPA-initiated demonstration of feasibility figured importantly in the decisions to proceed with the Service programs.[20] DARPA continued to cooperate with the Services, to assist in implementing the technology. About 10-12 individuals were involved in the early effort, and its success was due to their efforts.[21] In response to the rising problem that as RCS is reduced, the infrared signature becomes more important for detection, in 1984 DARPA and the USAF initiated a basic technology program at IDA to deal with that issue.

In 1988 the Director of DARPA, Dr. Raymond Colladay, prepared a briefing for the Presidential Transition Team with an illustration (Figure 8-1) bearing the legend that "Early work on low observables was started in DARPA in the early 1970s and once the initial feasibility was established, the programs transitioned to join efforts with the Air Force and other Services."

D. OBSERVATIONS ON SUCCESS

Not much can be said about the process in this area without violating the bounds of security. This seems to have been an area where

- There was early work, by ARPA and others, in the direction of trying to learn about and solve an important and difficult technical problem;
- ARPA, and then DARPA, maintained a sporadic but productive interest in the problem, expressed that interest through periodic projects that incorporated some of what was known about the technology at the time, and was responsive to suggestions to advance the technology when the technical situation had reached the point where further advances appeared possible;
- DARPA took the lead, in coordination with the DDR&E, to advance the technology and demonstrate new concepts through an experimental program;
- DARPA expended the managerial as well as the technical effort to insure that at least one Service would make use of the experimental results if they were successful.

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[20] Interview with John S. Foster, Jr., February 6, 1990.

[21] Heilmeier (op. cit.) specifically mentioned Moore (who had become Director of TTO during the period of program development); Bruce James, Moore's Deputy; and Kenneth Perko as individuals who made special efforts with him toward insuring the success of the DARPA program.

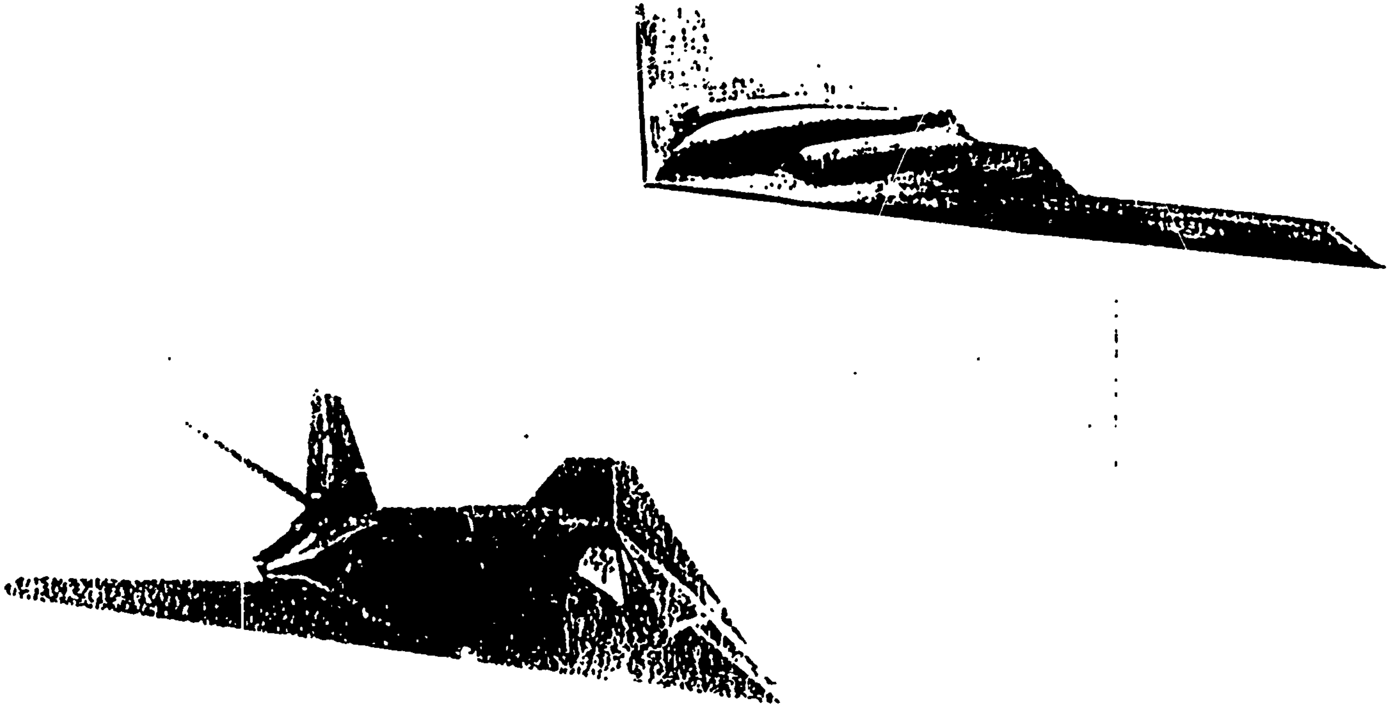

Figure 10-1. STEALTH

XI. X-29

A. BRIEF OVERVIEW

The X-29 program was undertaken to explore the advantages of forward swept wing and to overcome problems of structural divergence. Program directors[1] hoped that the X-29 and other "technology demonstrators" would perform some of the functions of an advanced fighter prototype.[2] Although this did not happen, the X-29 proved successful in demonstrating the ability of a forward swept wing aircraft to operate at high angles of attack; it also demonstrated the viability of advanced technologies such as a unique fly-by-wire flight control system, aeroelastic tailoring on a thin, forward swept, supercritical wing, and the use of close-coupled canards or foreplanes for pitch control. Technology breakthroughs, particularly flight control systems and composite materials, made possible the manufacture of a supersonic fighter class aircraft with a forward swept wing.

B. TECHNICAL HISTORY

1. Origins of Program, 1945-1976

The "X" series aircraft, from the Bell X-1 to the National Aerospace Plane (NASP), have been part of an intermittent experimental design and testing program begun in the 1940s. X-plane programs have pushed existing speed envelopes, endurance limits, tested innovative design concepts, performed maneuverability and high altitude tests, examined various new modes of propulsion, and served as prototypes for missiles such as Atlas and Navajo. Almost all X-planes were designed with a specific mission objective.

Unlike other X-planes, the X-29 was designed to be an integration testbed, not a demonstrator of a single technology or improved performance in a single regime. Application of the forward swept wing concept has a history dating back to 1944 when

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[1] IDA appreciates the assistance of Tom Taglarine and Glen Spacht of Grumman, Norris Krone and Bob Moore, formerly of DARPA, and Gary Trippensee of NASA Dryden Flight Research Center in helping to piece together the history of the X-29.

[2] "Forward Swept Wing Technology Integration for the ATF," *International Defense Review*, February, 1984, p. 209.

Junkers designed, built, and successfully flew the Ju-287 prototype.[3] The end of the war brought development of the Ju-287 to a close, but only after it had flown 17 times and attained an airspeed of 400 mph, not quite fast enough to suffer problems with wing divergence.[4] Since the 1940s, several other designs have experimented with forward swept wings as well. These aircraft did encounter problems with wing divergence, hence these experiments were unable to explore performance envelopes of modern fighter aircraft.

In the 1970s, two scenarios were unfolding simultaneously and would eventually merge in the production of the X-29. Air Force Lt. Col. Norris Krone, a structural engineer with the Air Force, became a strong proponent of the viability of forward swept wing design to application in modern aircraft. Krone's dissertation at the University of Maryland centered on forward swept wing design and the ability of advanced composite forward swept wings to overcome wing divergence.[5] Mr. Irv Mirman, scientific advisor to Air Force Systems Commander, attempted to interest Air Force aircraft design personnel to consider the forward swept wing concept proposed by Krone. This idea was rejected because of the high risk associated with the concept. At least one major aircraft manufacturer also rejected the concept because of the risks involved. As a result, Mirman and Krone contacted DARPA and Robert Moore to investigate the possibility of Krone working for DARPA.[6] Krone left Air Force Systems Command for DARPA's Tactical Technology Office,[7] specifically to work on air vehicle technology and the forward swept wing concept. DARPA was the only organization contacted by either Krone or Mirman that agreed to accept the risks of developing the forward swept wing aircraft.

In 1975, Grumman Aerospace embarked on an in-house wind tunnel program to determine why serious wing root drag problems caused the company to lose competition

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[3] Several papers had been written about the use of a forward swept wing, including those by Adolph Buseman (1935) and Bob Jones of NACA (1944).

[4] An aft swept wing bends under a load and twists leading edge down. This reduces angle of attack capability and wing load. A forward swept wing twists leading edge up, increasing angle of attack and load. Depending on various factors, including degree of forward sweep, above a critical speed (usually as the aircraft approaches .9 mach) the wing will fail, twisting off of the aircraft. Until strong composites were available, this phenomenon curtailed the use of forward swept wings. To offset twisting, or divergence, the wing had to be made stronger, and weight penalties incurred offset any performance gains made by the sweep of the wing.

[5] *Divergence Elimination with Advanced Composites*, Norris J. Krone, Jr., Ph.D. Thesis, University of Maryland, December 1974.

[6] An interesting sidelight to the story revealed by interviews with Krone and Moore is that Krone essentially called DARPA "out of the blue" to see if there was interest in his ideas.

[7] The Tactical Technology Office was headed by Dr. Robert Moore at the time; the Director of DARPA was Dr. Robert Fossum.

with Rockwell to build the HIMAT (highly maneuverable advanced technology) remotely piloted vehicle. Krone, because of his past involvement in forward swept wing design, took particular interest in Grumman's internal wind tunnel program, becoming familiar with Grumman's facilities and acquainted with lead engineer Glen Spacht. Eventually, Krone suggested that Spacht and Grumman try a forward swept wing design on the HIMAT in order to solve some of the problems associated with the original design, including wing root drag. Even though the HIMAT contract had been awarded to Rockwell, Spacht and Grumman were committed to solving the problem, and Krone's suggestions, combined with Grumman's innovation, helped solve some of the HIMAT design problems.

2. The Program, 1976-1984

The program that became known as X-29 officially began in 1976, when Krone was authorized to begin looking at the feasibility of forward swept wing technology. Combined outlays in FY76 and FY77 totaled $300,000, and were used to grant study contracts to Grumman, Rockwell, and General Dynamics.[8] The purpose of the study contracts was to verify the technical aspects of a forward swept wing design. All three companies verified the aerodynamic performance of the forward swept wing concept, and demonstrated that a wing could be fashioned with advanced materials and be used on an aircraft. In addition to fulfilling the obligations of the contracts, all three companies and NASA donated wind-tunnel time to the project.

By 1979 DARPA-funded research had made clear that use of lightweight composite materials could overcome the divergence problems associated with previous forward swept wing designs. In so doing, DARPA learned that certain maneuverability and angle of attack performance advantages could be gained by using a forward swept wing on a fighter-class aircraft. DARPA and the Air Force Flight Dynamics Laboratory decided to apply the forward swept wing concept to an experimental aircraft program. Norris Krone became the program manager for a project that was to explore the application of forward swept wing design to a fighter type aircraft.

DARPA, with the Air Force Flight Dynamics Laboratory acting as the agent, received proposals from Rockwell, General Dynamics, and Grumman in 1979. Krone and others in the DARPA Tactical Technology Office set the program requirements. The

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[8] DARPA issued AO 3436, to analyze the forward swept wing concept in 5/77. This AO also covered several other later tasks, totalling $8.85 million.

Grumman and Rockwell designs exploited more or less equivalent technology, but the Grumman design more strongly emphasized cost savings. The design that became the X-29, conceived in 1978 as Grumman Design 712, developed and demonstrated the associated technologies employing extensive use of off-the-shelf components and systems.[9] Rockwell, in contrast, had designed a new aircraft that was in some ways technologically superior, but more costly than the Grumman design. General Dynamics had essentially taken the F-16 design and applied a forward swept wing concept to it. Grumman's design represented a compromise between use of new technology/design and cost considerations.

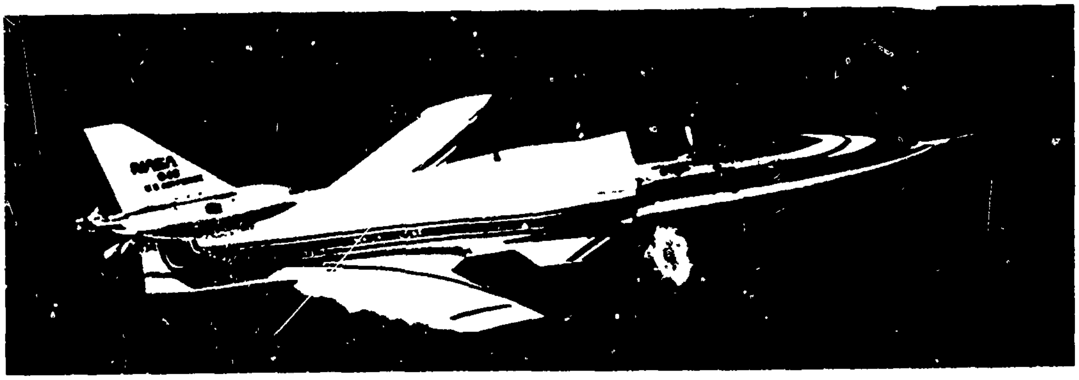

Figure 11-1. Grumman X-29, In the Flight Test Program, NASA Dryden Flight Research Center, Edwards Air Force Base, Cal.

The X-29 designation, the first X-plane in over a decade, was granted in September 1981. Two X-29's were developed and produced by Grumman at a cost of about $87 million.[10] Costs were controlled in part because Grumman was able to use many off-the-shelf components in constructing the X-29. The X-29 research program was funded by DARPA and administered by the USAF Wright Aeronautical Laboratories Advanced

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[9] For example, the Grumman design incorporated the nose assembly and ejection seat from the F-5, F-16 landing gear and hydraulic actuators, F-14 flight sensors, and other off the shelf equipment. See "Unusual Aerodynamics of X-29," *Aerospace America*, February, 1986, p. 34.

[10] "First Phase of X-29 Test Show Forward Swept Wing," *Defense Daily*, 20 January, 1989. Actual costs were slightly higher, as Grumman contributed about $50 million of its own money to the project. DARPA AO 4188 of 1/81 covering construction and tests, was for $118 million.

Development Program Office (ADPO). In the X-29 testing, the ADPO acted as the agent for DARPA, and initiated the contract with Grumman.

3. Flight Test Program, 1984-Present

The first phase of the flight test program proved the viability of design of a forward swept wing aircraft by flying and verifying the results of the simulation program. The first phase involved only the first X-29 aircraft. The second phase evaluated the ability of the forward swept wing design and technology to operate at higher angles of attack. Both aircraft were used during this phase, but the second aircraft was extensively modified (at a cost of about $4.65 million)[11] to look at high angle of attack (AOA) characteristics of forward swept wing aircraft.

First flight of the first aircraft was December 14, 1984. The first flight of the initial X-29 lasted 66 minutes. The second and third flights were undertaken in February 1985. These ended successfully, but not without controversy, as Grumman test pilot Chuck Sewell performed "unscheduled maneuvers" during the third flight. Sewell was replaced as pilot until the eighth mission.[12] The final technical report for the period January 1983 to December 1986 indicates that the first three flights were completed with no pilot discrepancies (from the predicted performance in the simulator) reported. The fourth flight revealed that on takeoff, 15-knot additional rotation speed would result in a more comfortable rotation. On both the high-speed taxi and during flight, forward stick was required to stop the rotation. This characteristic was not exhibited in simulation.[13] The end of the fourth flight effectively completed Grumman's initial obligations under the contract to USAF and DARPA. On March 12, 1985, after the first four flights, the program was turned over to the Air Force to continue flight tests. The X-29 program (both aircraft) completed more than 279 flights (as of April 27, 1990), the most ever for an X-series aircraft.[14]

The primary research objective of initial X-29 flight testing was to determine the flying qualities of the aircraft and compare the flight test results to predictions, design criteria, and existing military specifications. A secondary research objective was to

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[11] *The X-Planes*, Jay Miller, New York: Orion Books, 1988, p. 189.

[12] Ibid., pp. 186-193.

[13] *X-29 Aircraft, Flight Worthiness*, Grumman Aerospace, Bethpage, NY, March 1987, p. A-15.

[14] "X-29 Proves Viability of Forward Swept Wing," *Aviation Week and Space Technology*, 31 October 1988, p. 38, Vol. 129.

establish a flight test set of aerodynamic stability and control derivatives for the aircraft and compare these derivatives with wind tunnel predictions.[15] The X-29 flight test program reached both objectives.

In December, 1986, USAF, DARPA and NASA jointly funded a $30.2 million follow-on flight research program covering high angle of attack studies (up to 90°) using both X-29 aircraft. Also during the same month (13 December) the X-29 became the first forward swept wing aircraft to fly supersonically (Mach 1.03).[16] There was some hesitation on the behalf of NASA and the Air Force in the initial funding. Once this flight test follow-on program began, both NASA and the Air Force were eager to explore the potential of the aircraft. Although the Air Force originally had no interest in a forward swept wing fighter, as the test program evolved, it was interested in examining potential applications of the technologies on the X-29 to conventional fighters. NASA, on the other hand, has been trying to understand exactly why the aircraft has demonstrated specific capabilities. NASA has been responsible for the day-to-day events in the flight test program; as a result, it has been less willing to conduct risky flight tests suggested by the Air Force. NASA has proposed some interesting research directions for the future, which are discussed in Section C, Observations on Success.

The second aircraft entered flight testing in May of 1989.[17] The first aircraft verified performance characteristics up to the 20-22° AOA range. For the second aircraft, wind tunnel tests have demonstrated an ability to approach an angle of attack of somewhere between 70 and 80°. In actual flight tests, the second aircraft has flown at angles of attack up to 57° at mach 1. The second X-29 has demonstrated a high instantaneous rate of turn and roll control at high angles of attack, and is highly maneuverable through 42° angle of attack. The unique design of the aircraft, with three surface control configurations -- canards, wing control surfaces, and strake flaps -- provides the aircraft with significant longitudinal control at high angles of attack. Wind tunnel tests indicate that the aircraft's design limit is about 70° angle of attack, compared to 50-55° for the F/A-18,[18] the aircraft in the U.S. inventory with the highest design limit.[19]

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[15] "Flying Qualities Evaluation of the X-29 A Research Aircraft," Stuart L. Butts and Alan D. Hoover, Air Force Flight Test Center, Edwards Air Force Base, California, May 1989.

[16] *The X-Planes*, Jay Miller, New York: Orion Books, 1988, pp. 186-193.

[17] "First Phase of X-29 Test Show Forward Swept Wing," *Defense Daily*, 20 January 1989.

[18] In reality, the F/A-18 has not flown at an angle of attack greater than about 22°.

[19] "Second X-29 Will Execute High Angle of Attack Flights", *Aviation Week and Space Technology*, 31 October 1988, p. 36. Angle of attack is the relationship between an aircraft's longitudinal axis and its

The high angle of attack envelope is the flight regime that the Air Force would like to exploit with the ongoing flight test program. If this ability were improved, a new generation fighter would be able to out-turn its opponent without risking a stall and loss of control. This ability would improve the short take off and landing capabilities of an aircraft as well.[20]

Additionally, the angle of attack capabilities of the X-29 could be advantageous in later designs. Performance data for the X-29, F-16A, and F-15C aircraft were analyzed by Universal Energy Systems, Inc., Dayton, Ohio, under contract with USAF Wright Aeronautical Laboratories. The objective of the combat analyses was to obtain an assessment of the maneuverability of the X-29 versus the F-15 and F-16 in a one-on-one combat situation. The point mass digital simulation does accurately represent lift, drag, and thrust characteristics of the aircraft. During the analysis, approximately 70 percent of the firing opportunities for the X-29 occurred at angles of attack greater than 30°. This indicates an advantage for an aircraft with high angle of attack capabilities in a one-on-one situation.[21]

In most tests, the actual performance of the X-29 came close to the predictions that were generated before the testing program began. A meeting of aerodynamic specialists was held in December 1988, after four years of flight testing, to review initial aerodynamic design predictions and compare them with flight experience. The data indicate that the X-29's advanced technologies result in improved performance, especially in transonic maneuvering.[22] Drag and lift coefficients were for the most part, accurately predicted. There were some unexpected drag polar results at .4-.6 Mach which require further analysis to explain. The unique technology areas (discussed above) fared well in tests. The variable camber configuration provided significant drag reduction and the canards

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flight path, assuming that the wing is mounted so that the line from its leading edge to its trailing edge is parallel to that axis. At zero angle of attack, air flows parallel to the longitudinal axis. Angle of attack is related to lift, and therefore to maneuverability. At constant airspeed, a wing produces more lift as the angle of attack increases, and conversely, increasing angle of attack will maintain constant lift as airspeed decreases. But angle of attack cannot be increased beyond a certain point, or the airflow over the wing separates, and the wing will no longer produce necessary lift, creating a stall. High angle of attack is not usually attainable at high airspeed, because the aircraft will reach its maximum g-load before reaching the stalling point (greatest possible angle of attack). Low airspeed combined with a high angle of attack allows the wing to produce greater lift, allowing for greater maneuverability

[20] "X-29 to Explore New Flight Regime," *Defense Electronics*, September 1987 p. 52.

[21] "Fighter Class Aircraft Performance Comparisons," Universal Energy Systems, Inc., Dayton, Ohio, November 1988, p. 7.

[22] "X-29 Aerodynamics Specialists Meeting Report," Stephen M. Pitrof, Wright Research and Development Center, Wright Patterson Air Force Base, Ohio, April 1989.

increased lift and control. "Data showed that these advanced technologies, as configured for the X-29A aircraft, could provide significant decrease in drag coefficient when compared to a current tactical fighter. Consideration of these advanced technologies could be useful in the development of future USAF aircraft."[23]

4. Technical Accomplishments

The testing program was set up to evaluate several individual technology areas, and evaluate how these technologies interact. The initial flight test program was undertaken to evaluate both the benefits of the forward swept wing design and technology advances in aerodynamics, structures and flight controls. Other forward swept wing aircraft have been flown, but never in an extensive testing program with modern technology. Integration of the technology areas that occurred in the X-29 program resulted in significant technical accomplishments.

a. Technical Integration

The X-29 combines unique technology into a viable design, and has demonstrated performance limits for an aircraft design regime that was not accessible for experimentation earlier. The X-29 flight test program has demonstrated:

- Forward swept wing will produce approximately 20 percent better performance in the transonic (Mach 0.9) regime than will an equivalent aft-swept wing.
- Wing divergence studies have confirmed the X-29 configuration will tolerate dynamic pressures up to 1300 lb/ft^2 and still remain below the design divergence boundary, validating aeroelastic tailoring concepts used in the wing's composite structure
- It has flown up to 57° angle of attack at mach 1, reached a top speed of mach 1.5, performed well at altitudes above 50,000 ft, and achieved 6.4g in wind-up turns (80 percent of design load).
- Flight control system (FCS) software, although not designed to be a main part of the developmental program, has been an area of intense research. There have been on average 4-5 new releases of FCS software each year of the development. The changes have ranged from minor changes in built-in test features to major changes which have improved the aircraft's handling, such as halving longitudinal stick travel and improving pitch forces. As a result, the

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[23] "Performance Evaluation of the X-29 Research Aircraft," X-29A Program Office, Wright Aeronautical Laboratories, Dayton, Ohio. March, 1988, p. 33.

aircraft now handles more "like a fighter," allowing pilots to more readily complete testing procedures.[24]

b. Forward Swept Wing/Wing Construction

The forward swept wing used by Grumman has demonstrated reduced drag (about 20 percent) compared to advanced conventional wings.[25] Though inherently unstable due to wing design, the forward sweep of the wing significantly shifts the stall regime of the wing. The thin, supercritical wing is constructed of non-metallic, graphite epoxy composites.[26] The X-29's wing structure is an aluminum and titanium framework, over which is laid a one-piece graphite-epoxy composite wing cover that is lightweight, yet considerably stronger and more rigid (per unit weight) than steel.[27] The X-29 is one of the few aircraft ever to fly with an all-composite wing.

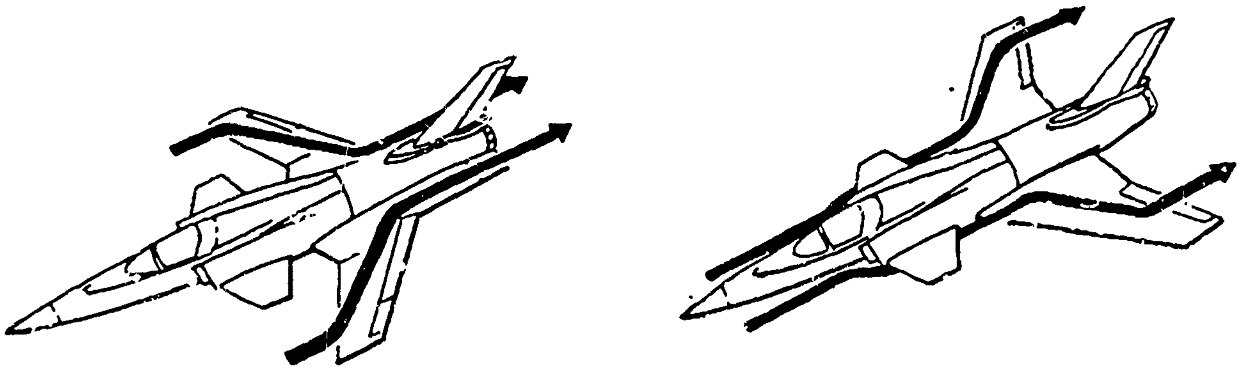

Figure 11-2. Forward Swept Wing Design. Air moving over the forward swept wing tends to flow inward rather than outward, allowing the wing tips to remain unstalled at high angles of attack.

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[24] "Second X-29 Will Execute High Angle of Attack Flights," *Aviation Week and Space Technology*, 31 October 1988, p. 36.

[25] *Interavia*, November 1983, p. 1197. Transonic and supersonic drag are related to the wing's "shock sweep," or the sweep of the line where the shock from the nose of the aircraft meets the wing. On a forward swept wing, the effect of the taper of the wing is to reduce the sweep of the leading edge and the structural axis Less sweep means that the wing structure can be shorter for equivalent span, or can be designed with a higher aspect ratio for the same weight.

[26] See *Aviation Week and Space Technology*, 4 January 1982, p. 19, for more detail.

[27] *Defense Electronics*, April 1985, vol. 17, p. 53.

Conventional Wing Design

Supercritical Wing Design

Thin Supercritical Wing Design

Figure 11-3. Relative Thickness and Shape of Conventional, Supercritical, and Thin Supercritical Wings. Supercritical wings enhance a high performance jet aircraft's maneuvering capabilities in transonic flight. The wing design delays and softens the onset of shock waves on the upper surface of a wing. This shock wave deteriorates smooth flow over the wing causing a loss of lift and an increase in drag. The only aircraft aircraft with supercritical wings are the AV-8B and the F-111 Mission Adaptive Wing Aircraft. The X-29 can use a thin supercritical wing because of the inherent strength of the aeroelastically tailored materials.

c. Advanced Materials (Aeroelastic Tailoring)

The forward swept wing has been made possible by the availability of composites which are lighter and stronger than metallic materials. The composite material bends in only one direction, allowing the X-29's designers to aeroelastically tailor the wing to resist twisting by laying down the material in a criss-cross pattern during fabrication. The skins are laid with about 70 percent of the carbon fibers aligned 9° forward of the leading edge sweep. This gives the skins asymmetric shearing characteristics: as the wing bends upwards, the upper skin tends to shear forward and the lower skin tends to shear aft. Because both are fused to the wing's substructure, neither skin can move. The net result is that the shear resistance of both skins creates a aeroelastic effect strong enough to counter the twisting forces caused by tip vorticity.[28]

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[28] "Forward Swept Wing Technology Integration for the ATF," *International Defense Review*, February 1984, p 207. Subsequent discussion with Norris Krone were invaluable in understanding performance of the X-29.

The strong, lightweight aeroelastically tailored composite wings were proven to be a successful design. Shear resistance of both skins was shown to be strong and the weight savings for the aircraft significant.[29]

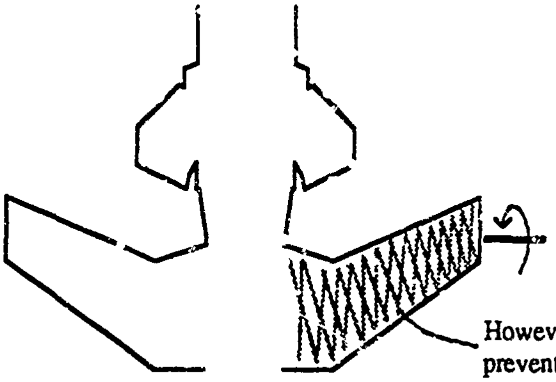

Figure 11-4. Aeroelastic Tailoring. Wing is designed such that the wing material prevents divergence. The criss-cross pattern of the material causes the wing skins to move counter to one another, preventing divergence.

d. Three-Surface control

The X-29 relies on the action of three different surfaces to control pitch. The X-29 features close coupled canard surfaces (foreplanes) directly forward of the forward swept wing for primary pitch control. These canards are designed for efficiency and stability at cruise speed, but are inadequate at low airspeeds. Therefore, small strake flaps at the rear of the aircraft provide additional pitch inputs for slow speeds, and act in the same manner as a tail plane. Pitch control is integrated with the wing's two segment trailing edge, which acts as a variable camber device to optimize the wing for various flight conditions. The variable camber device also serves as the wing's flaperons.[30] All three moveable surfaces are adjusted constantly for control and trim.

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[29] An interview with Charles B. McLaughlin, X-29 flight test support project engineer, revealed that "the aircraft has given credibility to the use of aeroelastically tailored composites, and the technologies incorporated into the aircraft have proved that when joined together, you can safely operate, in many flight regimes, a very unstable aircraft. It now appears that a forward swept fighter-type aircraft can be constructed with about 10-20% less drag and 5-25% less weight than conventional, aft-swept wing aircraft." See "Second X-29 Will Execute High Angle of Attack Flights," *Aviation Week and Space Technology*, 31 October 1988. p. 36.

[30] "Grumman will complete Initial X-29A Flight Tests This Month," *Aviation Week and Space Technology*, 7 January 1985, pp. 47-8.

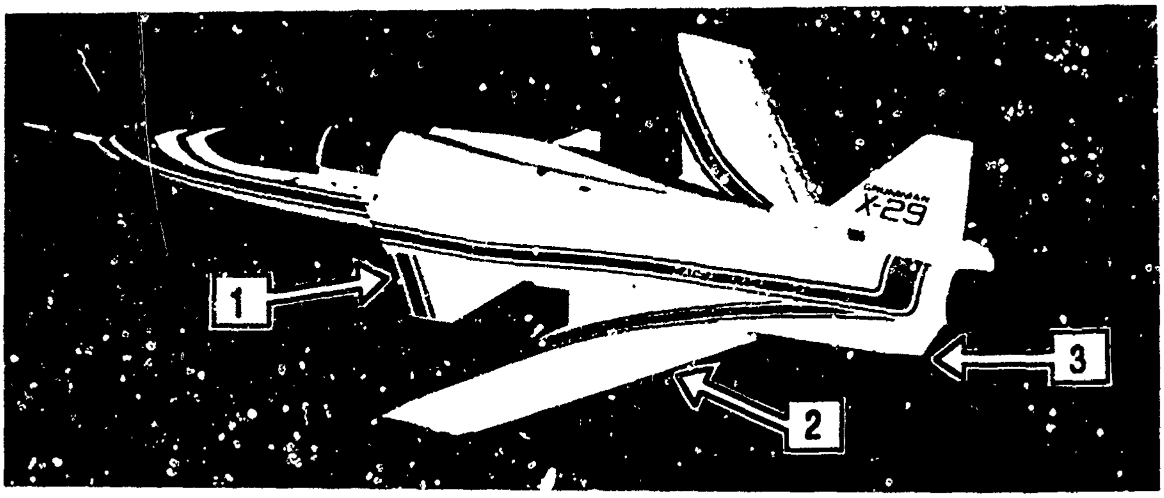

Figure 11-5. Three Surfaces are used for pitch and trim control: 1 is the close-coupled canard; 2 the variable camber device on the wing's trailing edge; 3 denotes the rear strake flaps.

The X-29 program demonstrated that an aircraft design can take advantage of a digital flight control system and control three surfaces at once. Pitch control using the canard surfaces and strake flaps is adequate. There are no limitations to handling, and camber control is unlimited. All three surfaces are constantly adjusted, and the flight control system is able to accommodate the design.[31]

e. Fly-by-Wire Flight Control System

Because the X-29 is inherently unstable, it must use its flight control system software at all times just to get off the ground, unlike other aircraft (e.g. SR-71 or the F-16) which can be flown (in basic design) without the software. The X-29 flight control system is all computerized (two digital systems, backed up by an analog system), and was developed by Honeywell. (Honeywell also performed rigorous analysis of the flight control laws developed by Grumman, modifying the laws as needed.) The flight control

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[31] "Analysis of the Flight Control Laws for the Forward Swept Wing Aircraft," Enns, Dale et al., Honeywell Systems and Research Center. Minneapolis, Minn., September 1985.

system software has been an important part of the development process, and bugs were worked out through the course of the testing program. Flight control system software was significantly reworked for the second X-29 in order to enable it to explore higher angle of attack regimes.

One goal of the X-29 was to develop flight control laws for a forward swept wing aircraft. In order for the flight control software to be written, the design limitations of the aircraft had to be ascertained, and a series of flight control parameters, or laws, developed and tested. The objectives of the control laws were to stabilize the aircraft and to provide good handling qualities, camber control for drag benefits, and gust suppression. The control law objectives were accomplished in the face of flexure effects and modelling uncertainty, while satisfying the available control power and surface rate constraints, and within the computational capability of the flight control computers. The driving feature of the pitch axis control problem for this aircraft is the high degree of instability brought about by the forward swept wing and canard configuration:

> The design and analysis showed that there are fundamental limitations to controlling such an aircraft. The limitations occur primarily in the stability margins area as a result of conflicts between bandwidth requirements, modelling uncertainties, and control power constraints. In the handling qualities area, there are no significant limitations and the control laws provide robustly stabilizing feedback, automatic camber control.[32]

Total costs of the DARPA forward-swept wing and X-29 program, from project records, was about $138 million.

C. OBSERVATIONS ON SUCCESS

The first observation that must be made is that the X-29 was a risky venture, so risky in fact that both the Air Force and private firms declined the opportunity to further develop the theoretical evidence offered by Krone in his dissertation. DARPA, on the other hand, agreed to take on a risky venture, and succeeded in producing an aircraft which has demonstrated significant technical accomplishments.

There is some debate as to whether programs such as the X-29 are suitable programs for DARPA to be involved in. Although the gains made by the X-29 are significant when applied to an aircraft with forward swept design, the accomplishments do not necessarily fit the profile that some would recommend are criteria for a DARPA

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[32] "Analysis of the Flight Control Laws for the Forward Swept Wing Aircraft," Enns, Dale et al., Honeywell Systems and Research Center, Minneapolis, Minn., September 1985.

program: high risk, high payoff with an order of magnitude improvement in technology.[33] Although digital flight control systems are commonplace now, the X 29 is the first aerodynamically unstable fixed-wing aircraft to fly. The advances in the flight control of the X-29 appear to be unrelated[34] to the digital systems now standard on advanced fighters. Some critics hold that the X-29 has not provided the Air Force with an aircraft that achieves an order of magnitude improvements in performance. This, however, raises for DARPA a difficult issue: particularly in aviation, how does one determine what constitutes an "order of magnitude improvement"?[35]

The X-29 does provide significant improvements in high angle of attack (a design limit of about 70° versus about 50° for the F/A-18, 57° in actual tests, versus 40° for the F/A-18) and maneuverability (the X-29 is highly maneuverable through 42° angle of attack), but the question remains whether these accomplishments are significant enough to warrant DARPA's involvement.

Separate from the discussion of the nature of the program is the fact that DARPA's management of the X-29 was effective. DARPA essentially brought in a person with special skills and allowed him to run the program with minimal interference. Although there was friction at times between Grumman, the Air Force, and NASA, Grumman's design remained intact from the outset of the program. Grumman had personnel uniquely qualified to work with the X-29 concept, and they were permitted to follow through on their ideas.

There is some question as to whether DARPA turned the program over to the Air Force at an opportune time, or if it should have been transitioned earlier, or terminated. The X-29 concept had been proven before the first aircraft was flown in 1984. Critics claim that DARPA should have turned the program over to the Air Force after the wind tunnel tests were complete and the design verified. However, given the initial lack of Air Force interest, it is unlikely that the X-29 would have been built if DARPA had followed this course.

Norris Krone's influence was important to the program from day one. Even those critical of the program acknowledge that the X-29 would not have been possible without

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[33] Heilmeir article.

[34] That is, development of the flight control system in the X-29 did not spawn developments used elsewhere.

[35] And what if the accomplishments of the X-29, can be duplicated with other technologies? Are these both considered order of magnitude changes, or is neither an order of magnitude accomplishment?

his efforts. Krone was in a position to initiate and execute the X-29 program, lending continuity to a unique endeavor. He was also able to maintain continuity in the program by selecting his successor at DARPA, Jim Allburn.

From the standpoint of accomplishing original goals, the flight test program of the X-29 was indeed successful. In the initial tests, Grumman proved that its design was viable and would behave as predicted, with few minor variations. Unlike other DARPA funded aircraft, notably the X-wing, the X-29 is still flying; Grumman, the Air Force and NASA are all still learning from it. The X-wing, a program that X-29 critics point to as a program that offered DARPA an order of magnitude gain in aircraft function, literally never got off the ground. The second phase of the X-29 test program has so far validated predictions that a forward swept wing aircraft can fly safely at high angles of attack, and is extremely maneuverable.

Technically, the X-29 program proved to be a success. The original goals of the program were met. New, dynamic technologies were integrated for the first time with only few variations from predictions. There is no evidence that the technical concepts of the X-29 have been applied to other programs. This could be due to the relatively recent development of the X-29, or to the fact that the military services have not yet established high angle of attack as an important requirement for new aircraft.

NAVAL TECHNOLOGIES

XII. ACOUSTIC RESEARCH CENTER

A. BRIEF OVERVIEW

Beginning in the early 1970s, new DARPA computing and networking technologies were used in several experiments, with joint Navy Laboratories and industry participation, which explored the limits to detection, localization, and tracking of submarines by advanced processing of acoustic data from existing SOSUS hydrophone arrays, without interfering with their normal operation. In the mid-1970s under the DDR&E-assigned SEAGUARD advanced ASW technology program, DARPA expanded this effort by setting up the Acoustic Research Center (ARC) which linked a number of advanced computers in a testbed primarily for disciplined development, testing and evaluation of algorithms for acoustic signal processing, in a series of large-scale ocean experiments. The results of these experiments assisted the Navy in upgrades for SOSUS processing. The fixed-mobile experiment conducted at the ARC in the late 1970s demonstrated the feasibility of real-time correlation processing, between a fixed array (SOSUS) and a mobile array (LAMBDA), and provided data useful for the Navy's SURTASS towed array ASW system.[1]

B. TECHNICAL HISTORY

In the late 1960s and early 1970s the issue of vulnerability of U.S. strategic weapons systems received a great deal of attention in connection with the Strategic Arms Limitations Treaty (SALT) negotiations. One of the related actions by DoD, in the early 1970s was to set up a standing panel of the Defense Science Board (DSB) to examine the vulnerability of current and future U.S. fleet ballistic missile (SSBN) submarines. The Navy had also set up a special SSBN security program in the early 1970 to assess SSBN submarine vulnerability. However, the DSB panel pointed out that the security of all elements of the U.S. strategic deterrent was a National issue, and that there was justification for another DoD program, for this purpose, separate from the Navy's. On

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[1] Testimony of Dr. G. Heilmeier, DARPA director, in DoD Authorization Hearings for FY 1976 and 1977, Part 4, 1975, p. 4912.

DSB's recommendation, DoD then set up a program in ARPA to assess the potential of new submarine detection technology and to determine the limits to detectability, tracking, and localization of future FBM submarines.[2] In response to this assignment, ARPA began to plan a program which included investigations of both acoustic and non-acoustic approaches to submarine detection. ARPA's acoustic program, in particular, began to explore the potential of focusing a number of technological developments, some from within its own programs, and some that were emerging from the Navy's programs at laboratories and in industry.

One of these initiatives came from ARPA's VELA UNIFORM program on seismic technology for detection of underground nuclear explosions. Some early work, begun in the late 1950s and early 1960s, involved correlating taped data from seismic observations separated by thousands of miles, and had given encouraging indications of signal coherence.[3] By the mid-1960s, the Large Aperture Seismic Array (LASA) had been constructed under VELA UNIFORM, to explore the possibility that "signals" from distant nuclear explosions might be "coherent" between widely separated sensor locations in the array, while the seismic noise might not, which would permit significant processing gains.LASA combined an unprecedentedly large (250 km) diameter array of subarrays, with on-line central processing of the seismic data from the array by an IBM group. A somewhat smaller follow-on array to LASA, called NORSAR, was built in Norway. One of the original motifs for NORSAR was to correlate its signals by satellite with that from LASA. LASA was dismantled in the late 1960s, but NORSAR still transmits signals over a satellite link to a seismic processing center in the U.S. The ex-LASA director, H. Sonnemann, who had joined the staff of the Assistant Secretary of the Navy for R&D at the time of the new ARPA assignment, played a key role in getting the ARPA acoustic programs underway, as discussed below.

Another related ARPA initiative came from its Information Processing Techniques Office (IPTO). In the mid 1960s IPTO funded construction of ILLIAC IV, the first large scale parallel processor. ILLIAC IV was the most powerful computer available in the mid 1970s. IPTO also began development of the ARPANET, in the late 1960's, which promised a capability to greatly expand the availability of computers for research. Because

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[2] Discussion with R. Moore, 12/89.

[3] LASA is discussed in Volume I, Chapter 13. The continental-scale seismic coherence measurements were made by B. Steinberg who had been involved earlier in a similar experiment with underwater accoustic signals under ONR's project ARTEMS. Discussion with H. Sonnemann, 6/90.

of these IPTO developments, at the time of setting up the Acoustic Research Center in the mid 1970s it appeared that computing power, until then a limiting factor in acoustic signal processing, might be a problem no longer. Further, along lines of the ARPANET program, computer interface techniques could be applied to securely access the data from operational Navy SOSUS acoustic receiving systems without interfering with their normal operation.[4]

A third initiative, started in 1973, was aimed at exploring the limits and utility of mobile underwater towed arrays as passive acoustic detection systems. DARPA funded experiments using a large ship-towed detection array, LAMBDA (Large Aperture Mobile Detection Array) which was built with robust seismic exploration technology.[5]

The operation of both SOSUS and LAMBDA depended on the fact that sound could travel long distances in the ocean, with low loss, through the "deep sound channel." The properties of this channel were investigated after WW II by Ewing and his collaborators at Columbia University. During the Korean War, Columbia set up the Hudson Laboratories, funded by ONR, for research on advanced underwater acoustic approaches to anti-submarine warfare. In the late 1950s, Hudson performed experiments on correlating data from spaced underwater hydrophones with encouraging indications of coherence.[6] Hudson's ARTEMIS project demonstrated that significant gains could be achieved by beam-forming using large underwater arrays, in a "multistatic" active acoustic experiment.[7] The signal processing for ARTEMIS, and later for LASA, was done by IBM.

In the late 1960s the National Academy's Committee on Undersea Warfare conducted a Summer Study to review potential advances in undersea surveillance, at the request of the Navy. Among other things this group recommended further research on both coherent acoustic processing and the utility of OTH (over the horizon) radar to locate ships which could also be acoustic noise sources.[8]

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[4] Statement by Dr. R. Fossum, DARPA director, before the R&D Subcommittee of the House Armed Services Committee, March 2, 1981.

[5] LAMBDA is discussed in Volume I, Chapter 24.

[6] "Correlation of Signals at Large Hydrophone Separation," by A. Berman, et al., Hudson Labs; Technical Report, Apr. 1957 (CLASSIFIED). ARTEMIS anticipated that passive detection systems could be defeated by submarine quieting.

[7] H. Sommeman, ibid.

[8] "Ocean Surveillance Study," Committee on Undersea Warfare, National Academy of Sciences, Oct. 1966 (CLASSIFIED), p. 101.

In the late 1960s the Bell Telephone Laboratories (BTL), which had designed and built SOSUS for the Navy, conducted experiments to investigate the coherence of underwater signals and noise at different acoustic receiver separations. Their results indicated how signal coherence deteriorated for wide spatial separations of hydrophones, and apparently discouraged further BTL efforts along these lines.[9] At the time BTL's views occupied a rather dominating position in regard to the Navy's undersea surveillance technology, and were apparently largely negative throughout the period of ARPA's efforts.[10]

The Navy's Naval Underwater Center (NUC) (West Coast) and Naval Undersea System Center, (NUSC) (East Coast) collaborated in the late 1960s to improve the processing of signals received by a large sonar dome on submarines.[11] Again important questions had to do with relative coherence of acoustic signals and noise. NUC built a multichannel, wide band recorder for this work which proved quite successful, and later NUC proposed to ARPA/IPTO to modify it for further investigation of coherence at different frequencies.[12]

In the late 1960s the ENSCO Company, under Navy sponsorship, developed a successful algorithm for correlating the signals received by a number of acoustic receivers at short distances from underwater sources. Several other companies, including GE, IBM and BB&N were also active at this time in development of acoustic signal processing techniques, under Navy sponsorship.

In the mid 1960s, Dr. H. Sonnemann of Hudson Laboratories, who had been the chief engineer for Hudson's project ARTEMIS, joined ARPA's VELA UNIFORM program, and as mentioned above became director of the LASA project. In the late 1960s Sonnemann left ARPA to join the Office of the Secretary of the Navy as an assistant to Dr. R. Frosch, the Assistant Secretary of the Navy for R&D (ASNR&D).[13] In 1969, apparently on his own initiative, Sonnemann obtained some unclassified SOSUS tapes of unprocessed ocean noise. With a transfer of funds from the Navy to ARPA's LASA

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[9] Cf., e.g., "Fluctuations in Low Frequency Acoustic Propagation in the Ocean," by R.H. Nichols and H.J. Young, *J. Acoustical Soc. of America*, Vol. 43, 1968, p.4.

[10] H. Sonnemann, ibid.

[11] Discussion with L. Griffith, 12/89.

[12] AO 2288 of 9/72, "Sonar Processing Facility."

[13] Dr. R. Frosch, who had headed the Hudson Labs, went to ARPA to head the VELA program, and later became ASNR&D.

program, these tapes were processed at the LASA facility. with the IBM algorithms used for the seismic work. The results were encouraging, and were followed up by a more specific effort by IBM. Sonnemann brought these results to ARPA's attention, and helped obtain funding for related Navy Laboratories' efforts.[14]

Some of the first ARPA actions, under its new program to explore the limits of underwater acoustic detection, were to expand and intensify ongoing efforts and exploit existing techniques. Thus ARPA funded an experiment in the early 1970s, which used an existing IBM algorithm for (incoherent) processing.[15] There was a considerable body of opinion, at the time, that only incoherent processing was likely to prove practical.

Another early ARPA IPTO action, in 1971, was a positive response to an NRL request for use of the ILLIAC IV, then located at NASA's Ames Laboratory, for the intensive processing required to carry out an experiment investigating fundamental aspects of the ocean acoustic propagation using data from SOSUS hydrophones.[16] To deal with the problem of interfacing the data from SOSUS with the ILLIAC IV, NRL had contracted with SCI, an offshoot of the ARPA IPTO-supported Stanford Computer and AI group. Some of this early NRL effort also had support from ONR.

A little later, ARPA IPTO also began to expand support of SCI toward constructing a "transparent," non interfering interface between the SOSUS stations and the ARPA data collection and processing facilities.[17] These ARPA facilities were then envisaged as mainly the ILLIAC IV, but also including some other computers to do preliminary processing. The problem of the "non-interfering" requirement for conducting any experiments involving SOSUS, an operational Navy system, had hampered previous efforts to do research using SOSUS data, although as previously mentioned Sonnemann had managed to obtain unclassified "unprocessed" SOSUS tapes. The interface built by SCI digitized and encrypted the acoustic signal data, and formed it into "packets," of the type used in ARPANET, for transmission to the ARPA data collection facility location, then called the "Acoustic Research Facility" (ARF).

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[14] H. Sonnemann and L. Griffith, ibid.

[15] A.O. 2054 of 1/72. This IBM experiment did not actually take place until 1973. Cf. "Technical Achievements of DARPA's Acoustic Research Center," July 1973 to March 1982, Tetra Tech., Inc. 1983 (CLASSIFIED).

[16] In 1971 ILLIAC IV was commencing a "shakedown and debugging" phase which lasted about two years. See Chapter XXVIII. of Volume I. NRL was supported under AO 2009 of 12/71 for ILLIAC IV programming, and later under AO 2275 of 8/72 for the underwater experiment.

[17] AO 2226 of 9/72.

In the early 1970s the Navy Undersea Center (NUC, later the Navy Ocean Systems Center NOSC) proposed an experiment to test a computationally efficient tracking and localization algorithm (the Trueblood algorithm) they had developed for processing of acoustic signals. DARPA provided funds for obtaining the data tapes, for the subsequent processing which was done off-line at NUC, and for later use by others. One of the significant conclusions of the successful NUC experiment, carried out in April 1973, was that their tracking and localization algorithm would work, in "real time" if desired, using state-of-the-art commercial computer technology.[18]

The NRL experiment, mentioned above, was actually carried out in 1973 and was successful in determining the correlation between acoustic signals received at different locations from a fixed source, under carefully measured conditions.[19] Data from this experiment was processed off-line, partly with ILLIAC IV, and subsequently at NRL.[20]

In this early activity, ARPA efforts were under its Information Processing Techniques Office (IPTO).[21] During the 1972-73 period, however, responsibility for most of this work was shifted from IPTO to the Nuclear Monitoring Research Office (NMRO), which then fostered the development of data transmission by satellite between SOSUS stations and the ARC, similar to what had been done for transmission of seismic data between the NORSAR array in Norway and the seismic data processing centers in the U.S.[22]

DARPA also began funding, in the early 1970s, an effort by ENSCO to modify and apply a version of their previously mentioned processing algorithm to the NUC data.[23] Apparently the Navy also funded this ENSCO effort and joined DARPA in funding several other similar efforts, by industry and laboratories, using the same data. After the NUC experiment, ARPA commenced a series of workshops on undersea surveillance, in order to get an overview of results of the various efforts now underway and provide a forum for scientific exchange.[24]

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[18] L. Griffith, op. cit.

[19] Some of the results are discussed in A.A. Gerlach, "Coherence of Acoustic Signals Propagated in the Deep Ocean," in *Journal of Underwater Acoustics*, Vol. 25-2, April 1975, p. 441-465 (CLASSIFIED).

[20] NRL was funded by DARPA under AO 2275, of 8/72.

[21] This was done at the explicit direction of Dr. S. Lukasik, then head of ARPA. R. Moore, op. cit.

[22] See Chapter 13 on LASA, Volume I.

[23] AO 2101 of 2/72.

[24] The proceedings were not recorded, L. Griffith, op. cit.

Another early related IPTO initiative was to fund an effort by Feigenbaum and others of the Stanford AI group, working at SCI, to apply heuristic Artificial Intelligence (AI) approaches to automation of acoustic signal recognition. This effort was called HASP (Heuristic Adaptive Signal Processing).[25] This was one of the early AI application attempts and it continued to be funded by IPTO after the transfer of most of the of ARPA acoustic work to other offices. HASP was considered important since "manual" signal recognition was still required at this time as an input to later processing of the acoustic signal. However, HASP proved to be computationally intensive, and after considerable work was apparently only able to recognize some signals under benign background conditions. At the same time as HASP was being developed and tested, "conventional approach" signal processing algorithms were being progressively improved and, to some extent, also automated. Some attempts were made to interface these conventional signal processing developments with HASP and its later version "SIAP," with limited success. Apparently the HASP/SIAP sequential heuristic approach "started from scratch" and did not take advantage of the information base provided by the conventional types of signal processing.[26] A careful review of the HASP and SIAP efforts was made in the mid 1970s, concluding that during the period of Acoustic Research Center activity these AI approaches did not achieve the desired objectives, due mainly to computational limitations.[27]

While the ILLIAC was improving its performance during this period (1971-74), its availability was still intermittent and its programming continued to make slow progress. This caused considerable difficulty not only to the ongoing research, but also for the concept of near "real time" processing for target localization and tracking, one of the main DARPA program objectives.

In 1974 a number of factors led DARPA to expand and shift responsibility for the program to its Tactical Technology Office (TTO) and to locate an enlarged processing facility, now named the Acoustic Research Center (ARC) at Moffett Field, Cal., Naval Air Station in proximity to the Ames Laboratory and the ILLIAC IV. The ARC was to be a joint project with the Navy Electronics Systems Command (NAVELEX) with an agreement that the Navy would take over at some point. DARPA chose not to locate the ARC at NUC as proposed by that laboratory, but to operate it independently, emphasizing industrial

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[25] AO 2288 of 2/73.

[26] L. Griffith and R. Trueblood, op. cit.

[27] Tetra Tech., op. cit., and R. Trueblood 12/89.

participation.[28] The main factors motivating the establishment and location of the ARC seem to have been the success that had been achieved so far in the processing experiments, and the continuing expectations for ILLIAC IV's performance, together with the intensive computation which was needed to approach a real time tracking capability. However, the ARC had to be physically separated from the ILLIAC IV, since that computer was then under NASA management and in an unclassified area.[29] The ARC eventually included a number of computers, notable among which was the Culler "Chi" processor, which was one of the earliest parallel intermediate-size systems especially efficient in executing Fast Fourier Transforms. Originally expected, and to some extent used, to "drive" the ILLIAC IV, later the "Chi" processor itself carried an increasing amount of the ARC processing load.[30] The ARC also included extensive data storage systems.

The ARC was one of the major "testbeds" built while Dr. George Heilmeier was Director at ARPA and was to be a major feature of the SEAGUARD program, which was assigned to DARPA by the DDR&E in the mid 1970s, Dr. M. Currie.[31] The SEAGUARD thrust was toward a major improvement in ASW capability. Under SEAGUARD the ARC was to be the processing testbed, one of the key features of the program along with the LAMBDA towed array and OMAT, a very large fixed array proposed by NUSC. The ARC was to provide a focus for interarray processing algorithm development and test in several demonstration experiments of increasing scale and complexity, moving toward a "real time" processing capability for localization and tracking, and possibly eventually also automatic detection of submarines.

SEAGUARD objectives stated by Dr. M. Currie were to determine and quantify the limits of detectability and localization accuracy of submarines, an area of ASW which was of greater importance as a result of the SALT agreement.[32] However, in some high

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[28] L. Griffith, op. cit., and R. Trueblood, op. cit.

[29] Classified processing on ILLIAC IV was eventually achieved but even then involved some difficulty: clearing the area, and after processing, purging the computer and its memories. Discussion with E. Smith, 11/89.

[30] The Chi processor led to some of the "floating point" processors now commercially available. L. Griffith, op. cit.

[31] Statement of Dr. M. Currie, DDR&E, DoD Authorization Hearings, Committee on Armed Services, House of Representative, R&D for FY 1976 and 1977, March 1975, Part 4, p. 3826.

[32] M. Currie, op. cit.

quarters it was held that accurate tracking of ballistic missile submarines would be destabilizing.[33]

There was also, under SEAGUARD, an effort led by W. Munk and the JASON group to develop a theory of the effects of ocean structure and dynamics on propagation over large distances.[34] Earlier, Munk had participated in a Navy study which critically examined the basis for the Navy's acoustic ASW systems, and as a result had been motivated toward leading a major effort linking underwater acoustics and oceanography. Interplay between theoretical modelling with experiments was to be a key feature of the scientific effort centered at the ARC, in DARPA's program plans. This theoretical effort seems to have had a limited effort on most of the work at the ARC. However, one ARC experiment, discussed below, was funded by ONR and dedicated to "ocean tomography", one of the offshoots of this theoretical work.

The Fixed Mobile Experiment (FME) planned in 1974 was the largest effort conducted at the ARC. In this experiment, coordinated by NUC, a ship-towed LAMBDA array was linked via satellite with the ARC. The signals received from LAMBDA were correlated at the ARC in order to do interarray processing.[35] A spur to this satellite demonstration was provided by the fact that the commercial liner Queen Elizabeth had already used a communications satellite link to shore.[36]

The feasibility of correlating data from the mobile LAMBDA with that from SOSUS had actually been demonstrated earlier by NUC using taped records "off-line."[37] However, some of the data received at the ARC in the FME were processed in near "real time" for tracking, an important demonstration for the follow on SURTASS system. The ILLIAC IV was used for some of this processing but eventually several available PDP computers were connected in parallel for most of the work. For the FME, a secure wideband ARPANET link was used between NUC and the ARC which was apparently the first of its kind, and used a new encrypting device developed partly with DARPA IPTO

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[33] H. Sonnemann, op. cit.

[34] "Sound Transmission Through a Fluctuating Ocean," eds., S. Flatte and R. Dashen, Cambridge U. Press, 1979.

[35] Statement of Dr. G. Heilmeier, DoD Authorization Hearings, Committee on Armed Services, House of Representatives, FY 1978, R&D, Part 3, March 1977, p. 1469.

[36] R. Moore, op. cit.

[37] L. Griffith, op. cit.

support. Several interarray processing algorithms were tested "on-line" during the FME. At one stage of FME, some 20 computers were linked to the ARC by ARPANET.[38]

ENSCO, IBM, GE and others were involved in the Navy's NAVELEX program in the mid to late 1970s to develop improved processing for SOSUS. A version of a new processing system was tested using the data obtained with ARPA support in the early 1970s and afterwards adopted by the Navy for SOSUS.[39] The objectives of the NAVELEX program appear to have been to develop an evolutionary, "modular" approach to processing improvement. The ARC provided a disciplined environment in which all eligible processing algorithms were tested with the same data and in the same processing facility, and were involved in the same experiment. Some of those involved felt that in this way the ARC improved the quality, speed and economy of the Navy's decision on selection of upgrades for SOSUS processing.[40]

In the late 1970s the ARC participated in several operational experiments conducted by the Navy.[41] Multi-level security apparently proved a problem for the ARC's computer network in these experiments.[42] There were also problems having to do with the location of important information relative to the various operational commands.[43]

A fundamental experiment was also performed in this time frame, using the ARC and supported by ONR, to explore to what extent ocean structure could be inferred from coherent processing of acoustic data received at several locations from several fixed, controlled sources. This was a preliminary experiment toward "ocean tomography" which had been proposed by W. Munk and his collaborators as an approach to large scale ocean measurement, and was based in part on some of the theoretical work under SEAGUARD.[44]

In 1978, a "semi-alerted search experiment" was conducted at the ARC which included the first attempt at automating a part of the surveillance process over an area of

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[38] G. Heilmeier, 1977, op. cit.

[39] Ibid.

[40] L. Griffith, op. cit.

[41] Statement of Dr. R. Fossum, DARPA director, DoD authorization Hearings for FY 1979, R&D, April 1978, part 3, p. 1567.

[42] R. Moore, op. cit.

[43] H. Sonnemann, op. cit.

[44] See e.g., "Ocean Acoustic Tomography, A Scheme for Large Scale Monitoring," by W. Munk and C. Wunsch, *Deep Sea Research*, Vol. 26A, 1979, p. 123.

nearly 3/4 million square miles, in addition to localization and tracking emphasized previously. The Stanford WARF (Wide Aperture Radar Facility) OTH radar facility also participated in this experiment, correlating its data on locating ships at the ARC, to help determine sources of acoustic noise. The results were encouraging and with further increase in processing speed due in part to use of optical processors, a more ambitious experiment, covering a larger area, was undertaken in the early 1980s.[45] For this experiment, only the PDP type computers in the ARC were used.[46]

Also in the early 1980s the ARC's capabilities were used in an experiment using active-acoustic sources, and in an at-sea test of the Advanced Acoustic Array, an air-dropped self-deployable underwater acoustic array.

In October 1982 the ARC was formally transferred to NOSC (ex-NUC) as a technology (6.2 budget) project. Before this an attempt was made to "sell" the ARC as a system to the Navy's Op 95, responsible for ASW, but without success.[47]

NOSC was agreeable to the transfer of the ARC equipment and communication links to San Diego partly because this dovetailed with the centers' mission assignment in ocean surveillance and R&D. Initially, NOSC had planned to operate the transferred and transformed ARC facility as a "cost center" for Navy R&D and operational experiments. There was considerable opposition in the Navy, however, to conduct operational experiments centered at an R&D facility.[48] With NAVELEX support, NOSC began to replace several of the ARC's internal set of computers with more modern systems.[49] However, the Navy did not keep up the same level of funding for the NOSC ARC-type R&D work.[50] The SOSUS data communication links were maintained and expanded with the relocation of the ARC to NOSC until the Navy's SPAWAR-PMW 180 project office assumed control of the facility in FY87. By 1987 NOSC had completely replaced all the

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[45] Statement of Dr. R. Fossum, The DARPA Budget Request FY 1982, p. II-1, E. Smith, op. cit.

[46] E. Smith, ibid.

[47] E. Smith, ibid.

[48] This problem had also occurred earlier at the ARC. H. Sonnenman, op. cit.

[49] The ILLIAC IV had remained at Ames.

[50] The ARC research remained in the Navy's Exploratory Development (6.2) budget. The request for ARC support in that budget arrived at the same time as other sizeable requests. Discussion with L. Hill, IDA, 5/90.

older ARC processors with equipment to be used in a new project under PNW-180.[51] The ARC was shut down a little later.[52]

Shortly after the transfer of the ARC, Navy and National appreciations greatly sharpened about the new threat posed by the quieting of Soviet submarines. In response, DARPA and Navy-funded research and exploratory development for ASW has intensified, and appears to be addressing many of the the same general questions as did SEAGUARD about the limits of detectability in the ocean. The emphasis, however, now seems to be more on what can be done with increased physical apertures, together with appropriate processing, than following the ARC approach of exploiting existing SOSUS receivers.

C. OBSERVATIONS ON SUCCESS

DARPA's activity culminating in the Acoustic Research Center seems to have involved several converging factors. One was the great increase in computing capability promised by the IPTO programs, for ILLIAC IV, and the ARPANET. These advances promised to remove some of the major previous limitations in acoustic signal processing. Another factor was the Navy-funded laboratory and industrial initiatives which had been going on for some time. The issue of SSBN vulnerability had increased in importance due to the SALT talks, and the related DSB panel's recommendation, implemented by DDR&E, gave an assignment of working this problem to ARPA, in parallel with a dedicated Navy effort. The apparently key initiative of H. Sonnemann came from his unique background of participating in the earlier ONR-funded ARTEMIS experiments, and later being responsible for ARPA's LASA large "array of arrays" seismic processing experiment. Sonnemann took advantage of his position in the office of the Assistant Secretary of the Navy to link SOSUS with LASA processing. He also brought many key players together.

ARPA's initial actions seem to have been based primarily on exploitation of IPTO technology, the ILLIAC IV and ARPANET. This exploitation might be regarded as offering a breakthrough in computational power, but it was risky because of the still developing status of these IPTO programs. The initial DARPA actions could also be regarded as cautious, backing two Navy laboratory groups which had fairly well developed ideas and initiatives. These groups were quite successful in their first experiments which

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[51] See e.g., testimony of Dr. P. Selwyn before Senate Armed Services Defense industry and Technology subcommittee, April 1990, quoted in *Aerospace Daily*, Vol. 154, #22, May 1, 1990, p. 2.

[52] L. Griffith, op. cit.

made limited use of this IPTO technology. In particular one of the earliest of these experiments, by NUC, employed an algorithm which was very efficient, so that extraordinary computer capability such as ILLIAC IV was not required. In the ARPA effort, "remote non-interfering access" to SOSUS data was successfully achieved for the first time.

The DARPA effort "took off" when Dr. Heilmeier became director, and pushed the concept of a major test bed for ASW, where advanced processing would be tested in a controlled environment in major exercises. The ARC testbed served as a way to test and evaluate a number of improvements in processing technology economically, using existing SOSUS assets, competing all the competitive algorithms against each other in a common environment. This procedure provided help to speed improvements in the efficiency and quality of the Navy's decisions on SOSUS processing upgrades.

The ARPA attempts at AI applications automating signal recognition, HASP and SIAP, were evaluated in the ARC program as not sufficiently successful to lead to any implementation at the time (mid 1980s). It was recognized that this was a judgement about AI of the time, and in fact with neural net "parallel" approaches, rather than sequential "linear" heuristics, the problem is now being attacked again.

The attempts to go beyond localization and tracking to extend the ARC interarray processing technology to search were very computationally intensive, as expected. Dr. Fossum, DARPA director, stated at the time of the formal transfer of the ARC that acoustic ASW had become mature and that further marginal improvements would be very difficult and costly.[53]

When ILLIAC IV operated it was very productive, but it did not prove as reliable as had been hoped, and its programming problems also seem to have slowed progress somewhat. The Navy (with its continuing responsibility to keep upgrading SOSUS) didn't wait for the final results from the ARC, but was encouraged by the general results of the early DARPA experiments and proceeded to field a processing scheme developed by one of its contractors, and tested using results of these early DARPA-funded experiments.

The major experiment with the ARC was the FME, in which data from fixed and moving (LAMBDA) receivers were correlated for the first time on-line. The FME results,

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[53] Fossum, op. cit., p. II-2.

also obtained a little late due to difficulty with ILLIAC IV reliability, nevertheless seem to have been a useful input for the Navy's SURTASS program.[54]

The SEAGUARD program also attempted to pull together the ARC, LAMBDA and OMAT. An OMAT array was deployed in the Atlantic, but plans for a similar effort in the Pacific were abandoned mainly for the operational reason of potential vulnerability of large fixed facilities.[55]

The ARC succeeded in showing what could be done with greater computing capability, and with the fusion of other information such as that provided by OTH radar, thus giving a picture much desired by decision-makers: information on possible marginal improvements and estimates of associated costs. The Navy's actions in implementing a more evolutionary set of processing improvements rather than a larger step toward coherent, real time processing may have been due to concerns about cost effectiveness, given the ILLIAC problems, and perhaps also due to some of the difficulties experienced in the operational experiments involving the ARC. However, the change in the threat seems to have eventually influenced the Navy's judgment about a system tied to existing underwater arrays In retrospect this judgment may have been wiser than one that would have moved more quickly to use DARPA technology.

DARPA's costs of the ARC program, from project records, was $64 million. The Navy provided a relatively small additional amount before transfer. The costs of SURTASS, affected by the FME results, are estimated at about $4 billion. The costs of the Navy processing upgrades tested on the ARC are classified.

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[54] Earlier off-line correlation processing had been demonstrated between fixed and mobile receivers. H. Sonneman, and L. Griffith, op. cit.

[55] Discussion with H. Cox, 5/90.

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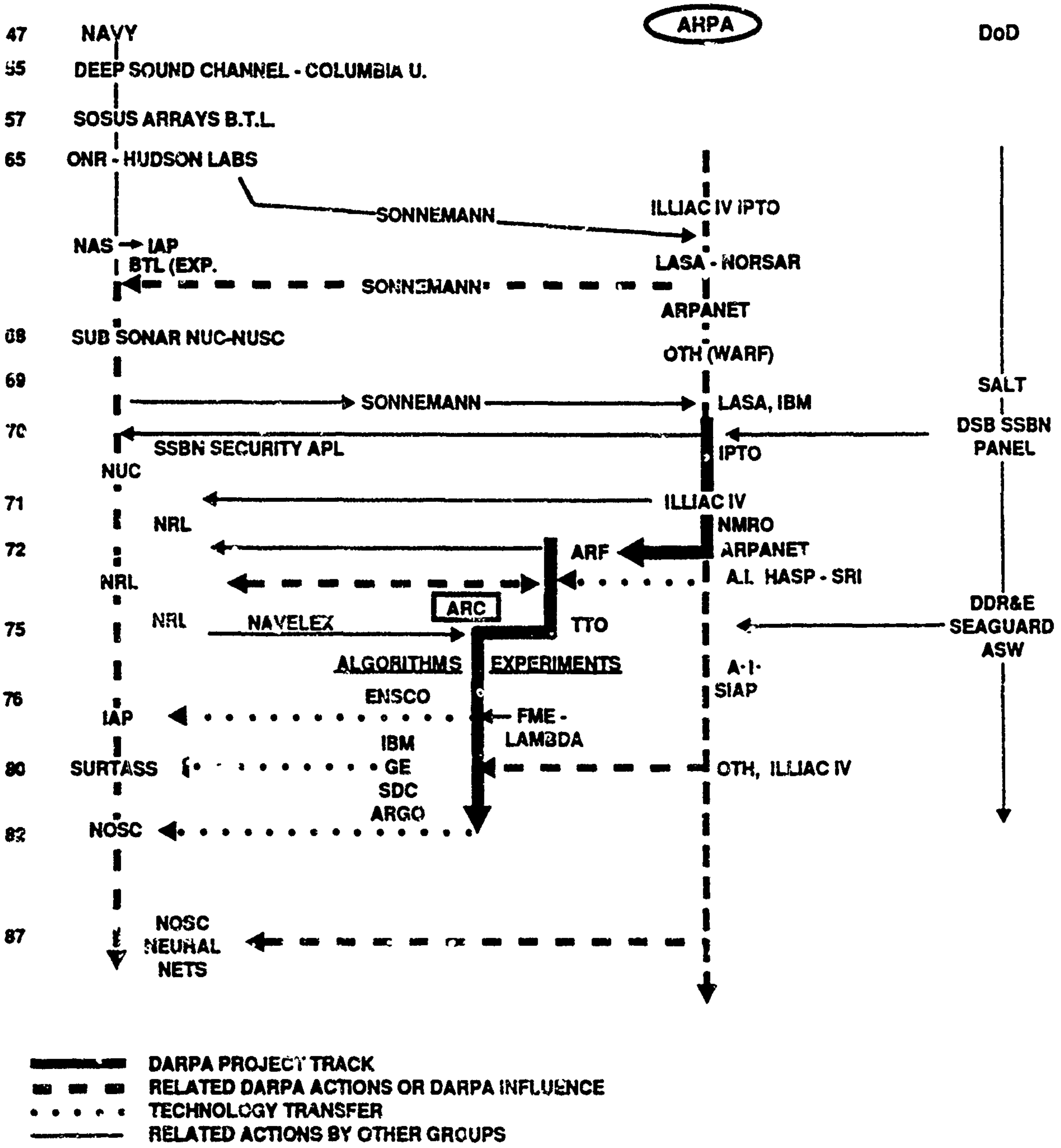

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INFORMATION PROCESSING

XIII. INTERACTIVE COMPUTER GRAPHICS

A. BRIEF OVERVIEW

Effective human-machine communication has always been an area of interest in the field of computing. Beginning in 1946, computations were being performed electronically, greatly increasing the speed at which the resulting information was available for human consumption. The idea of using graphical symbols for input and the capability of "drawing" computational results prompted research and development of interactive computer graphics.

ARPA's role in the development and promulgation of interactive computer graphics began as a component to the early computer time-sharing projects. While Project MAC[1] is more widely known, ARPA funded another computer time-sharing effort in 1963 with System Development Corporation, which included a General Purpose Display System. Along with the MAC graphical display terminals, this is the earliest ARPA involvement in the area of interactive computer graphics.

Concurrent with ARPA's efforts in interactive graphics were privately funded efforts to develop a capability for Computer Aided Design (CAD). Though ARPA was not directly involved, the interactive graphics work for the ongoing MAC project prompted the publicity of these private efforts, thus encouraging technology exchanges among industry, academia, and the government.

B. TECHNICAL HISTORY

1. The Need for Interactive Computer Graphics

The developments of the first truly electronic computers set the stage for development of interactive graphics. Speed and power were the key and the electronic computer promised both. The ENIAC (Electronic Numerical Integrator and Calculator)[2]

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[1] MAC, originally Machine Aided Cognition, see Volume I, Chapter 19 of this paper for the story of MAC.

[2] Jean-Paul Tremblay and Richard B. Bunt, *An Introduction to Computer Science, An Algorithmic Approach*, McCraw-Hill Book Company, 1979, p. 9.

was the first completely electronic computer. Developed from 1943 to 1946 by John W. Mauchly and J. Presper Eckert at the University of Pennsylvania with support from the Ballistic Research Laboratory of the Aberdeen Proving Grounds, ENIAC was comprised of arrays of vacuum tubes functioning as its logic network. ENIAC's electronic technology allowed it to calculate 1000 times faster than that of its electro-mechanical predecessors. The teletype and its descendants would be the mainstay of interactive input/output until the introduction of the Cathode-Ray Tube (CRT).

Following ENIAC were the electronic stored-program computers that came in the late 1940s and throughout the 1950s. Although their developments pre-date ARPA, the ILLIAC from the University of Illinois, JOHNIAC from Rand Corporation, and WHIRLWIND from MIT, would all later be funded by ARPA and it was those later projects that led to the spinoff of interactive graphics.

The earliest financial contributor to computer development was the DoD. Demands for strategic and tactical as well as defense computations initiated several projects. Two such projects were SAGE, an air defense system, and BMEWS, a ballistic missile early warning system. These systems were sponsored by the Air Force and a majority of the computing development was performed by System Development Corporation (SDC), which at that time (1950s) was an arm of the Rand Corporation. Like other Command and Control (C^2) systems that would follow, the desire to display information pictorially was expressed. Such expressions helped to spur the development of interactive graphics.

Perhaps the most important push for computing that eventually included interactive graphics was the result of one individual's vision. Dr. J.C.R. Licklider, who would become the first director of ARPA's Information Processing Technology Office (IPTO) in 1962, promoted a concept he termed "man-computer symbiosis " A summary of Dr. Licklider's vision[3], which was first published in March 1960, follows.

> Man-computer symbiosis is an expected development in cooperative interaction between men and electronic computers. It will involve very close coupling between the human and the electronic members of the partnership. The main aims are 1) to let computers facilitate formulative thinking as they now facilitate the solution of formulated problems, and 2) to enable men and computers to cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs. In the anticipated symbiotic partnership, men will set the goals, formulate the hypotheses, determine the criteria, and perform

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[3] J.C.R. Licklider, "Man-Computer Symbiosis," *IRE Transactions on Human Factors in Electronics*, Vol HFE-1, March 1960, p. 4.

> the evaluations. Computing machines will do the routinizable work that must be done in to prepare the way for insights and decisions in technical and scientific thinking. Preliminary analyses indicate that the symbiotic partnership will perform intellectual operations much more effectively than man alone can perform them. Prerequisites for the achievement of the effective, cooperative association include developments in computer time sharing, in memory components, in memory organization, in programming languages, and in input and output equipment.

When Dr. Licklider came to ARPA in 1962, he proceeded to turn his vision into a reality. His attention was first focused on time-sharing systems. ARPA's initial involvements in interactive graphics came as spinoffs from these time-sharing projects. To quote Dr. Licklider again:[4]

> Certainly, for effective man-computer interaction, it will be necessary for the man and the computer to draw graphs and pictures and to write notes and equations to each other on some display surface. . . . He [the man] could sketch out the format of a table roughly and let the computer shape it up with precision. He could correct the computer's data, instruct the machine via flow diagrams, and in general interact with it very much as he would another engineer. . . .

Dr. Licklider foresaw interactive computing and its associated interactive graphics as the key to effectively marrying computers and people. In fact, when asked what he considered to be his primary achievement in his tenure at ARPA, Dr. Licklider said, "I feel best about the fact that I convinced people to take interactive computing seriously long enough to give it a chance."[5]

2. Early Development Efforts

The development of interactive computer graphics started in the 1950s, but before they would become a reality three fundamental building blocks were needed:

- Graphical devices, such as the CRT
- Rapid, interactive computation to drive the graphics devices
- Algorithms for the various computational aspects of manipulating and displaying graphics.

Since 1962, ARPA has funded efforts, both directly and indirectly, to support all three of these fundamental building blocks.

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[4] Ibid., p. 9.

[5] J.C.R. Licklider, "The Early Years: Founding IPTO," *Expert Systems and Artificial Intelligence*, Thomas C. Bartee, Ed., 1988, p. 220.

a. Graphical Devices

The first known use of the CRT as an input/output device on a computer system occurred in 1950 on the WHIRLWIND computer at MIT.[6] CRTs had been used in many applications prior to this, such as radar screens, oscilloscopes, and, of course, in the fledgling television industry. However, their use in computers certainly provided a critical component for truly interactive computing and, as a result, interactive graphics. The CRT, as a basic device, has not changed radically since its introduction 30 years ago. What has changed is the additional, specialized hardware associated with CRTs, such as dynamic refresh memory and pointing devices.

Dynamic refresh memory allowed the individual points of light, or *pixels*, on CRTs to be changed on the fly, creating a near real-time display capability. This capability, coupled with powerful central processors, enabled new algorithms for solids modelling and consequently CAD to be developed and demonstrated.

Pointing devices also contributed to overall graphics algorithm development by providing physical human control over the graphics. The first of these devices was the light pen. Developed at MIT, the light pen is pointed at the CRT screen and with the use of a trigger mechanism is able to select pixels or groups of pixels for manipulation. The light pen was originally used for SAGE consoles, but their use extended into other systems. However, light pens were not sufficiently ergonomic, were tiring to use, and were subsequently replaced first by a stylus operated tablet, then later by the mouse.[7]

b. Rapid Interactive Computing

ARPA purchased an IBM AN/FSQ-32V, simply referred to as a Q-32, for use at SDC in their Super Combat Center (SCC) Project. However, the SCC was cancelled, but as the SDC ARPA Project Manager, Dr. Licklider reshaped SDC's contract to focus on developing a timesharing system. An SDC project was formed in December 1962 with the challenge from Dr. Licklider to have a timesharing system running in six months, i.e., mid-1963. SDC not only met the deadline, but their Time-Sharing System (TSS) was a manifestation of Dr. Licklider's man-computer symbiosis vision. Most notable in this respect was the development and inclusion in TSS of the General Purpose Display Systems (GPDS). The GPDS was the first system of its kind to integrate hardware and software

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[6] William M. Newman and Robert F. Sproull, *Principles of Interactive Computer Graphics*, McGraw-Hill Book Company, 1973, p. xxii

[7] J.D. Foley, and A. Van Dam, *Fundamentals of Interactive Computer Graphics*, Addison-Wesley Publishing Company, 1982, p. 22.

into an interactive graphical user interface. It used graphical symbols for its input/output and so served as the "ancient" predecessor to the icon-based interfaces developed in the 1980s. The principal developer for the GPDS, Sally C. Bowman, remembers it as the "friendliest system I've ever used."[8]

Another major effort in timesharing sponsored by ARPA was Project MAC. Project MAC began in early 1963. The acronym MAC is derived from its overall research objective, Machine-Aided Cognition, and its major tool, a Multiple-Access Computer. The original proposal to ARPA stated:

> The broad long-term objective of the program is the evolutionary development of a computer system easily and independently accessible to a large number of people and truly flexible and responsive to individual needs. An essential part of this objective is the development of improved input, output and display equipment, of programming aids, of public files and subroutines, and of the overall operational organization of the system.[9]

.ie intent on pursuing the display of information graphically is clearly evident.

MAC was born out of an original timesharing effort on MIT's TX0 computer, an IBM 7090 which was the first transistorized computer. This early effort was moved to the TX2, a larger and more powerful IBM 7094 computer. This system provided the base for the doctoral work of Ivan Sutherland which pioneered interactive computer graphics and for subsequent work by others in three-dimensional interactive graphics.

By July 1964, MAC included the initial model of a multiple display system for computer-aided design, which included the KLUDGE terminal. KLUDGE had an oscilloscope display with a character generator and a light pen and included hardware facilities to rotate images in three dimensions.[10] A more complete discussion of MAC is presented in Volume I, Chapter XIX.

c. Algorithm Development

Developing computer hardware to handle some special needs of interactive graphics was an important effort. More importantly however, was the development of computer software to generate, manipulate, and display the graphics. The hardware, as discussed in

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[8] C. Baum, *The System Builders - The Story of SDC*, System Development Corporation, 1981, p. 92.

[9] R. Fano, "Project MAC," *Encyclopedia of Computer Science and Technology*, 1979, p. 339.

[10] Thornhill, et al., "An Integrated Hardware-Software System for Computer Graphics in Time Sharing," MIT Project MAC, TR-56, Dec 1968.

the last section, provided the platform, but it was the software that "created" interactive computer graphics.

Dr. Ivan E. Sutherland is credited with being the father of modern interactive computer graphics. Dr. Sutherland's doctoral research culminated in the development of *Sketchpad*,[11] which has been heralded as the first software specifically designed to provide a capability to do interactive graphics. Sketchpad was not directly funded by ARPA it was developed on the TX-2 computer running the MAC timesharing system and was done so with the cognizance and enthusiastic concurrence of Dr. Licklider.

From a user-perspective, Sketchpad was exactly what its name implied, a system that "makes it possible for a man and a computer to converse rapidly through the medium of drawings."[12] The system used a light pen to draw line segments which are joined to form polygons. These polygons are then manipulated into regular shapes, stretched, shrunk, moved, or joined with other polygons. Combined with circles and arcs, the system provides a powerful interactive graphics capability for the user.

Dr. Sutherland left MIT after receiving his PhD and succeeded Dr. Licklider to become the second director of IPTO. This is a prime example of the important relationship ARPA had between its project managers and their graduate students. This relationship led to a cohesive and directed effort in the development and promulgation of much of ARPA's early work, in this case interactive graphics. Dr. Sutherland says of his time at ARPA that the ARPA project managers were fully capable scientists themselves; they were not just government bureaucrats. They therefore knew how to communicate what they wanted done and subsequently could understand the research results presented to them.[13]

Following his tenure at ARPA, Dr. Sutherland moved on to the University of Utah in Salt Lake City, Utah, at the request of Dr. David Evans, the Computer Science Department chairman. Dr. Evans was building a department with an impressive group of faculty and was able to recruit talented graduate students. His efforts were rewarded as Utah became recognized as the first ARPA Center of Excellence.[14]

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[11] I.E. Sutherland, "SKETCHPAD: A Man-Machine Graphical Communication System," Doctoral Thesis, MIT Lincoln Lab TR-296, May 1965.

[12] Ibid., p. 1.

[13] From a telephone conversation with Dr. Sutherland, September 1990.

[14] From a telephone conversation with Dr. Evans, November 1990.

3. Follow-on and Related Efforts

Work on interactive graphics under Project MAC continued at MIT throughout the 1960s with ARPA support. As a follow-on to Dr. Sutherland's work with Sketchpad, an advanced version for drawing pictures in three dimensions was produced.[15] Sketchpad III allowed 2-D pictures to assume 3-D characteristics as they were rotated about any of the three axes. This three-dimensional interactive graphics capability became the foundation for surface and solids modelling and eventually led to CAD systems.[16]

At the University of Utah, Dr. Evans was hard at work building his faculty and attracting the talent needed to undertake a variety of projects from ARPA. Dr. Evans fondly recalls that the program at Utah was offbeat and attracted offbeat, but very talented, individuals, such as Alan Kay.[17] Another one of those talented students was John Warnock.[18] Both Dr. Sutherland and Dr. Evans agree that the single most important piece of ARPA-sponsored work at Utah in the area of computer graphics was Warnock's hidden-line algorithm work.[19] When looking at a non-transparent solid object, areas exist that cannot be seen, being merely hidden from view. By rotating the object or by shifting the viewpoint, areas that were previously hidden are now visible and vice versa. The application of this break-through work took graphics out of the laboratory and placed it into everything from CAD to aircraft, seacraft, land, and space vehicle simulators. Even the entertainment industry has applied this technology to video animation.

Kay and Warnock were just two of the many talents that ARPA sponsored at Utah. According to Dr. Evans, other students have gone on to other academic and industry positions where they have continued to pursue interactive graphics.[20]

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[15] T.E. Johnson, "SKETCHPAD III: A Computer Program for Drawing in 3-Dimensions," MIT ESL, ESL-TM-173, June 1963.

[16] S.A. Coons, "Surfaces for Computer Aided Design of Space Forms," MIT Project MAC, TR-41, June 1967.

[17] Kay eventually became a founder of Apple Computers and is generally recognized as a driving force in the development of the personal computer.

[18] Warnock is credited with developing the algorithm that allowed solid-surface depiction and manipulation of objects

[19] S. McAllister, and I. E. Sutherland, "Final Report on the Area Warnock Hidden-Line Algorithm," Evans and Sutherland Computer Corp, Salt Lake City, February, 1970.

[20] Evans, op. cit.

C. APPLICATIONS

ARPA's push for the advancement of computer technology led to the development of architectures of ever-increasing computing power. Over the years, it became evident that the bottleneck in deriving maximum benefit from these powerful computers was in how information was input and output. The birth and promulgation of the field of interactive computer graphics is a direct result of the work and projects undertaken through ARPA support.

Perhaps the best single application of ARPA-funded computer graphics success is in computer-aided design (CAD). Although used for a variety of applications today, DARPA-directed efforts were mostly in the application of CAD for Very Large-Scale Integration Circuits (VLSI). This work is spread among many institutions as testament to DARPA's direction:

- MOSIS - The MOS Implementation System is operated by the Information Sciences Institute of the University of Southern California
- VLSI Design Generators - Northwest University's Laboratory for Integrated Systems.
- High-speed Rendering of 3-D Objects - The University of North Carolina at Chapel Hill.
- SPLASH CAD System - Part of the Wafer-Scale Integration for Strategic Computing Program at MIT's Lincoln Laboratory.
- Berkeley MAGIC CAD Tools - University of California at Berkeley, Electronics Research Laboratory.

In addition to these projects, DARPA also funded hardware development to support graphics, such as the SUN workstation.[21] The goal of the SUN 68000 workstation's graphics subsystem is to provide a high-speed display and high-speed manipulation of raster images. The graphics subsystem solves the problem of high-speed frame buffer updating. The frame buffer is the part of the system memory that is set aside for storing the information that makes up the digital image. By increasing the speed at which this buffer is updated, more real-time type graphics can be achieved.

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[21] See Chapter XVII, "VLSI: Advanced Computer Architecture," in this Volume.

D. OBSERVATIONS ON SUCCESS

The effect DARPA has had on interactive graphics has been both instrumental and substantial. It was mostly achieved through support of academic research programs at such universities as MIT, University of Utah, and Stanford. In essence, interactive graphics was an important element of DARPA's broader programmatic vision in information processing with an emphasis on supporting an infrastructure of basic research capabilities, rather than explicit or specific graphics technologies or systems. The development of interactive graphics in this environment was fostered substantially by the wider range of hardware, software, and microelectronics that DARPA's information science programs enabled. In turn, advances in interactive graphics contributed to such applications as CAD, which improved these other aspects of information processing. Not only did ARPA-sponsored pioneering work promote technology exchange among the government, research institutions, and private industry, but it also has found its way into our transportation, our education, and our workplaces.

XIV. IMAGE UNDERSTANDING

A. BRIEF OVERVIEW

ARPA first began research into the capabilities of machines to duplicate the human cognitive vision and speech processes in the mid-1960s. Early research investigating the roots of human perception (speech and vision) focused on developing a fundamental understanding of each process. Two research efforts were aimed at duplicating human speech and vision capabilities to the extent possible with available computer systems. Image Understanding (IU) which was differentiated by attention to high-level vision became a formal DARPA program in 1975.

The formation of the program established DARPA as one of the principal supporters of vision/image research in the world. DARPA initiated original research, and also provided a purposeful focus to research already underway. Many of the research efforts undertaken as part of the image understanding program were started in conjunction with (in the 1970s) work on the DARPA image processing program, and (in the 1980s) with work associated with artificial intelligence (AI) and the Strategic Computing Program. The concept of image understanding was in its infancy when DARPA became involved, and DARPA served an important function in broadening thinking related to image recognition capabilities of machines and artificial intelligence.[1]

Two important legacies of the DARPA program are discernable. First, DARPA efforts involved funding interdisciplinary research related to IU and as a result, there is a broader base of scientific knowledge and a growing cadre of trained researchers pursuing problems related to IU and its applications.[2] Second, DARPA-funded efforts resulted in

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[1] See Volume I of this report, Chapter XXI, "Artificial Intelligence," pp. 21-6 through 21-18.

[2] Interview with Dr. Azriel Rosenfeld, Director of the University of Maryland's Computer Vision Laboratory, 7 July 1990.

two testbeds,[3] work with the National Science Foundation, and several internal IU program initiatives and technology transfer efforts within DARPA.

The two testbeds were located at the Defense Mapping Agency (DMA), and the Central Intelligence Agency (CIA). The work with the National Science Foundation (NSF) resulted in the generation of new research thrusts and ideas for IU research. The internal program initiatives exposed the "boundaries" between IU and other technologies and applications: between IU and parallel computers; between IU and software development technology; and IU applied to autonomous navigation tasks. In addition, technology was transferred to the Tactical Technology Office (TTO) in DARPA from the IU program to produce an image exploitation applications for the U.S. Army. DARPA supported IU research and technology also were utilized for target recognition research and development programs of the U.S. Army and the U.S. Air Force.

B. TECHNICAL HISTORY

The DARPA image understanding program was a continuation of research efforts that were started either independently or as part of the DARPA image processing program. Research efforts sponsored as part of the image processing program included work in image restoration, encoding for bandwidth compression, and visual systems modelling. Research in image understanding and computer vision are relatively new scientific fields with origins in the multi-spectral sensor programs of the U.S. dating back to the early 1950s.[4] The first experiments in image computer vision were conducted in the late 1950s, with many of the essential concepts of the field being developed in the 1970s and 1980s.

1. Defining Image Understanding

Image understanding has as its end goal to ascertain information about a scene from one or more images. A major focus is on understanding the relationship between objects in the scene. A human is able to interpret the objects in a scene and if the proper context is provided, to determine their relationships. An image understanding system obtains information from images through a combination of hardware and software components.

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[3] The term "testbed" is used to connote that more than the hardware platform was the purpose of the enterprise, rather these efforts encompassed with the hardware, the software and the procedural aspects to establish standards and performance metrics.

[4] Dana H. Ballard and Christopher M. Brown, *Computer Vision*, Prentice-Hall, Inc., 1982, p. xiii.

The IU program currently draws upon a number of scientific disciplines. Each of the circles in Figure 14-1 represents a discipline some portion of which is involved in imagery research. Figure 14-1 provides a theoretical representation of the relationships among the disciplines that are integral to the IU program. DARPA has funded institutions with particular expertise in each of these academic disciplines to contribute to the larger program. The image understanding program has to date focused on specific interpretation or classification problems and attempted to generate solutions based on this interdisciplinary approach.

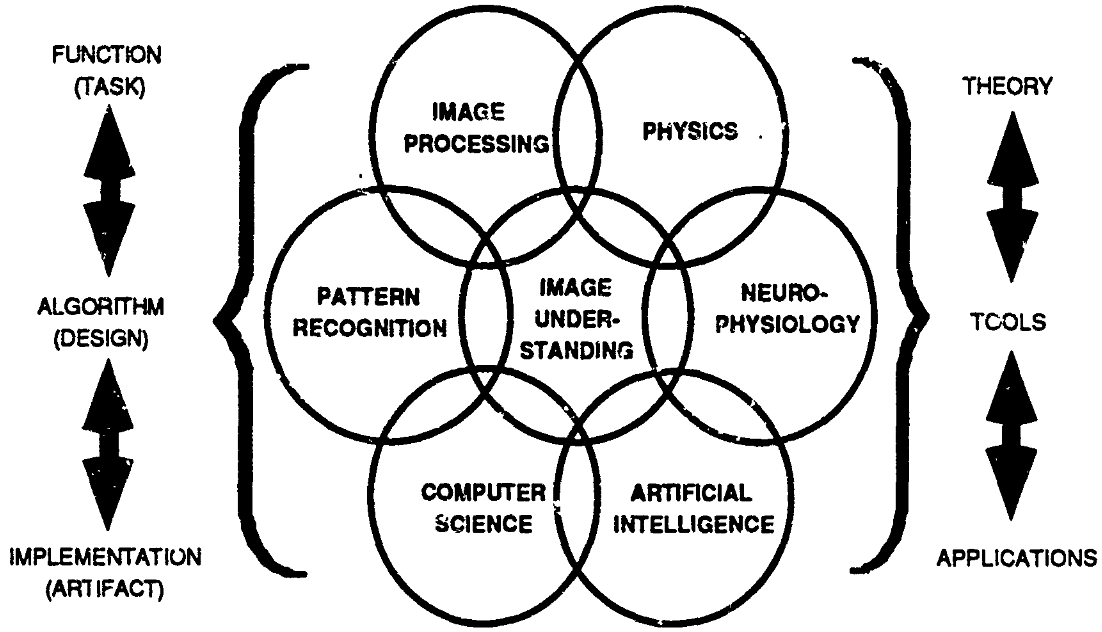

Figure 14-1. Conceptual Model of Image Understanding Program[5]

Subtle but important differences exist between image understanding, image processing or pattern recognition, and artificial intelligence. Image processing may be characterized as image transformation; the encoding and transmission of an image or the processing of an image to yield another image of improved or different qualities. Pattern recognition (in imagery) classifies objects that exist in or are represented by an image often using statistical decision theory applied to general patterns. Artificial intelligence attempts to

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[5] Larry E. Druffel, "Summary of the DARPA Image Understanding Research Program," in J. Kittler, K.S. Fu, and L.F. Pau, eds., *Pattern Recognition Theory and Applications*, D. Reidel Publishing, 1982, pp. 265-281.

simulate the information-processing capabilities of humans (often focussing on cognitive tasks without regard to biological realism).[6]

Image understanding is very different from image processing, which studies image-to-image transformation, not explicit symbolic description building. Such symbolic descriptions are more computationally efficient in recognizing and classifying an object. Image understanding can potentially explain the scene and objects in a processed image using pattern recognition, and can attempt to explain the significance of the information using artificial intelligence techniques of symbolic information-processing. Image understanding applications can be thought of as an agent that integrates image processing, pattern recognition, and artificial intelligence to produce an automated analysis of information from an image.[7]

2. Motivations for Starting the Image Understanding Program

There were a number of motivations for DARPA to form the image understanding program in 1975. The first impetus was prior work performed by the Information Processing Technologies Office (IPTO) in artificial intelligence.[8] At the time, AI research was focusing on providing automated symbolic information processing techniques for military and civilian applications. One example of a project that would foreshadow the IU and computer vision work was a medical application of symbolic reasoning in a project called DENDRAL.[9] This project produced artificial intelligence-aided automated tools to analyze mass spectrograms and nuclear magnetic resonance spectral images.[10] These spectral images where analyzed to reveal the structure of organic molecules to aid in the diagnosis (classification) of lung problems. This project was funded by DARPA, the National Institute of Health (NIH) and the National Aeronautics and Space Administration (NASA). The DENDRAL project was widely considered the first major application of an AI expert system; it made possible the exploration of other applications for AI expert systems to complicated analyses that involved signal-to-symbol transformation plus symbolic reasoning.

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[6] Dana H. Ballard and Christopher M. Brown, *Computer Vision*, Prentice-Hall, Inc., 1982, p. 2.

[7] Druffel, op. cit..

[8] See Volume I of this report, Chapter XXI, "Artificial Intelligence," pp. 21-6 through 21-18.

[9] Ibid.

[10] *The Seeds of Artificial Intelligence*, National Institute of Health, PO-2071, 1980, pp. 18-19.

The artificial intelligence work performed prior to the formation of the image understanding program in 1975 was influenced by pattern recognition and focused on a bottom-up approach to interpretation tasks like DENDRAL. The bottom-up approach uses statistical samples of expected data to define the terms of reference in a pipe-line of successively more restrictive recognition tasks. In a sense, the bottom-up approach builds an *a priori* structure for recognizing its terms of reference from "learned" expectations. An alternative is the top-down approach, which also uses *a priori* expectations represented in a knowledge base. A system based on a top-down approach has a pre-existing set of rules or knowledge to distinguish for example an apple from a tree, or a red apple from a green based on contextual information that may not ever be in any image. The top-down approach is less sensitive to missing or unexpected data. The image understanding program adopted the top-down approach to represent and use symbolic information in addition to or in combination with traditional bottom-up pattern recognition methods. The image understanding program sought to understand how knowledge is gained and utilized in a top-down fashion. This desire by ISTO and the AI community to research and build an *a priori* knowledge base was one of the major impetuses to the beginning of the image understanding program and represents its value added to other computer vision activities.[11]

Other motivations were two independent projects that eventually influenced image understanding efforts undertaken by DARPA. The first was the "hand-eye" project, an informal coordination of research efforts at Stanford University and the Massachusetts Institute of Technology in the late-1960s. The project produced a demonstrator for robotically assembling building blocks. Using a robotic arm and camera eye, this demonstrator assembled and replicated pre-designated block constructions. The hand-eye project dealt only with very simple blocks and shapes. The efforts conducted at both Stanford and MIT were constrained by the limited memory capabilities of the computers available at the time. The hand-eye project was the first attempt to use computer recognition of a three-dimensional object for a purpose, in this case construction/assembly and replication. Although the actual results of this project were limited, it did promote cooperation and coordination of research activity among researchers interested in different aspects of problems for which DARPA was trying to generate solutions.[12]

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[11] Interview with Dr. Robert Simpson, former Image Understanding Program Manager, 1985 to 1990, 11 May, 1990.

[12] Interview with Dr. Azriel Rosenfeld, Director of the University of Maryland's Computer Vision Laboratory, 7 July, 1990.

The second project was the Pattern Information Processing System (PIPS), initiated in the mid-1970s by the National Science Foundation. This was a response to a Japanese effort to develop an advanced speech and vision pattern information processing system. The Japanese effort was extensive, funded at slightly above $100 million. The U.S. response was the first well-funded pattern-information-processing effort. It too was constrained by the computer technology of the time. In retrospect, the type of capability that the U.S. researchers sought required fifth-generation computer architecture in order to be possible. Computer capabilities that would satisfy the requirements of this program were not available until at least ten years after the start of the PIPS project.[13]

An additional motivation to the image understanding program's formation, was the work of Lt. Colonel David Carlstrom, USAF. Carlstrom wanted to start a very long-term program, in the 1960s, which looked at the use of machines to augment human performance. Experts in the field held several symposia sponsored both by DARPA and the academic community to evaluate the potential development and use of the man-machine interface (cybernetics). As a result of these symposia, DARPA funding gave rise to a research community that looked at the components of a man-machine interface such as vision and speech recognition/understanding. The combination of on-going interest in the scientific community in man-machine interfaces, the initial funding of projects to study man-machine components, and the personal involvement of David Carlstrom all provided a significant impetus to start the IU program.[14] DARPA proceeded to fund research efforts aimed at investigating the viability of computer technology for military application, specifically to speech and vision.[15]

The DARPA image processing program also influenced the decision to pursue the image understanding program. DARPA had funded an Image Processing Program from 1966 to 1975. The earlier programs succeeded in pushing image processing technology forward. The original DARPA-sponsored work in image processing was conducted at the University of Southern California, Purdue University, and the University of Utah. These and other universities and other research institutions[16] received contracts to transform

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[13] Ibid.

[14] Lt. Colonel David Carlstrom's early involvement in the field and at DARPA resulted in his becoming the first program manger for the IU program in 1976

[15] See Volume I of this report specifically the discussion on the speech recognition project HEARSAY, Chapter 21, "Artificial Intelligence," pp. 21-6 through 21-18.

[16] Including Stanford, MIT, Carnegie-Mellon, Maryland, Columbia, the University of Rochester, and the Stanford Research Institute.

efforts in image processing research into new efforts investigating possible ways to develop an image understanding capability for use in defense systems.

In the mid-1970s, a three-page letter was sent by Dr. Azriel Rosenfeld of the University of Maryland to Dr. Porter, head of the Image Processing Program at DARPA, proposing an image understanding system and real interest was garnered to start something new. A new and key step took place with the concept of signal-to-symbol mapping. This process borrowed or made use of methods from the AI community (e.g., DENDRAL) to transform signal data into a symbolic data structure. This structure could then be used to infer missing data and to group the data into more abstract structures (e.g., objects). This insight influenced the formation of a group of researchers that was the predecessor of the first DARPA-sponsored Image Understanding Workshop. These investigations provided additional input to the vision and image understanding research program in the mid-1970s.[17]

DARPA initiated the Image Understanding (IU) program to investigate techniques which offered the potential to derive more information from an image and improve our national technical capabilities in image interpretation. Military research laboratories and other DoD agencies also began to study applications of vision/image understanding techniques and to sponsor complementary research. The previous work by DARPA performed in AI knowledge-based systems, DARPA-sponsored symposia on computer vision and cybernics, and DARPA-funded research in image processing all provided powerful stimulus to the formation of the image understanding program in 1975.

3. Formation of the Image Understanding Program

The image understanding program officially began in 1975. The original program was a planned five-year effort covering the period from 1975 to 1980, which has been renewed periodically ever since. DARPA initiated the IU program to investigate techniques which offered the potential to derive information from an image.[18] At the initial workshop of the image understanding program in March 1975, Dr. J.C.R. Licklider, then Director of the Information Processing Techniques Office which sponsored the program, made this observation:

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[17] Simpson, op. cit., 11 May 1990.

[18] Larry E. Druffel, "Summary of the DARPA Image Understanding Research Program," in J. Kittler, K.S. Fu, and L.F. Pau, eds., *Pattern Recognition Theory and Applications*, D. Reidel Publishing, 1982, pp. 265-281.

> The objective (of the image understanding program) will be to develop the technology which can be exploited by the DoD components to solve their specific problems. Thus, the activities that will be supported in the program will not be the engineering of specific solutions to specific problems. The philosophy in the program will be to develop generalized technology by driving research in particular directions. However, at the end of the five year period the technology developed must be in a state in which it can be utilized by the DoD components to solve their specific problems without requiring a significant research effort to figure out how to apply the technology to the specific problems. For this reason, the program must result in a demonstration at the end of the five year period that an important DoD problem has been solved.[19]

Because the research area was so new, program goals remained consistent throughout the late 1970s and early 1980s DARPA retained its preferred, interdisciplinary approach to solving broad, complex problems. Program manager Major Larry Druffel, United States Air Force (USAF), summarized program goals in 1981, and his successor, Lt. Colonel Robert Simpson, USAF, reiterated those same goals in 1985:

> ...to investigate application of a priori knowledge to facilitate an understanding of the relationship among objects in a scene. The appropriate focus is on the word understanding....[The image understanding program] is a catalyst which attempts an integration of many sciences (image processing, pattern recognition computer science, artificial intelligence, neurophysiology, and physics) in search of methods for automatic extraction of information from imagery.[20]

The managers of the IU Program realized from its inception that the goals stated by Dr. Licklider would be difficult to attain. The image understanding program funded research efforts at institutions with demonstrated expertise in the areas depicted in Figure 14-2 below, and the ability to perform research designed to investigate total vision systems. The major accomplishment of the program to date has been research that has more clearly defined the challenges to fielding systems with imbedded image understanding components. There are at least three major areas in which computer assisted image understanding techniques could be beneficial to DoD:

- provide a means of viewing enormous amounts of collected imagery (scanning for alert functions)
- improve the time and pace with which information from imagery can be reviewed (data overload for image analyst)

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[19] Lee S. Baumann, ed., *Seventh Image Understanding: Proceedings of a Workshop held at Cambridge, Massachusetts May 3-4, 1978*. DARPA, p. i-ii.

[20] See Druffel, 1982, *Proceedings: Image Understanding Workshop*, 1981, pp. 2-3; *Proceedings: Image Understanding Workshop*, 1985, pp. i-ii.

- provide capabilities to receive and process information from images in hostile environments (i.e., deep space or deep oceans) (e.g., robotics, etc.).[21]

4. Program Management and Funding

The initial program manager, in 1975, for the image understanding program was Dr. Larry Roberts. From 1976 to 1990 the image understanding program manager's job was filled by a military officer until the tenure of Dr. Rand Waltzman, a student of Dr. Azriel Rosenfeld at the University of Maryland's Computer Vision Laboratory. The program manager from 1976 through 1979 was Lt. Colonel David Carlstrom, USAF. Lt. Colonel David Carlstrom was an electrical engineer from MIT who received his degree under U.S. Air Force sponsorship. The next program manger was Lt. Colonel Larry Druffel, USAF, who held that position from 1979 to 1981. Commander Ron Ohlander, United States Navy, followed Lt. Colonel Larry Druffel, serving as program manager from 1981 to 1985. Cmdr. Ohlander was a former student of Dr. Rej Reddy at Carnegie-Mellon University. Lt. Colonel Robert Simpson (USAF), followed Cmdr. Ron Ohlander and served as program manager in that position from 1985 to 1990, when Dr. Rand Waltzman assumed the position of IU program manager in 1990.[22]

When the image understanding program started in 1975 funding ranged between 2 to 3 million dollars a year. In the mid-1980s, with the advent of the Strategic Computing Program, the budget grew to between 8 and 9 million dollars a year. The funding for the image understanding program came from three primary sources:

(1) the ISTO basic science budget,

(2) the ISTO robotics budget, and

(3) in the mid-1980s, the Strategic Computing Program.

This last period was one of rapid growth. The IU program made a transition from being a scientific research program to one focusing on producing hardware and software testbeds (the bulk of effort was always in software).[23]

In addition, the IU program created and controlled a number of vision tasks undertaken by universities and research institutions. The ARPA orders associated with image understanding or vision testbed components totalled 72 million dollars. This

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[21] Druffel, op. cit.

[22] Simpson, op. cit., 11 May, 1990.

[23] Ibid.

represents the total expenditure of DARPA funds contracted from 1971 to 1985 on vision/image understanding research testbeds. A specific breakdown of some of the budget items by major projects funded by DARPA from 1974 to 1985 in image understanding and computer vision is outlined below in Table 14-1.

Table 14-1. Image Understanding Major Project Commitments: 1974-1985[24]

Selective Project Titles	Commitments	Year
Image Understanding Program	$4,068,333.00	1975/1984
Joint DARPA/DMA Testbed	$1,584,537.00	1974
Cartographic Station (IU System Testbed)	$2,595,081.00	1979
Joint DARPA/CIA Testbed (Pre-Scorpius)	$649,929.00	1982
Automated Cartographic Station (Scorpius)	$1,836,512.00	1985
IU Tech for Autonomous Land Vehicle	$1,125,000.00	1985
Total	$14,454,473.00	

[Dollars as Contracted by ARPA Order/Year When ARPA Order was Originally Signed]

These programs are representative of the contracts awarded to either initiate or to carry on major image understanding program initiatives. The commitment of money to these efforts is representative of the contracted activities in the original and follow-on amendments to the initiating ARPA Orders.

The testbed efforts described in the next section were efforts funded to field test systems and proof-of-concept platforms to implement IU research results in potential military applications. Funding for the joint DARPA/CIA project has continued under the project name RADIUS. In addition, funding is continuing at Carnegie-Mellon (i.e., the NAVLAB) on the further exploration of computer vision and its applications to robots and vehicular movement. The DARPA image understanding program is forecast to receive a substantial level of funding at least through Fiscal Year 1991.

5. Major Programs in Image Understanding

In addition to funding a collection of research efforts organized around the scientific and technical issues in IU, DARPA also coordinated efforts that originated outside the research institutes it funded directly. The Defense Mapping Agency (DMA), the Central Intelligence Agency (CIA), and the National Science Foundation (NSF) continued to fund projects aimed at developing image understanding theory and applications, and DARPA attempted to leverage these interests into joint programs where agency goals were

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[24] ARPA Orders 1974 to 1988.

complementary and synegistic. DARPA conducted several major IU initiatives under the Strategic Computing Program, culminating in the development of the Autonomous Land Vehicle (ALV), the Image Understanding Architecture (a parallel processor hardware design), and the Image Understanding Software Environment. The IU program transferred IU technology that was used by the Tactical Technology Office (TTO) among others at DARPA for image exploitation projects for the U.S. Army and U.S. Air Force. Some of these efforts will be detailed in later sections.

The results of DARPA's image understanding program joint projects are mixed. The Defense Mapping Agency dropped out of its basic technology relationship with DARPA and embarked on its own testbed developmental effort, while DARPA experienced reasonable success coordinating with the CIA and the NSF. DARPA's coordination efforts resulted in many DARPA-funded research institutions maintaining ongoing work with the CIA on photo interpretation projects like SCORPIUS, and a new follow-on thrust, RADIUS.[25] The IU program in the late 1980s also included several universities, independent research institutes, and manufacturers in the development of technologies associated with the Strategic Computing Program's ALV project and related vision-based.

Before the IU program was begun in 1975, each of the sponsored institutions had an established history of research excellence in at least one of the areas listed in Figure 14-2. The IU program funded research efforts at the Carnegie-Mellon University, Columbia University, the University of Maryland, the Massachusetts Institute of Technology, the University of Massachusetts, the University of Rochester, Stanford University, Stanford Research Institute, and the University of Southern California. The National Science Foundation also sponsored some of the early related work that fed into the IU program and recently participated with DARPA on a joint venture outlined in later sections.

Each of these institutions has performed research or development in different aspects of image understanding, as Figure 14-2 indicates. There is some overlap, but for such a decentralized program, minimal duplicative research. This figure provides a history of the major academic and industrial participants and a sampling of their contribution to the IU program since 1975. Most of these institutions participated in the development of the Defense Mapping Agency (DMA), Central Intelligence Agency (CIA) and the Strategic Computing Program's Autonomous Land Vehicle program testbeds, as well as the image

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[25] Simpson, op. cit., 11 May 1990.

understanding program's hardware/software vision system developments DARPA has undertaken in the 1980s.

a. External Image Understanding Joint Efforts

The IU program built a series of demonstration testbed systems to evaluate the maturity of IU technology for automatic mapping, charting, and geodesy functions. While focusing on specific cartographic photo-interpretation functions, the testbed attempted to offer the entire image exploitation community an opportunity to assess the future application of image understanding methodologies to their specific problems. The following section details each testbed produced by DARPA's image understanding program from 1974 to the present.

DARPA/DMA Testbed. Since its inception a major goal of the IU program was to produce applications of critical importance to DoD. DARPA, through several IU workshops, became interested in exploring fundamental computer vision techniques applicable to image-interpretation tasks to transfer to the defense community. To provide a framework for evaluating and demonstrating some of these capabilities, the Defense Mapping Agency (DMA) in conjunction with DARPA, sponsored the establishment of the Image Understanding Testbed facility at the Artificial Intelligence Center of Stanford Research Institute (SRI).[26] The primary purpose of the Image Understanding testbed was to provide a means for technology transfer from DARPA-sponsored IU research programs to DMA and other interested defense organizations. The testbed served as a major vehicle for demonstrating, testing, and evaluating the applicability of IU research and its results to automate cartography and image interpretation tasks.[27]

Many software packages were submitted to the testbed by participants funded by the IU program. These packages were adapted to the SRI format with additional hardware and software utilities as needed. The testbed was supported by an ARPANET[28] network link with network addresses at the Stanford Research Institute's Image Understanding facility and the U.S. Army Engineer Topographic Laboratories Research Institute.

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[26] Andrew J. Hanson, *Installing a Copy of the ARPA/DMA Image Understanding Testbed at the U.S. Army Engineer Topographic Laboratories*, SRI, Menlo Park, Cal., 10 June 1985, pp. 3-6.

[27] Simpson, op. cit., 11 May 1990 and Druffel, op. cit.

[28] See Volume I, Chapter 20, "ARPANET," pp. 20-1 through 20-29.

Institution	Research Focus and Project Involvement
Carnegie-Mellon University	Modelling the physics of perception; vision systems for navigation; color understanding; parallel vision; SAR image understanding
Columbia University	Cooperative efforts with AT&T Bell Labs in low-level stereo; middle level vision research; spatial relations;parallel algorithms; robotics
Hughes Aircraft Company	Photographic interpretation system; demonstratedapplication of research results from Stanford's ACRONYM system, SCORPIUS prime contractor
University of Maryland	Autonomous navigation system; research in motion analysis, stereo and range sensing, 3D shapes; cooperative research with Westinghouse
Massachusetts Institute of Technology	"Hand-Eye" project; representation of early and middlevision; object recognition using MARKOV Random Field paradigm
University of Massachusetts	Basic research in knowledge-based vision, perceptual organization, 3D models, mobile robot navigation, image understanding architecture
University of Rochester	Connectionist implementation of Model-based system for inspection and visual control in repetitive manufacturing tasks; processing of aerialphotographs; installed prototype system at DMA
SRI International	Model-based cartographic vision system which answers queries about overhead images. Prime contractor for DMA testbed.
Stanford University	Developed ACRONYM and follow-on SUCCESSORsystem concept, three- dimensional modelling systems; geometric reasoning
University of Southern California	Mapping from images; robotics vision; motion detection for Autonomous Land Vehicle; parallel processing, 3-D vision

Figure 14-2. Institutions Conducting Research for the IU Program[29]

An automated cartography machine was produced by this joint sponsorship called the MARK 90. This system utilized IU techniques to automate feature analysis in support of cartography. One important feature of this system is the Road Expert. This package was developed by SRI to acquire and track linear features, such as roads, in aerial imagery. The tracking is done automatically in imagery with a known and validated physical features database. Once a road has been identified and tracked, a separate subsystem is available to

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[29] Collected and compiled from several IU workshop proceedings from 1977 to 1988.

analyze road surfaces, markings, and vehicles. The machine was designed to assist mapping, charting, and geodesy production process for DMA.[30]

The DMA utilized about 2 million dollars of its research and development funds in conjunction with DARPA funds. This program quickly outgrew the original scope DARPA and DMA had agreed upon (i.e., joint sponsorship of research and prototype building), resulting in DMA's decision to proceed unilaterally. DMA did not build on the previous DARPA/DMA joint research effort but elected to instead build their own machine which is expected to be delivered sometime in 1990. A copy of the testbed still resides at SRI with another functional copy transferred to DMA branches DMAHTC and DMAAC; to the U.S. Army Engineer Topographic Laboratories Research Institute, at a DMA site in Fort Belvoir, Virginia, in June 1985. The DMA testbed was the first research effort within the IU program to develop a significant DoD application of IU research and technology.

DARPA/CIA Testbeds. Originally, DARPA's IU efforts focused primarily on developing systems to improve the processing of images. This was due in part to the poor quality of the initial data received from space-based overhead assets. As the processing and quality of imagery data improved in the mid-to late-1970s, more emphasis was placed on algorithms and hardware which could automatically detect changes in images over time. With the advent of the IU program in 1975, the task of producing an image recognition system replaced the previous emphasis on image processing. This effort has continued with the availability of new spectral sensors and increased quality of overhead imagery, culminating in a series of testbeds to apply vision research to deal with CIA's photo-interpretation problems. The first of these testbeds was the Image Understanding System (IUS) begun around 1980. Another testbed was produced for the Central Intelligence Agency and DARPA under the SCORPUIS code name in 1985 and the new follow-on RADIUS projects, continue these developments into the 1990s. This project envisioned the use of semi-automated multi-spectral overhead imagery interpretation process to analyze shipping movements in and out of selected ports of interest.

Hughes Aircraft, with support from DARPA and the Office of Naval Research (ONR), conducted research into a series of programs applying research results from DARPA's IU program to military applications. This effort integrated several IU

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[30] Andrew J. Hanson, *Overview of the Image Understanding Testbed*, SRI, Menlo Park, Cal., September 1983, pp. 1-5 and 10.

applications, such as the ACRONYM vision system design.[31] These applications were used as the framework to form an initial IU system design. The goal of this effort was to produce a stand alone automated photo-interpretation workstation testbed. DARPA wanted to test the application of their IU research to a photo interpretation system using real imagery. The CIA was interested in co-sponsoring such a testbed workstation, resulting in joint activities of growing involvement and increased levels of funding throughout the 1980s.

The initial work for this system was based on the ACRONYM vision system developed by Dr. Rod Brooks and Dr. Tom Binford at Stanford University under the image understanding program. ACRONYM is a high-level vision system.[32] Additional modifications were made to this work by Hughes and Dr. Brooks to include low-level vision modules. The ACRONYM vision system was selected because of its sophistication (at the time) and the relative ease with which it could be modified (given the primitive state of IU software development tools).

This project started as the Image Understanding System (IUS) by Hughes Aircraft Company as a test case from 1980 to 1985. Then in 1985, DARPA and the Central Intelligence Agency collaborated on producing an automated image system project, SCORPIUS. The SCORPIUS system attempts to identify objects by matching shapes extracted from digitized images to shapes generated by geometric three-dimensional object models, and information derived from camera angles and illuminating conditions. Using low-level vision, the system identifies areas of interest in each scene. Shapes are extracted from the scene and are compared with pre-determined shapes to find matches with the pre-constructed database. Finally, multiple scenes and objects can be tracked and scripted to provided additional insight on the object's identification and predict future behavior.[33]

It is hoped that this testbed or its derivative could aid or replace a photo-interpreter with an automated workstation, which could detect changes in images over time. A test of the SCORPIUS system was conducted using 100 images of ports and associated assets. The workstation recognized maritime objects and attempted to track their changes through several images taken at different times and slant angles.

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[31] G.R. Edwards, *Image Understanding Application Project: Implementation Progress Report*, August 1983, p. 156

[32] Ibid.

[33] Ibid.

This effort has proven difficult, but since 1980 a substantive effort has been underway with the CIA to provide a solution. However, the effort culminated in the production of an end-to-end automated imagery workstation. This was the first large-scale attempt at producing such an automated imagery workstation. This demonstration was successful, but the application of the technology to operational needs was not undertaken. It was felt that a man-in-the-loop between the workstation and the finished product was required. Based on the new requirement and the relative success of SCORPIUS, a new thrust was undertaken in 1990 with project RADIUS.

RADIUS will develop, based on the accomplishments of the SCORPIUS project, a man-in-the-loop imagery workstation, thus moving away from the autonomous automated imagery workstation concept attempted by project SCORPIUS. The ultimate goal of the DARPA effort in this field is to produce an automated real-time multi-spectral image workstation to identify significant changes over long-periods of time in imagery data with little or no human interaction.[34]

DARPA/NSF Joint Effort. DARPA and NSF co-sponsored an effort to generate new and innovative proposals on computer vision and image understanding research to supplement the IU program. DARPA provided half the money and the NSF the other half and each agency reviewed and selected the winning proposals. Over 40 proposals were received, these were peer reviewed by NSF and 8 finalists were judged to be qualified bidders. Of the 8 finalists, 3 research efforts were selected by DARPA based on their relative addition on complementary relationships to the other IU activities.

b. Internal DARPA Image Understanding IU Initiatives

DARPA has conducted several major computer vision initiatives under the overall umbrella of the Strategic Computing Program culminating in the development of the Autonomous Land Vehicle (ALV), the Image Understanding Architecture (IUA), and the Image Understanding Software Environment. The IU program also transferred IU technology that was used by the the Tactical Technology Office (TTO) at DARPA for image exploitation projects for the U.S. Army and U.S. Air Force. The next sections will detail each initiative conducted by DARPA's image understanding program to extend the image understanding program's basic computer vision/image understanding tools, architectures, and applications.

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[34] Interviews with Dr. Robert Simpson on 5 May 1993.

Autonomous Land Vehicle and the Strategic Computing Program. The overall goal of DARPA's IU program within the Strategic Computing Program was to demonstrate application of the technology to critical problems in the defense community. DARPA's activities in the Strategic Computing Program have been geared toward producing capabilities far greater than those demonstrated by present computer-based systems. One specific military application area targeted by DARPA for initial technology demonstration was the area of autonomous navigation as exemplified by the Autonomous Land Vehicle (ALV). In this program DARPA attempted to demonstrate artificial intelligence and computer vision techniques applied within an eight wheel autonomous land vehicle testbed using imagery obtained from multiple sensors to determine possible routes for on or off road navigation.

The Computer Vision Laboratory at the University of Maryland and twelve other image understanding research institutions were major participants in DARPA's Strategic Computing Program. The Computer Vision Laboratory developed one of several prototype computer vision systems for autonomous ground navigation of roads and road networks. The complete vision system runs on a VAX 11/785 with certain portions running on a VICOM image processing system, the entire prototype system was eventually transferred and demonstrated on the ALV testbed at Martin Marietta in Denver, Colorado.[35]

Recognition is a major goal in almost all computer vision applications. What does it mean to recognize an object? Does it require a thorough description? These questions point out the fact that vision is always task dependent and that the vision component of a system is conditioned by these tasks. The ALV's application of vision must distinguish a bush from a rock or a large obstruction, so that the ALV can determine whether the vehicle should stop or continue on. Seeing an object and inferring the impact on task accomplishment is a vision problem, it is a processing problem to communicate what that object is. Recognizing or identifying that object and inferring the impact on task accomplishment is an image understanding problem. The IU program deals with the image understanding problem and deals with the latter two only as needed to solve the IU problem.

Computer vision was only one component of the ALV. Before inclusion in the ALV program, computer vision was often a stand alone effort which was not coupled to any particular application or system context. The ALV project made available an application

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[35] Larry S. Davis and Todd R. Kushner, "Road Boundary Detection for the Autonomous Vehicle Navigation," *SPIE*, Vol. 579, 1985, p. 362.

platform testbed. As such, computer vision was an important but not the sole focus of the ALV program. As noted by Dr. Clinton W. Kelly III, at the time head of the Strategic Computing Program, the ALV was chosen as a demonstrator because it offers "a strong pull for vision and image understanding technology" rather than a near-term military requirement.[36] This collaboration helped to resolve how the ALV would receive and process information. Before the ALV project, the vision program had centered on defining the terms and building a lexicon to discuss the mechanics of vision and image understanding. The ALV was one of the first real tests of IU techniques in practice.

While many in the scientific community viewed the ALV effort as overly ambitious and premature relative to the state of image understanding in the early 1980s, Cmdr. Ron Ohlander wanted to push the technology to force complexities within the vision problem in autonomous navigation to surface.[37] Building and experimenting on an integrated ALV testbed would point out shortcomings in the scientific processes and would push the state of the art forward in a focussed way.

The ALV testbed as a project within the Strategic Computing Program has been suspended. It ultimately suffered from the fact that the national customer, the U.S. Army, had not yet established a requirement for robotic vehicles. But, thanks to the ALV and other robotics projects, that is changing. However, as noted by Kelly in 1985, the work performed by the University of Maryland's Computer Vision Laboratory in their ability to work effectively with ALV prime Martin Marietta and others made the ALV program more effective. Kelly also stated "...that these university-industry teams will become the hallmark for our applications program because they offer a useful mechanism for providing on-the-job training of graduate students,"[38] in artificial intelligence and vision research. Autonomous navigation is still a major target and research area in the Strategic Computing Program at DARPA. Work is still being performed in the Navigation Laboratory (NAVLAB) at Carnegie-Mellon University, continuing research into areas not pursued by the ALV project.

Image Understanding Architecture (IUA). The Image Understanding Architecture (IUA) project, also sponsored by the Strategic Computing Program, was

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[36] "DARPA Envisions New Generation of Machine Intelligence Technology," *Aviation Week & Space Technology*, Vol. 122 No, 16, April 22, 1985, p. 46.

[37] Simpson, op. cit., 5 May 1990.

[38] "DARPA Envisions New Generation of Machine Intelligence Technology," *Aviation Week & Space Technology*, Vol. 122 No, 16, April 22, 1985, p. 46.

broken into two parallel efforts, the establishment of a conceptual vision system and the testing of vision systems against existing computer hardware. The first phase was development of an IUA conceptual vision system. The IUA effort establishes the "pyramid" philosophy on which vision systems would be designed utilizing iconics, symbolics, and knowledge based constructions.[39] This first phase involved the entire IU community and represented a major effort by the IU community to define the next generation IU vision system's processes, methodologies, and designs.

The second phase involved analyzing existing computer hardware against a complete vision systems benchmark to provide the IU community comparative hardware performance using a completed end-to-end vision system. The University of Maryland and others defined a set of low- and intermediate-level basic vision tasks to properly evaluate the parallel computer architectures. The benchmark was intended to achieve an initial understanding of the benefits to end-to-end vision applications of the growing number of parallel computer architectures and to provided a metric for future development of computer hardware to support the IU research program.[40]

This activity was a two-year effort. The first benchmark work was deemed a success by outsiders and participants alike. A second benchmark based on the expe   ce of the first benchmark has been defined by the University of Maryland and the University of Massachusetts. The University of Massachusetts, using these benchmarks, refined their original design of an Image Understanding Architecture System.[41] Computers included in the benchmark test were the BUTTERFLY Parallel Processor machine by Bolt Beranek and Newman (BBN), the ENCORE MULTIMAX by the Encore Computer Corporation, the CUBE and MOSAIK by California Institute for Technology, the WARP Programmable Systolic Array Processor at Carnegie-Mellon (CMU), the Columbia NON-VON, Thinking Machines' CONNECTION MACHINE, and the Image Understanding Architecture, a machine defined by the University of Massachusetts and built by Hughes Research Laboratories.[42] The results of the second image understanding benchmark resulted in

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[39] Interview with Chip Weems, researcher at the Computer Vision Laboratory at the University of Massachusetts, on 7 December 1990.

[40] Weems, ibid.

[41] *Image Understanding Architecture Project: Second Annual Report*, University of Massachusetts, March 1989, p. ii.

[42] A. Krikelis and R. M. Lea, "Performance of the ASP on the DARPA Architecture Benchmark," *IEEE* , 2/89, 1988, pp. 483 and 485-6.

CMU's WARP machine's meeting and in some cases exceeding the benchmark.[43] The IUA project represented a tiny fraction of the new projects initiated by the IU program in the late-1980s and will likely continue into the early-1990s.

Image Understanding Software Environment. One of the many challenges to the development of advanced vision applications using IU technology is the specific software engineering problems associated with vision software. The Image Understanding Software Environments is a portion of the IU program which is developing special software development environments that can be used to quickly prototype, test, and customize image understanding vision system applications. The specifications for a software development environment are currently being defined by the entire IU community. The intent is to develop within this environment a standard whereby software can be transferred from researcher to researcher and from researcher to developer in a quick and complete format. A first generation attempt at such a standard was undertaken by the University of Massachusetts and Amerinex Artificial Intelligence, Inc., using a software environment called KBVision. Two other prototype IU environments previously developed are: (1) PowerVision by Advanced Decision Systems (ADS), and (2) Cartographic Modeling Environment by SRI international. The components of this research, to take place in the 1990s, are to define an IU software standard utilizing existing research coupled with new efforts. The Intelligent Integrated Interactive Image Understanding System (I^4U) is a major example application program to start off the next phases of vision research and image understanding architectures in the 1990s and will be used as a testbed for the next generation software development environment for vision system applications.[44]

Transfer of Technology from IU to TTO: The Advanced Digital Radar Imagery Exploitation System (ADRIES) and the Image Exploitation System (IES). The most recent application of IU techniques and research is the Image Exploitation System (IES). This program began as the Advanced Digital Radar Imagery Exploitation System (ADRIES). The goal of the ADRIES program was to reduce the false alarm rate in radar imagery while improving the detection threshold of vehicles in a given terrain setting using IU developed decision theories. This program began in 1984 and lasted until 1988. The funding for this program was provided by the Tactical Technology Office (TTO) at

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[43] Weems, op. cit., 7 December 1990.

[44] Ibid.

DARPA and the U.S. Army's Engineer Topographic Laboratories (ETL) under the Strategic Computing Program.[45]

The ADRIES program was redirected in 1988 and renamed the Image Exploitation System (IES). The program was redirected to broaden its input to include multi-spectral imagery, not just radar. The IES is the most advanced fielded application of IU technology, research, and techniques performed to date. The system processes both low and high resolution imagery for use by the U.S. Army in surveillance and targeting of enemy ground forces. The system uses an expert system, which uses terrain databases and military tactics knowledge to smartly filter collected radar imagery providing data on inferred enemy vehicle concentrations and movements.

The expert system uses this data to generate alternative hypotheses based on the likelihood of vehicle detections being real or false alarms. If more information is required the software tasks the collection systems to produce more confirming information before making a decision. The software system models much of the human decision process. Inquiry workload is distributed by the software among tightly coupled and distributed processing engines, such as the CONNECTION MACHINE, the ENCORE machine, and SUN workstations.

Decisions are made on a probablistic basis, using a Baysian probability model to produce a rational basis for decisions. Older methods using pattern recognition and image processing techniques to detect vehicles have a 70 to 80 percent detection threshold and a high false alarm rate. At the battalion or higher organizational levels the IES is able to detect 100 percent of the targets with an extremely low false alarm rate.

The IES uses model-based reasoning, image registration methods, and terrain reasoning, techniques which were researched and developed by the DARPA image understanding and AI programs.[46] Currently, the IES platform is one of the U.S. Army's top five research and development projects to be fielded in Fiscal Year 1991. A new expert system is currently being constructed for Middle Eastern terrain, military operations, and tactics for use by the U.S. Army in Operation Desert Shield. The Image Exploitation System was developed by Advanced Decision Systems (ADS), Science Applications

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[45] Interview with Tod Levitt of Advanced Decision Systems (ADS) on 6 December 1990.

[46] Ibid.

International Corporation (SAIC), and the MRJ Corporation. The total funding for the two programs from 1984 to present is approximately 25 million dollars.[47]

Past, Present, Future of the Image Understanding Program. The future direction as well as a historical summary of projects conducted by DARPA's image understanding research efforts are illustrated by Figure 14-3. As shown, DARPA plans in the future to improve the three areas of low- through high-level vision: (1) computational theory of shape recovery--to include stereo and real-time vision capabilities, (2) model-based vision systems--to include fully automated cartography systems, automatic target recognition systems and the development of a "vision-based language," and (3) commercial vision systems--to include the practical uses of 3-D sensing and the fully automated inspection of machine parts. These programs represent the major areas of emphasis in DARPA's image understanding program through the mid-1990s. These efforts show DARPA's commitment to field significant vision applications in the mid to late-1990s.

Image understanding technology has a limitless range of possible applications. Potential military applications include:

- Image to map registration
- Photo interpretation for both intelligence functions and cartography
- Target cueing
- Passive navigation
- Remote sensing
- Bandwidth compression.[48]

Image understanding technologies will have wide application in the civilian world as well. Possible applications include:

- Use in automated manufacturing
- Multiple applications in robotics
- Cell biology
- Automated cartography.

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[47] Ibid.

[48] Druffel, op. cit.

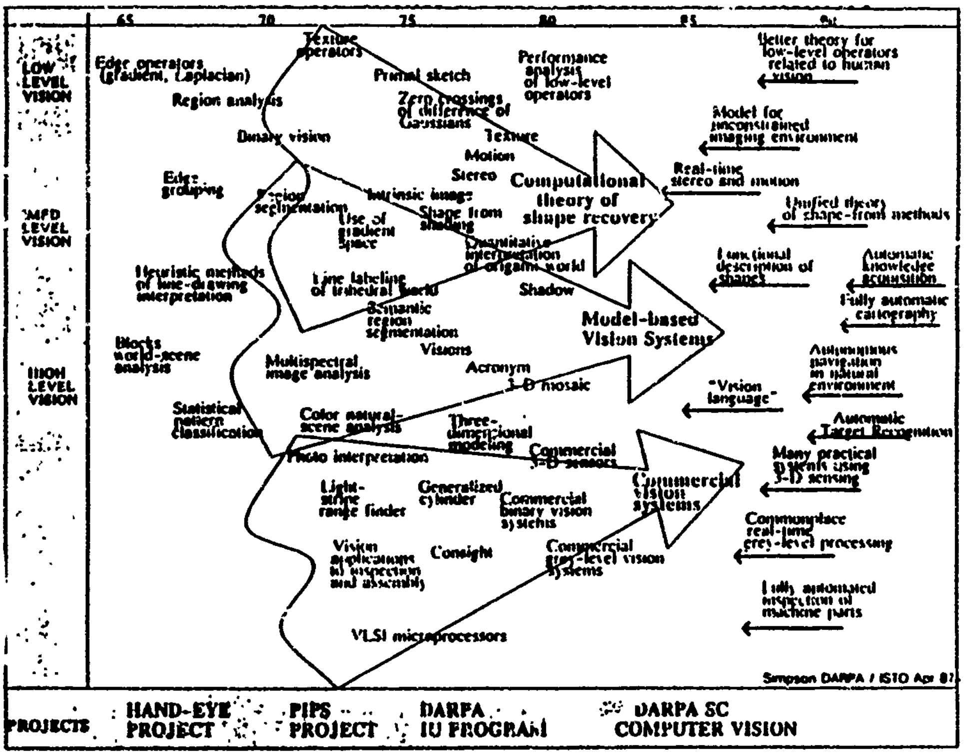

Figure 14-3. Past, Present and Future Research Thrusts of DARPA IU Program[49]

C. OBSERVATIONS ON SUCCESS

DARPA's persistent funding of IU research has supported a coordinated, broad based, multi-disciplinary research effort that promises to deliver image understanding systems for important military and civilian applications. Much like artificial intelligence, image understanding is essentially an ambitious objective to achieve new capabilities through technology advances. Without DARPA support, current knowledge associated with image understanding, voice recognition, and pattern recognition would be diminished.

DARPA has promoted and expanded upon a field which is new and growing. DARPA has sponsored IU Workshops and built a cadre of researchers and manufacturers to continue the long path toward significant application. DARPA funding fostered a special

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[49] Chart provided and produced by Dr. Robert Simpson. This chart was produced for ISTO in April 1987 as an overview.

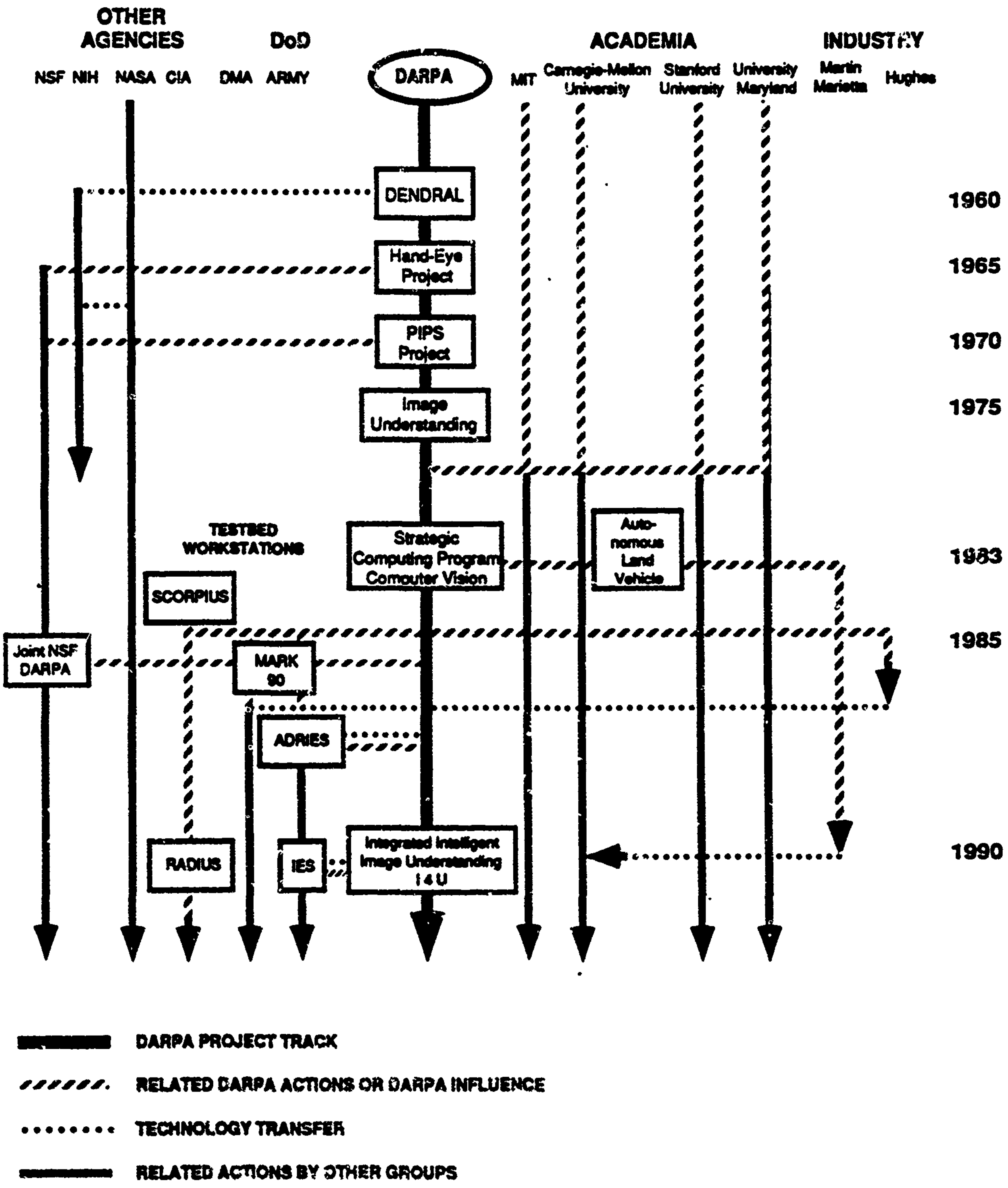
body of knowledge and expertise in the vision and IU research. In a sense, DARPA created the critical research mass in vision and image understanding.

The IU Program has begun to move from scientific research and infrastructure building into exploratory development. In its joint programs with DMA, CIA, NSF and the Strategic Computing Initiative's ALV, the IU Program has applied new IU developments to specific military problems. While some have thought it to be premature to look at actual applications of IU research, both past IU program managers and DARPA Directors have stressed the importance of pushing technology to force complexities within emerging technology areas, such as image understanding to surface new problems and areas of exploration. Building testbeds has pointed out shortcomings in current knowledge and pushed the state of the art forward.

The goals and milestones set up for this program have proven to be ambitious since its inception in 1975. This is in part due to the computational limits of the computers available at the time of its birth and the over-optimistic belief that common three-dimensional images could be recognized easily with the available equipment and algorithms. This initial over-optimistic approach plagued several of DARPA's early vision efforts. Throughout the course of the IU program, the computer technology available to researchers often limited their ability to produce direct military applications. This concern was a major driver of DARPA's strong push for advanced computing capabilities in the Strategic Computing Program, particularly the massively parallel machines. It was not until the late-1980s that computer technology had sufficient speed and memory to enable some image understanding programs to work under approximate time constraints.

In short, the IU program has accomplished much in the 15 years of its existence in basic scientific exploration, but has had less notable success in applying its research findings toward fielding significant military applications for DoD. Image understanding is an on-going research program which may pay significant dividends in the next decade. Already some specific operational systems are in the process of being fielded.

IMAGE UNDERSTANDING



XV. ADA

A. BRIEF OVERVIEW

During the early 1970s, a growing interest was being expressed by top management at DoD in a strategy for overcoming technical and cost problems associated with the proliferation of programming languages used in embedded computer systems (ECS). Part of the reason for this interest was the potential for savings of $1 billion or more a year in the cost of software development and maintenance if a common language were adopted. DoD commissioned studies pointed to ECS software as a major reason behind escalating procurement costs. In addition, hundreds of languages and their dialects were being used by the Defense Department and its vendors, making it virtually impossible to interchange software programs and personnel, and seriously affecting system interoperability.

Air Force Lt. Col. William Whitaker was assigned by the Director of Defense Research and Engineering (DDR&E) to chair an inter-service and inter-agency working group to lay the plans for and oversee the development of a common higher order programming language. Successive drafts of a requirements document for a high-level language were widely circulated for review and critique by programmers and computer scientists at home and abroad. DARPA was given the responsibility in 1977 to issue an RFP for the design, development, and testing of the common programming language that was in 1979 to become known as Ada. Cii-Honeywell Bull won the competitive award for Ada development. The focus of the overall program was not only on building a common language but on designing a support environment that would facilitate the spread and adoption of Ada. Until the advent of Ada, no programming language had ever been systematically planned and built from the top down. Ada was approved as an ANSI standard in 1983, and the International Organization for Standardization (ISO) adopted the existing standard in 1987.

With OSD's guidance and DARPA's leadership, Ada has achieved several important milestones: widespread agreement on its basic design; ANSI and ISO standardization; validated compilers; and an increasing number of Ada-trained programmers. Pockets of resistance still exist, however. While DoD has mandated that all its projects adopt Ada, some have obtained waivers from this requirement. However, DoD is increasingly reluctant to grant waivers, and Ada is becoming the most prevalent language for DoD systems software development. Moreover, an increasing number of domestic and foreign companies, as well as several government agencies, have begun to adopt Ada because of its productivity improvement and potential cost savings.

B. TECHNICAL HISTORY

In the early 1970's, DoD officials began to recognize that serious problems existed in their development and acquisition of weapon system software. Missile system operators, submarine commanders, AWACS pilots, and fleet admirals all had become dependent upon computer software to carry out their assigned duties.[1] Over 450 different program languages and dialects were being used to run embedded computer systems (ECS).[2] A special task force within DoD studying ADP cost trends[3] found that far too much effort and expense was being invested in the development, maintenance, and updating of weapons system software. A series of DoD-sponsored independent studies[4] confirmed that each of the services shared a common programming language requirement and that substantial benefits could be derived from "tri-service cooperation and DoD-wide standards."[5] Software savings of between $100 million and $1 billion a year could be

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[1] B.C. DeRose, "An Introspective Analysis of DoD Weapon System Software Management," *Defense Management Journal*, Vol. 2, No. 4, October, 1975, p. 2.

[2] The phrase "embedded computer systems" is used to describe computers that play a key role in larger systems (e.g., a tactical weapon) whose primary function is not computation. Incorporated into the ECS is support software that may require up to 100,000 lines of code. Such programs must be reliable, long-lived, modifiable (to accommodate evolving system requirements), and able to operate under demanding conditions.

[3] See, for example, D.A. Fisher, *Automatic Data Processing Costs in the Defense Department*, IDA Paper 1046, October 1974, pp. 1-68. See also J.H. Manley, "Embedded Computers--Software Cost Considerations," *AFIPS Conference Proceedings*, Vol. 41, 1974, NCC, pp. 343-347.

[4] In December of 1974, the Office of the Assistant Secretary of Defense (Installations and Logistics) funded a two-phased software acquisition study program to identify methods for controlling costs and improving the quality of software in weapon systems. The MITRE Corporation and Johns Hopkins University's Applied Physics Laboratory were asked to conduct separate but coordinated studies. See: A. Asch, et al., *DoD Weapon Systems Software Acquisition and Management Study, Vol. I.* MITRE Corp., MTR 6908, May, 1975, pp. 1.1 - 4.5; and A. Kossiakoff, et al., *DoD Weapon Systems Software Management Study*, Johns Hopkins University, June, 1975, pp. 1.1-8.3.

[5] W.E. Carlson, "Ada: A Promising Beginning," *Computer*, Vol. 14, No. 6, June, 1981, p. 14.

achieved if DoD were able to persuade the Services and their vendors to adopt a common programming language to meet their needs.[6]

The absence of an ECS language standard for use in military systems had resulted in a proliferation of new languages or the extension of old languages in nonstandard ways. Operators and maintenance personnel were constantly being retrained to handle modified software requirements. The edge enjoyed by an original vendor's software often overshadowed potential competitors when equipment upgrades were contemplated. The reliability of system software was being questioned, and costs were mushrooming.[7]

Lack of ECS programming language commonality had led to costly investment for each separate language, their translators, and their associated software support tools. Widely diffused expenditures for support and maintenance software had resulted in the development of only primitive programmer aids. Information exchanges among DoD software practitioners were limited by the diversity of languages being employed. It was thought this investment could be focused with much greater effectiveness if greater commonality were achieved. This "Tower of Babel" effect had been avoided by the adoption of COBOL as the language of choice for ADP applications and FORTRAN for most scientific applications within the Defense Department. The next challenge was to significantly reduce the number of general-purpose programming languages used in ECS throughout DoD.[8]

In December 1974, the Assistant Secretary of Defense (Installations and Logistics), the Comptroller, and the Director of Defense Research and Engineering (DDR&E) jointly sponsored the establishment of the Office of the Secretary of Defense/Service Weapon System Software Management Steering Committee whose charge it was to develop a "comprehensive and integrated solution to the problem of weapon system computer resource acquisition, management and use."[9] Shortly after its formation, the committee

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[6] B.W. Boehm et al., *Information Processing/Data Automation Implication of Air Force Command and Control Requirements in the 1980s (CCIP-85)*, Vol. 1, Highlights (Revised Edition), February 1972.

[7] In his opening remarks at a conference convened by DoD on the high cost of software, Bruce Ward said "We are here because software costs too much and doesn't work well enough." *Proceedings of a Symposium on the High Cost of Software*, Naval Postgraduate School, Monterey, California, September 1973.

[8] D.A. Fisher, "Introduction," in G. Goos and J. Hartmanis, eds., *Lecture Notes in Computer Science: Design and Implementation of Programming Languages*, Springer-Verlag, No. 54, 1976, p. 2.

[9] De Rose, 1975, ibid., p.4.

issued a statement of proposed principles that later became DoD Directive 5000.29.[10] The directive recommended that the Defense Department "develop coordinated embedded computer systems software engineering methodology and discipline to improve the quality of software and provide for the effective management control of its development."[11] The Management Steering Committee subsumed the on-going DDR&E program by requesting that a single, powerful, high-level programming language be developed and adopted by all ECS suppliers. By 1975, DoD had begun the process of designing the language that was later to become known as Ada.[12]

Lt. Col. William Whitaker, who at that time was serving as Military Assistant for Research in DDR&E,[13] initiated an investigation of whether a single high-level programming language could meet the needs of all of the Services. With the backing of the Assistant Director of DR&E, George Heilmeier,[14] in January 1975 Whitaker formed the Higher Order Language Working Group (HOLWG), under the Management Steering Committee, as an inter-Service committee whose role would be to set policy and oversee the development of the program. HOLWG was comprised of representatives from the Army, Air Force, Navy, Marines, Defense Communication Agency (DCA), NSA, DARPA, and other offices within DoD. Whitaker was its chairman, HOLWG's primary mission was to clarify and recommend solutions to DoD's language problems.

A second key actor in the evolving common language initiative was Dr. David Fisher then of the Institute for Defense Analyses. Already noted for his work at Carnegie Mellon University on computer language control structures, Fisher joined IDA in 1972 and was immediately tasked to assist Heilmeier and Whitaker in their pursuit of a higher order programming language.[15] Shortly after joining IDA, he authored a report analyzing ADP

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[10] Department of Defense Directive 5000.29, "Management of Computer Resources in Major Defense Systems," April 26, 1976.

[11] Ibid, p. 7.

[12] Ada was named after Augusta Ada Byron, the daughter of the English poet, Lord Byron. She is credited with being the world's first computer programmer. She was a close associate of Charles Babbage, the inventor of the first computer. Miss Byron developed the initial software for Babbage's "analytic engine," circa 1830.

[13] J.E. Sammet, "Why ADA is Not Just Another Programming Language," *Communications of the ACM*, Vol. 29, No 8, August 1986, p. 723.

[14] Discussion with G. Heilmeier, 1990. Heilmeier's hope was to narrow the field from 450 languages down to three or four. In 1975, he was appointed director of DARPA and took Whitaker with him as his special assistant.

[15] Discussion with D. Fisher, 1990.

costs in DoD and, in Appendix A of that document, suggested how a common programming language might be structured.[16] Fisher became the group's technical advisor.[17]

Whitaker became the "driving force of the HOLWG...the father of Ada."[18] While he had a clear vision of a common language product, he was also a pragmatist; he realized that his vision did not necessarily guarantee acceptance of the product throughout the bureaucracy. Strong political support would be necessary to accomplish that task. With this in mind, he used his strong personality to gather others within the Pentagon to his side.[19] At each critical stage in the project, key Defense officials were asked to endorse or mandate the concept of a commonly used HOL.

Whitaker continued to recruit supporters for the product when he moved to DARPA with Heilmeier, when Heilmeier became Director of DARPA later in 1975. By this time, Whitaker had already developed a strategy for designing and testing a common HOL, and then creating a market for it. The first step in realizing that objective was the creation of HOLWG. It provided synergy to the common language effort by bringing together a diversity of resource persons and by coordinating their efforts. Coordination was the HOLWG's major function; the technical work itself was done by Whitaker, Fisher, and Phil Weatherall, a programming expert on loan to DoD from Great Britain.[20] The representatives were carefully selected for their technical and organizational skills; the group itself provided advice and counsel to on-going projects. HOLWG's initial effort was to urge USDRE to issue a memorandum that no more money be spent to develop new programming languages in support of major defense systems.[21]

Heilmeier recounts that he brought the Ada development effort with him to DARPA in 1975 because, unless either he or Whitaker watched over it "the Ada effort would have

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[16] D.A. Fisher, "Automatic Data Processing Costs in the Defense Department," Institute for Defense Analyses, Paper P-1046, AD-A004841, October 1974.

[17] D.A. Fisher, "DoD Common Programming Language Effort," *Computer*, Vol 11, No. 3, March, 1978, pp. 24-33.

[18] Discussion with J.F. Kramer, December 1989.

[19] Discussion with D.A. Fisher, May 1990.

[20] Discussion with W.A. Whitaker, August 1990.

[21] Malcolm R. Currie, "DoD Higher Order Programming Language," Memorandum issued by Director, Defense Research and Engineering, January 28, 1975.

died in DDR&E."[22] He noted that "at the time, the Ada program was completely out of character for DARPA, but DARPA today is doing more projects like Ada."[23]

Shortly after HOLWG's formation, Malcolm Currie, the DDR&E, signed DoD Directive 5000.29 announcing the common language project.[24] It was the first in a series of directives that provided the necessary support to insure the continuity and integrity of the program through three different administrations.

To justify the undertaking of such a comprehensive common language effort, Whitaker and other project insiders realized that an economic rationale was needed. The studies cited earlier provided the necessary support: a common language would help stem the proliferation problem and, at the same time, save hundreds of millions of dollars.[25] Since ECS accounted for most of the money DoD was spending on software,[26] the potential economic benefit to be derived from standardization was significant. Whitaker realized this, and the ECS focus became part of his procurement strategy for common language products.

1. Requirements Specification

HOLWG's next step was to issue a set of requirements. All the requirements documents were generated by HOLWG, with much of the detailed writing and editing done by Fisher at IDA.[27] These requirements would become the basis for language design and standardization suitable for embedded computer applications. The standardization requirements largely addressed technical issues. These included language simplicity and completeness, program reliability and correctness, maintainability and portability, real-time programming, strong data typing, and error handling.[28] Certain requirements were added to specifically satisfy different user communities (e.g., avionics, and command and control) though they were also applicable to more general usage.[29] While different

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[22] Discussion with G. Heilmeier, October 29, 1990.

[23] Ibid.

[24] Department of Defense Directive 5000.29, "Management of Computer Resources in Major Defense System," April 26, 1976.

[25] Boehm, op. cit.

[26] Carlson, op. cit., p. 14.

[27] Discussion with S. Squires, November 1985.

[28] N. Gehani, *Ada: An Advanced Introduction*, 1974, Prentice-Hall, Inc., Englewood Cliffs, 1983.

[29] Fisher, op. cit.

communities favored different language approaches, it was later determined that these differences were more preferential than technical.

In 1976, a conference at Cornell University was convened involving 62 knowledgeable computer scientists from academia, industry and the military. Sponsored by the Computer Systems Commands of the Army, Navy, and Air Force, some of the delegates argued that the existing languages being used by DoD satisfied less than 75% of the extensive requirements identified by the conferees.[30] Opponents used this as a criticism of the common language approach. They felt that it would be too difficult, expensive and time-consuming to develop a language that would satisfy all of DoD's needs. It was agreed that these concerns should be put aside until further evidence could be gathered, and the requirements documents initially authored by Fisher, were circulated for public comment.[31]

"Strawman" was the first of a series of requirements documents. It was reviewed by domestic and international groups, both public and private, including the U.S. Armed Forces, foreign military organizations, industrial organizations, and universities. Feedback led to subsequent requirements[32] which were named according to their level of completeness and finality: Woodenman, Tinman, Ironman, Ironman Revised, and finally Steelman. The widespread review of the requirements documents exemplifies the capacity of HOLWG to bring together and utilize the available information resources possessed by knowledgeable individuals worldwide. Sammet observes: "The importance and uniqueness of this process of producing requirements, evaluating them, based on public commentary, revising them, and then repeating the cycle is often underestimated....In Ada's development, however, the language design occurred only after numerous refinements to the requirements had been made."[33]

Twenty-three languages were evaluated against the "Tinman" requirements by 16 organizations and companies. None of the languages met all of the requirements. However, the evaluation did conclude that a single language could be developed that would

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[30] G. Goos and J. Hartmanis, eds., *Lecture Notes in Computer Science: Design and Implementation of Programming Languages*, Springer-Verlag, No. 54, 1976.

[31] Carlson, 1981, op. cit.

[32] D.A. Fisher, "WOODENMAN - Set of Criteria and Needed Characteristics for a Common DoD High Order Programming Language," IDA, Working Paper, August 13, 1975.

[33] Sammet, op. cit., p. 723.

meet the "Tinman" specifications.[34] In November 1976, an interim list of seven DoD-approved HOLs was published.[35] The approved languages were not considered to be the final solutions to the DoD's language needs. The directive acknowledged that the languages were the most widely used at that time and that the most cost-effective approach was to: a) improve the support for those languages; b) ban the use of other languages until a new language was proven to offer significant advantages; and c) focus all language development resources on the development of a single language based on the "Tinman" specifications.

Throughout the period 1975-1980, William Carlson served as DARPA's program manager for the Ada effort.[36] He ran the contractual aspects of the common language program, including requirements studies, language definition, and language procurement, while HOLWG and its chairman, Whitaker, provided policy direction.

2. Design Competition

The evaluators found that no existing language simultaneously satisfied the needs of embedded computers, of reliable and maintainable software, and of machine independence. DDR&E tasked DARPA to manage the contract with Service dollars in order to issue a single RFP to develop a common language that would satisfy all of the Services' requirements.[37]

The RFP was based on the "Ironman" requirements document and specified that bidders should use PL/I, ALGOL 68 or Pascal as a basis for the new language. Most bidders chose Pascal. The development of the new language was left intentionally open ended because DoD wanted a language that would be acceptable to the Services; to companies that make military equipment; and to its Allies, who were concerned about issues of compatibility.[38] The developmental strategy was also designed to garner support within the community of programming experts, and encourage organizations outside of the

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[34] Amoroso, P. Wegner, D. Morris, and D. White, "Language Evaluation Coordinating Committee Report to the High Order Language Working Group," Defense Technical Information Center, AD-A037634, January, 1977.

[35] Department of Defense Directive 5000.31, "Interim List of DoD High Order Programming Languages," November 1976.

[36] Discussion with J.F. Kramer, December 1989.

[37] L.E. Druffel, P.M. Fonash, J.A. Kramer, and V.A. Mall, *AJPO Program Plan*, 1983.

[38] R. Halloran, "Pentagon Pins Its Hopes on Ada: Just Ask Any Computer," *New York Times*, November 30, 1980.

DoD vendor network to become involved. The RFP served as a catalyst for change, promoting a simultaneous problem-solving effort among a number of companies resulted in the collaboration of a diverse array of knowledgeable people from a diverse array of organizations.

The HOLWG received 17 bids and evaluated them with the participation of Service personnel. Four of these were selected for further development. All 4 had based their designs on Pascal.[39] Each of the designs was assigned a color code to provide a measure of anonymity, and to ensure the impartiality in the review of products. Each of the contractors -- Cii-Honeywell Bull (Green), Intermetrics (Red), Stanford Research Institute-International (Yellow), and SofTech (Blue)--were funded for 6 months to allow them to refine their designs.[40] Between mid-February and mid-March, 1978, the four sets of designs were sent to 125 teams (comprising a total of 390 individuals) who volunteered or were paid to review them.[41] A few groups (or individuals) were selected by each of the military services to look at the proposals from the perspective of that particular Service.[42] Cii-Honeywell Bull and Intermetrics were selected to develop a final language design.

The final selection was based on the technical quality of the language. Since "Steelman" was the evolved level of requirements at that point, it became the basis for the work of the design teams.[43] Whitaker arranged for ACM to publish 13,000 copies of the document[44] and these were subsequently distributed worldwide at no cost to DOD for discussion and comment.[45]

In May of 1979, the Ichbiah team from France was awarded the project. Members of the runner-up Red Team from Intermetrics were hired as technical consultants to the project. A team led by John Goodenough, the lease designer of the Blue Team won a competitive contract to develop a suite of tests to validate Ada compilers. Archives were set

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[39] Fisher, 1978, op. cit.

[40] Ibid.

[41] DARPA, "Plan for the Analyses of the Preliminary Designs for A Common Programming Language for the Department of Defense," December 30, 1977.

[42] Sammet, op. cit.

[43] Department of Defense, "Requirement for High Order Computer Programming Languages, STEELMAN," June 1978.

[44] Department of Defense "Preliminary Ada Reference Manual and Rationale," *ACM SIGPLAN Notices. 14, 6, Parts A & B*, June 1979.

[45] Discussion with W.A. Whitaker, August 1990.

up and details of the new language were put on-line via the ARPANET computer network. There was planned a period of time to complete the design of the language and to complete the standardization process; the process took 2 years.[46]

From June through October of 1979, Ada was tested by more than 100 different groups each of whom wrote programs addressing some small but realistic problem of their choosing. Reports of these test programs were published through December 1979, and in June of 1980 the final language specifications were delivered. This specification was the basis for the military standardization of Ada, promulgated as MIL STD 1815 in December of 1980.[47] Any changes made to Ada after this time required DoD approval.

3. Ada Programming Support Environment

Parallel to the language development process was the problem of programmer support tools. In June 1978, a workshop was convened by the HOLWG to discuss issues and policies relevant to the specification of programmer support tools (e.g., compilers, loaders, editors, debuggers) needed to write Ada programs. Whitaker (with the assistance of Peter Elzer, a German computer scientist on loan to DoD from Germany)[48] subsequently published the "Pebbleman" document outlining what would be needed for an integrated programming support environment. Professor John Buxton took a one year sabbatical from Warwick College in England to work at Harvard, under contract to DARPA, to develop the technical requirements. In November 1979, a follow-up workshop was held to review "Pebbleman" and discuss the technical issues involved in developing the environment.[49] The review led to the "Stoneman" document, which established the requirements for an integrated collection of programming support tools or APSE (Ada Programming Support Environment).[50]

At this juncture (1980), the HOLWG shifted its focus from the development of the language to supporting the technical and management tasks involved in the design,

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[46] Discussion with S. Squires, November 1985, and review comments of L. Druffel, January 1991.

[47] J.F. Kramer, "Ada Status and Outlook," AJPO, undated.

[48] Discussion with W.A. Whitaker, August 1990.

[49] Discussion with J.F. Kramer, December 1989.

[50] Department of Defense, "Requirements for Ada Programming Support Environments - STONEMAN," February 1980.

development, and maintenance of computer programs.[51] The tools set described in the "Stoneman" document became important to the overall long term success of Ada. The potentialities of Ada would only be realized when a sophisticated APSE became available and widely utilized.[52]

4. The Role of AJPO

With the development of the Ada language itself having been accomplished and the APSE specified, DARPA's role and responsibility for developing Ada had been realized. At this point the focus of the effort transitioned to implementation, standardization and policy concerns, which the Management Steering Committee (under Mark Grove) and the HOLWG determined would best be done by a joint-service project office in the Office of the Secretary of Defense.[53]

The Ada Joint Program Office (AJPO) was created in December 1980, under the Office of the USDRE (OUSDRE). Initially it fell under the Deputy for Acquisition Management, but then moved under the Deputy for Research & Advanced Technology, as part of the Computer Software and Systems Directorate. Members from each of the Services served as deputy directors of the office, thus encouraging the joint ownership and acceptance of Ada.

Establishing AJPO temporarily marked the end of direct DARPA involvement, though the Agency did continue to manage Ada-related contracts.[54] Larry Druffel, an Air Force officer, then the DARPA program manager for several of the Ada related contracts became AJPO's first director. At that time, the deputy directors of the Joint Program Office were Robert Mathis (technical director), Peter Fonash (Army deputy director), John Kramer (Navy deputy director), and Al Kopp (Air Force deputy director).[55] Druffel states he "did not intend to move from DARPA with Ada," but finally agreed to head up the AJPO. After 9 months on loan from DARPA, he was asked to reconsider and agreed to

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[51] W. Rolling, "Ada: Within DoD and Beyond. Some Perspectives on the Promises and the Achievements." Speech presented at the Federal Computer Conference, Washington, DC, September 9-11, 1985.

[52] Discussion with J.F. Kramer, December 1989.

[53] Discussion with Larry Druffel, November 1990.

[54] Kramer, 1989, op. cit.

[55] J.F. Kramer, *Ada Technology Transfer* (a slide presentation), AJPO, 1981-1982.

transfer to the AJPO.[56] In retrospect Druffel believes the transfer of the program from DARPA to the AJPO facilitated the transitioning of Ada to the Services. He believed it was essential that the AJPO Director was a military officer.

The AJPO was created to coordinate the introduction and implementation of Ada, and to provide life-cycle support and maintenance for the language and its support systems.[57] It employed a strategy of public review for the requirements documents, drafted RFPs, supported multiple and competitive designs, and provided high visibility and continuous critical assessment of the implementation process to facilitate the adoption of Ada by the military, the business, and the international community.[58]

The Ada Information Clearinghouse created by the AJPO became the focal point for assembling and distributing information about Ada. Even though the Clearinghouse did not become fully operational until 1983,[59] it significantly increased the visibility of Ada and aided in the language's acceptance. It provided information on seminars, courses, textbooks, and other training materials available on Ada, and an on-line collection of documents, status reports, and products to anyone with access to ARPANET or MILNET. ARPANET was especially helpful in that it provided an essential link for researchers to share information and coordinate the activities necessary to promote the development of compilers, supplied information on Ada training, and encouraged the use of the language.[60]

Although an important component of the DoD software strategy, the Ada Language and the Ada Programming Support Environment were not sufficient to solve the problems associated with the high cost of language proliferation and maintenance. A new joint task force was established by Edith Martin, the Deputy Undersecretary for Research and Advanced Technology, to analyze DoD's software problems.[61] In early 1983, the Software Technology for Adaptable Reliable Systems (STARS) program was launched to "achieve greater systems reliability and adaptability while hopefully improving software

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[56] Discussion with Larry Druffel, November 1990.

[57] J.F. Kramer and C.W. McDonald, *Ada Joint Program Office Objectives and Progress - Through 1983*, Institute for Defense Analyses Memorandum Report M-22, September 1984, p. vi.

[58] L.E. Druffel, P.M. Fonash, J.F. Kramer, and V.A. Mall, *AJPO Program Plan*, OUSDRE, 1983.

[59] J.F. Kramer, *Ada Technology Transfer* (a slide presentation), AJPO, 1981-1982.

[60] Discussion with S. Squires, November 1985.

[61] Report of Joint Service Task Force on DoD Software Problems, Office of the Under Secretary of Defense, Research and Engineering, 1982.

productivity, particularly in the post-delivery phase which amounts to as much as 80 percent of the systems costs."[62] Organized as a 7-year effort, the STARS program focused on a range of concerns, including:

(1) software reliability/adaptability

(2) software portability

(3) development of software tools

(4) educating the software community.

The STARS Program is currently a part of DARPA and continues to pursue its long-term mission.

By 1983, the refinements made to Ada were completed, and implementation as a standardized common language was well on its way. Congress passed the 1983 Defense Authorization Act which allocated money to weapons systems utilizing Ada and encouraged the acceleration of Ada implementation.[63] In June 1983, USDRE Delauer issued a memorandum mandating the use of Ada for all DoD mission-critical software after July 1984.[64] This memo was designed to ensure that Ada would continue to have DoD's support and backing.[65]

One of Ada's program objectives was standardization, a requirement that was to prevent the proliferation of unauthorized dialects and subsets. Once Ada was standardized by the U.S. Military,[66] it was hoped that it would also be accepted by the American National Standard Institute (ANSI), and the International Organization for Standardization (ISO).[67] In January 1983, Ada passed a canvas by ANSI, and in February it was officially adopted by ANSI.

One of AJPO's key functions was to publish a language reference manual (LRM) whose function would be to define the Ada language and provide the basis for

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[62] Special Issue of *IEEE Computer*, November 1983.

[63] Kramer, 1989, op. cit.

[64] E. Lieblein, "The DoD Software Initiative - A Status Report," *Communication of the ACM*, Vol. 29, No. 8, August 1986.

[65] Carlson, 1986, op. cit.

[66] MIL-STD-1815.

[67] Druffel, et al., op. cit.

standardization and configuration management of Ada. Designated as MIL-STD 1815, in December 1980, it was distributed worldwide by ACM (SIG/Ada) as a way of soliciting detailed questions from Ada language implementors, public and standards review committees, and initial applications programmers.[68] Currently, Ada is undergoing its second review by ISO.[69]

The Federal Information Processing Standard (FIPS) approval under the aegis of the National Bureau of Standards followed closely on the heels of the ANSI approval. ISO standardization was received in March 1987. Ada's relatively rapid approval by ANSI and ISO was based on the involvement of the ISO Technical Working Group on real-time languages throughout most of Ada's development effort. The Director of AJPO served as the convener of the ISO expert group in Paris, Brussels, and Washington, D.C.[70]

5. Acceptance by the Services

Following the standardization and mandating that the Services adopt Ada as its mission-critical software, each of the individual Services approached the "embracing" of Ada in its own way. Ironically, the Navy which had been very active in the early design, was the last of the Services to actually implement Ada. Its heavy investment in CMS-2 (a less powerful language than Ada) and in other types of software may have slowed its pace of adoption.[71]

The Army, on the other hand, was slow to support Ada's early development, but it was the first to mandate its adoption. In the early 1980s (for example), the U.S. Army Communications and Electronics Command (CECOM) contracted with SofTech (one of the four semi-finalists in the language design competition) to design, develop, document, and verify an APSE based on the requirements specified in the "Stoneman" documents.[72] The prototype environment built for the Army became known as the Ada Language System (ALS).[73]

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[68] Kramer and McDonald, op. cit., p. 2.

[69] Mathis, op. cit.

[70] Kramer and McDonald, op. cit., p. 5.

[71] J. Fawcette, "Ada Tackles Software Bottleneck," *High Technology*, February 1983, p. 51.

[72] M.J. Wolfe, W. Babich, R. Thall, and L. Weissman, "The Ada Language System," *Computer*, June 1981.

[73] Discussion with A. Hook, IDA, 1985.

The Air Force had a similar contract with Intermetrics (also one of the four semifinalists); its product was the Ada Integrated Environment (AIE). DARPA and the Army also funded an effort at the New York University to develop prototype compilers.[74]

The ultimate acceptance of Ada rested on acceptance at the program manager level of responsibility. In the Army, for example, CECOM Command at Fort Monmouth, N.J., strongly favored Ada, while the avionics laboratory at Wright-Patterson Air Force Base expressed a preference for JOVIAL.[75]

6. Ada Compiler Validation

Paralleling the Army and Air Force efforts to develop prototype environments, DARPA contracted with SofTech to carry out a project on the Ada Compiler Validation Capability (ACVC)[76] which would produce validation test suites of compilers to ensure conformity to language standards. The ACVC was crucial to Whitaker's original plan to derive industrial support for needed Ada products. DoD contractors and other companies were likely to make investments in Ada only if their products were likely to find a ready-made market.[77]

Because one of the major goals of the Ada program was to ensure software portability and reliability, the validation process was essential for the success of the entire project. Though validation is usually an afterthought in language design, it became a prerequisite in the Ada program. The validation process became the certification mechanism for Ada compilers and the AJPO served as the regulatory body.[78]

Validated compilers were correctly perceived by AJPO as one of the keys to the spread and adoption of Ada by industry.[79] Well-defined software development methodologies (as specified in another requirements document, "Methodman"[80]) was intended to serve as a mechanism for systems planners to make hardware/software

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[74] Discussion with G. Fisher, IBM, September 1990.

[75] Fawcette, op. cit.

[76] Goodenough, "The Ada Compiler Validation Capability," *Computer*, June 1981.

[77] Carlson, op. cit.

[78] Discussion with A. Hood, 1985.

[79] W. Rolling, "Ada: Within DoD and Beyond. Some Perspectives on the Promises and Achievements," Speech presented at Federal Computer Conference, Washington, D.C., September 9-11, 1985.

[80] A. Wasserman and P. Freeman, "Ada Methodologies: Concepts and Requirements," Department of Defense, November 1982.

tradeoffs as new technologies became available over the life cycle of a particular weapon system or application.[81] Not much progress resulted from this effort, however.[82]

Designing reusable, easily transportable software components necessitates isolating and minimizing dependencies on the operating or hardware systems.[83] Kernel was the term used to describe the machine instructions at the operating level of the hardware system.[84] To help standardize operating systems and facilitate software portability, the Kernel Ada Programming Support Environment (KAPSE) was developed under the watchful eye of AJPO.[85] DoD also sponsored a study group, the KAPSE Interface Team (KIT), to develop the specifications for the standard mechanism to control software interface with operating systems. This interface mechanism is called the Common APSE Interface Set (CAIS). While CAIS was designed to facilitate software and tool portability and reusability,[86] its actual use by program managers has been limited.[87]

The final phase of this developmental stage was the validation of compilers. The first prototypes were not efficient enough to be practical or workable, but were a step in the direction of gaining widespread usage of Ada. In 1983, the first Ada compilers were validated. The organizations producing these compilers were New York University's Courant Institute (with its interpreter), to be Rolm/Data General compiler developed by Rational (which had the first validated compiler), and Western Digital/Gensoft. By 1986, 19 organizations had received certificates from AJPO with Alsys leading the field with 24 validated base compilers.[88]

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[81] Kramer and McDonald, op. cit., p. 27.

[82] Discussion with W.A. Whitaker, August 1990.

[83] Rolling, op. cit.

[84] The basic concept behind the development of reusable, easily transportable software components contains three levels: KAPSE, MAPSE, and full APSE. The KAPSE (Kernel APSE) level operates just above the native operating system and serves as the interface between the operating system and everything else. MAPSE (Minimal APSE) covers such facilities as the compiler, a linker/loader, a debugger, an editor, etc. The full APSE covers the other tools needed to support the applications written in Ada. For a full rendering of the "Stoneman" concept, see Department of Defense, "Requirements for Ada Programming Support Environments - STONEMAN," February 1980.

[85] Discussion with A. Hook, 1985.

[86] Rolling, op. cit.

[87] Discussion with W. A. Whitaker, August 1990.

[88] K. Nyberg, "183 Validated Compilers on List," *Government Computer News*, Vol. 7, No. 12, June, 1988, p. 74.

The Institute for Defense Analyses, under contract to USDRE, became the Ada validation office for the AJPO in 1983. There are now five Ada validation facilities (two in the U.S., and three in Europe) authorized by AJPO to do the actual certifying. IDA still reviews the validation reports. The end of 1984 and 1985 saw the validation of the first production-quality compilers by Alsys (a French company), Data General, DDC International, Digital Equipment, Honeywell Information Systems, Rational, Rolm, Telesoft, Verdix, the University of Karlsruhe (in Germany), and SofTech (for the U.S. Army CECOM), and Intermetrics (for the U.S. Air Force). The first "Ada engine" was developed also in 1985.[89] It was developed by Rational and offers a complete operating environment.[90]

C. ADA IMPLEMENTATION AND APPLICATION

Since Ada's official implementation, sales of Ada software companies have grown to $150 million in 1990.[91] Intellimac developed the first proprietary software product using Ada in a commercial MIS application--a payroll system.[92] Japan's Nippon Telephone and Telegraph has developed switching software using Ada; two-thirds of Finland's banking industry uses Ada software.[93] Several European countries have adopted air traffic control systems implemented in Ada.[94] The increasing availability of Ada trained programmers (thanks in part to early DoD support) and recent advances in compiler technology and hardware storage capacity and speeds have helped to reduce the risks associated with the adoption of Ada. Within DoD Ada's application was initially slow, as waivers to its use were granted for reasons of scheduling and cost and because the language was insufficiently proven for "mission-critical" applications. However, as the pool of vendors with Ada experience has grown and the DoD acquisition system has

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[89] A computer specifically built around Ada and an Ada compiler.

[90] Discussion with A. Hook, 1985.

[91] Discussion with Jerry Rudisin, Alys, 1990.

[92] Rolling, op. cit.

[93] K. Nyberg, "Commercial Market Undeveloped but Could Be Huge," *Government Computer News*, Vol. 7, No. 12, June 10, 1988, p. 76.

[94] Discussion with W. A. Whitaker, August 1990.

increasingly insisted on Ada, rather than allowing waivers, Ada is now a critical competitive advantage for DoD software suppliers.[95]

Outside of DoD, Ada's spread to the Federal civilian sector is evidenced by such agencies as the U.S. Post Office, Federal Aviation Administration, Department of the Interior, and NASA.[96] The Post Office uses Ada in its mail handling system; NASA uses it in support of its Space Station Program. High reusability, controls on cost, improved interoperability, and the increased productivity of programmers are benefits that these agencies report from the use of Ada. The typical constraints imposed by hardware systems are eliminated by Ada's design. The language isolates and limits operating system dependencies. Reifer, in a recent study of 107 Ada use projects, found that programmer productivity was enhanced by 20% when compared with the use of other programming languages. He states:

> A number of our clients look at portability of applications across platforms. With certified compilers, they can achieve that. They also look at economies of scale through reuse of Ada components. They are not forced to use Ada by DoD regulations. The reason they are moving to Ada is the bottom line--money. Its cheaper, and it does the job.[97]

Ada is now being used as a way of teaching software engineering principles to prospective programmers and computer scientists, and as a mechanism for teaching specialized topics such as numerics, concurrent processing, and data structures.[98] An article which compares the strengths of Ada as a teaching tool with Modula-2, concludes that

> Ada, we can often combine the complex, difficult to implement language features in a simpler way. So the more complicated Ada language often leads to simpler Ada programs; the Ada compiler writers have taken the burden off my students shoulders, and placed it on their own....They can solve more complicated problems more quickly and simply. Beyond the learning curve, there is a net gain in productivity.[99]

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[95] J. Goldberg, "The Pentagon's Software Crisis Jeopardizes Key Weapon Programs," *Armed Forces Journal International*, June 1990, pp. 60-62.

[96] B. Brass, "Complexity Keeps Ada from Reaching Its Potential," *Government Computer News*, Vol. 8, No. 23, November 13, 1989, p. 67.

[97] Reifer, president of Reifer Consultants in Los Angeles, was quoted in Brass, op. cit.

[98] Many computer science departments have already switched from Pascal to Ada because it offers a better abstraction method.

[99] R. Pattis, "One Teacher's Perspective of Ada and Modula-2," *Alsynews*, Vol. 3, No. 2, June 1989, p. 13.

Foreign military organizations are also working with Ada. It is the standard language for Canada's Ministry of Defense and its Aviation Administration. NATO has mandated the use of Ada for all common support systems whose development is jointly sponsored or funded by NATO. By the 1990s, Ada will be the mandatory language for real-time systems throughout all of NATO.

Britain's Ministry of Defense, however, had initial difficulties implementing Ada. A directive issued in 1984 mandated Ada's use for real-time programming in defense systems as of July 1987. This directive was then rescinded in light of the United Kingdom's failure to develop an Ada compiler. Britain's former defense secretary, Michael Heseltine, may have indirectly contributed to this delay when he insisted on fixed-price instead of cost-plus contracts for Britain's ECS software. Defense vendors allegedly built in languages with which they were more familiar (e.g., FORTRAN and Pascal) rather than run the risk of higher costs gearing up with Ada.[100]

D. OBSERVATIONS ON SUCCESS

The notion of DoD support for developing a common programming language for embedded computer systems originated within DDR&E, based on several studies that showed there were potentially very large dollar savings and productivity gains to be made from adopting a standard DoD language for such applications. The program was directed and managed by the Higher Order Language Working Group (HOLWG) with Col. Whitaker of the DDR&E's office as chairman. When Whitaker moved to DARPA with Heilmeier in 1975, after the HOLWG was established, he maintained his involvement with the Ada program. Indeed Heilmeier states he brought the Ada program into DARPA because both he and Whitaker were moving over there, and he feared the program would die if orphaned in DDR&E. While DARPA was responsible for contracting and managing the Ada development effort, the HOLWG reviewed the proposals and decided which to support. In late 1980, DARPA's role was further reduced, when the AJPO was created under the Office of USDRE (formerly the DDR&E), with Druffel, an Air Force officer who managed several of DARPA's Ada efforts becoming the first director of the AJPO.

DARPA thus was an effective institution for managing the initial contracts to develop the Ada language and supporting software development tools. It was tasked to do

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[100] M. Brown, "Users Worldwide Find Ada an Aid to Productivity, [illegible] *ament Computer News*, Vol. 5, No. 18, September 12, 1986.

this by the DDR&E, delivered the Ada language and an infrastructure base for its implementation, and these efforts resulted in implementation through the AJPO.

DoD has persisted in its interest in developing a standard language for its systems application, but the adoption of Ada has not been as rapid or ubiquitous as some of its supporters have hoped. Subsequent efforts to provide support for software tools and techniques, including STARS, which only recently was transferred into DARPA after 7 years as a DDR&E program, evidence continuing concerns with the cost and productivity of software in defense systems. The Ada language technically is a successful development effort; its ultimate evaluation depends on the degree to which it is applied and its characteristics, including re-usability, are found to be valuable in overcoming the problems of software cost and productivity. That implementation has begun, but its success now depends upon a range of factors including the availability of trained, proficient programmers, the development of tools and techniques to support programming, the degree to which broader applications beyond DoD affect both of these, and the degree to which DoD remains committed to the implementation of Ada.

DARPA, as a flexible mechanism for contracting and contract management, played a major role in this development. While most of the impetus and direction for Ada's development was external to DARPA, DARPA's Ada program managers played active roles on the HOLWG, and DARPA explicitly funded such efforts on the Pilot Validation Facility for Ada compilers to facilitate the language's implementation.

XVI. SIMNET

A. BRIEF OVERVIEW

SIMNET, an acronym for "Simulator Networking," was initiated as a DARPA project on Large Scale Simulator Networking in 1983.[1] It is a proof-of-principle technology demonstration of interactive networking for man-in-the-loop, real-time, battle-engagement simulation and wargaming. It is the first system to achieve true interactive simulator networking for the collective training of combat skills in military units from mechanized platoons to battalions. SIMNET is also adaptable for training or exercising commanders and staffs at higher echelons, useable in the development of military concepts and doctrine, and suitable to the testing and evaluation of alternative weapon-system concepts prior to acquisition decisions. As of January 1, 1990, the available SIMNET components consisted of about 260 ground vehicle and aircraft simulators, communications networks, command posts, and data processing facilities distributed among nine sites--five in the continental United States (CONUS) and four at U.S. Army locations in Europe (USAREUR).[2] In 1989, SIMNET technology was transitioned to the Army as "SIMNET-T," a collective or unit training capability that the Army is planning to extend Army-wide through a large-scale follow-on acquisition program. "SIMNET-D," another version located at Fort Knox, Kentucky, and "AIRNET" at Fort Rucker, Alabama, provide a developmental capability that can be reconfigured to simulate new design concepts for evaluation in SIMNET trials. These are the basis of a new joint Army-DARPA initiative to

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[1] ARPA Order (AO) #4739, signed 15 February 1983.

[2] The CONUS sites are at Fort Knox, Ky., Fort Benning, Ga., Fort Rucker, Ala., Cambridge, Mass. and Washington, D.C. The USAREUR sites are in West Germany at Grafenwöhr, Friedberg, Schweinfurt, and Fulda. The Fort Knox site is currently the largest SIMNET facility with simulators for 44 M1 Abrams tanks, 28 M2/3 Bradley Fighting Vehicles, 2 Scout/Attack Helicopters, 2 Close Air Support Fighter Aircraft, a Battalion Task Force Tactical Operations Center, an Administrative-Logistics Operating Center, and other command and control, artillery and mortar-fire, and close air support control elements--all fully interactive on a local area network.

demonstrate "Advanced Distributed Simulation Technology (ADST)" for use in system development, studies and analyses.[3]

B. TECHNICAL HISTORY

SIMNET's history can be divided into five phases: (1) the origins, including related efforts at DARPA prior to 1979, (2) gestation and planning, resulting in DARPA's initiation of the SIMNET Project in 1983, (3) component development and early demonstrations, from 1983 to 1985, (4) system development, networking and testing, from 1985 to 1987, and (5) full system development and field testing, culminating during 1989 in transition to the Army and subsequent planning for system expansion to demonstrate the capabilities and assess the potential benefits of using new SIMNET-D technology in weapon-system evaluations and acquisition decisions and for the development of military concepts and doctrine.

1. Origins

The pervasive scientific and management culture that led DARPA to support many special developments and applications of computer technologies was especially stimulated and influenced by J.C.R. Licklider who, in 1962, became the first director of ARPA's[4] Information Processing Techniques Office (IPTO).[5] He had a broad and prescient view of the benefits, for the military specifically and society more generally, that would result from progress in the man-machine interactive computer technologies.[6] Indeed, ARPA subsequently instituted and carried out a wide range of information processing projects in areas such as computer time sharing, networking, and artificial intelligence.[7]

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[3] See R.J. Lunsford, Jr., *US Army Training Systems Forecast, FY 1990-1994*, Project Manager for Training Devices (US Army Materiel Command), Orlando, Fla., October 1989.

[4] The Advanced Research Projects Agency (ARPA) became the Defense Advanced Research Projects Agency (DARPA) in 1972 under the terms of a revised charter, *DoD Directive 5105.41*, dated March 23, 1972.

[5] The name of the office was later changed to the Information Processing Technologies Office and then, in 1984, to the Information Sciences and Technologies Office (ISTO).

[6] See J.C.R. Licklider, "The Early Years: Founding IPTO," in *Expert Systems and Artificial Intelligence*, T.C. Bartee, ed., Howard Sams, 1988, pp. 219-ff. See also: J.C.R. Licklider, "Man-Computer Symbiosis," *IRE Trans. on Human Factors in Electronics*, 1960, *1*, 4-11.

[7] See Volume I, Chapters XIX, XX, and XXI, respectively.

Licklider influenced the establishment of what became DARPA's Cybernetics Technology Office (CTO) and served as its first director.[8] During the late 1960's, after Licklider had returned to the Massachusetts Institute of Technology (MIT), the office was directed by Davis B. Bobrow, a political scientist, followed late in 1969 by Austin W. Kibler, a U.S. Air Force officer and engineering psychologist.[9] Robert A. Young, who joined the staff after Bobrow's departure, was named CTO director when Kibler retired from military service in August 1975.[10] Craig I. Fields, who later played a crucial role in supporting SIMNET development, joined the CTO staff when he completed graduate work at MIT at the end of 1975.[11]

During Bobrow's and Kibler's tenures, ARPA's behavioral science research, although "under attack" by Congressional sources and staffers, continued to be supported by the ARPA management. Congressional pressure on the ARPA budget, and especially on the budget for the behavioral science research projects, led not only to the name change to CTO,[12] but also to a shift in program emphasis--a shift intended to reflect the still broader changes in DARPA's direction or "philosophy" that were instigated during the latter half of the 1970's by George H. Heilmeier who had been appointed DARPA Director in 1975.[13]

From the beginning, Heilmeier began raising "fundamental and pragmatic questions" of all DARPA's project managers.[14] For example, he is quoted as saying:

> ... I tried to apply my catechism questions: What are the limitations of current practice? What is the current state of technology? What is new about these ideas? What would be the measure of success? What are the

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[8] Initially called the Behavioral Science Research Office (BSRO), this office was redesignated the Human Resources Research Office (HRRO) during Kibler's tour as director, and later became the CTO during Young's stewardship; discussion with A.W. Kibler, Falls Church, Virginia, on 18 January 1990.

[9] Bobrow and, at first, Kibler were dual-hatted, working part time in ARPA and the Office of the Secretary of Defense (OSD). The CTO staff in 1969 consisted of Bobrow, Kibler, and George H. Lawrence, who managed a project on biofeedback. Kibler, ibid.; telephone discussion with G. H. Lawrence, Army Research Institute, on 9 February 1990.

[10] The staff then consisted of Young, Lawrence, and Harold F. O'Neil, Jr. Kibler, ibid.; Lawrence, ibid.

[11] Fields transferred from the IPTO to the CTO to replace Lawrence, who left DARPA early in 1976. Lawrence, ibid.

[12] See fn. 8.

[13] Kibler, ibid.

[14] See Volume I, Chapter XXI, pp. 21-10 ff.

> milestones and the "mid-term" exams? How will I know you are making progress? I asked these of all programs....[15]

As a result of his review and subsequent actions, there was a shift in the balance of DARPA work towards applications, especially in certain "software-oriented" areas such as artificial intelligence.[16] The general trend was away from studies and analyses that resulted in reports, and towards the development of technology that led to "things" that could be used by the military. The CTO was not immune to the new trend. Its projects backed away from their past involvement with studies and analyses of behavioral and social science models and research in more-or-less basic or academic areas, and moved towards adaptations of the rapidly developing new computer technologies in areas of military decision making and training.[17]

Changes relevant to the later development of the SIMNET project took place in both the CTO program and its personnel during 1977. Among these was the arrival of J. Dexter Fletcher, who had been recruited earlier by Kibler from the Xerox Corporation.[18] Fletcher began in the CTO by consulting with Stephen J. Andriole to develop applications of computer technology to training issues. When he became a full time staff member late in 1977, there was a sense of urgency in the CTO. Heilmeier had cut the program by half before he left DARPA. All work in the behavioral sciences was being questioned, and internal DARPA support for CTO projects seemed increasingly limited.[19] The projects that fared best were those dealing with applications of computer and advanced information technologies to military issues such as operational decision aiding. So, Andriole, with the support of Robert R. Fossum, who had replaced Heilmeier as DARPA Director, pressed the staff to make rapid conversions of technological developments and findings into demonstrable capabilities.[20]

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[15] Ibid., p. 21-10.

[16] This change is discussed by Licklider and Kahn, IPTO directors at the time, in Bartee, op. cit., pp. 225 and 246.

[17] Telephone discussion with S. J. Andriole, George Mason University, 7 February 1990.

[18] At the time, Fletcher was at Xerox on unpaid-leave status from the Navy Personnel Research and Development Center, San Diego, California; discussion with J. D. Fletcher, IDA, on 4 January 1990.

[19] Young initiated the personnel action that culminated in Fletcher's full-time appointment when a CTO project manager working on instructional strategies left DARPA (O'Neil; see fn. 10). However, by the time Fletcher arrived, Young had left and Andriole had been named CTO director. At the end of 1977, the CTO staff consisted of Andriole, Fields, Fletcher, Judith A. Daly, and Lt Col Roy Gulick, USMC. Andriole, ibid.; Fletcher, ibid.

[20] Fossum had indicated his interest in further reducing the proportion of studies-and-analyses types of projects in favor of increasing the proportion of technology development projects in the DARPA program. He emphasized especially the need for the DARPA program to advance into areas that would

Experience had led the CTO staff to believe that their chances of success in obtaining both Service-user and DARPA-management support were better when they could demonstrate their concepts and proposals in concrete form.[21] So they established a facility or demonstration room near the headquarters building at Rosslyn in Arlington, Virginia, for this purpose, and Andriole invited Fossum and his deputy, Eugene Kopt, to visit and view some of the new technologies that might be used to advance military (and civil) education and training in the future--specifically, Fletcher's new Apple-II personal computer.[22]

Fletcher demonstrated the Apple-II, and they (Fossum, Kopt, Andriole, and Fletcher) discussed some of the things that might be done with microcomputers in the domain of military training. One idea hit a receptive chord:

> Videodiscs are coming on line now. Why not use videodisc pictures from the real world, say with tanks, and overlay them with computer graphics to build a low-cost tank gunnery trainer?[23]

Fossum was enthusiastic and said that this was the correct direction for future CTO projects in training technology. The conclusion reflected the prevailing mood that characterized not only CTO, but also the whole of DARPA at the time: "Why not do it now?"[24] So, Fletcher set out to write a DARPA proposal for a project to develop a low-cost Tank Gunnery Trainer. The need was expressed in terms of the high cost of tank gunnery practice in the field, and the resultant severe limitations on the amount of practice that tank gunners acquired in the then current training systems. Thus, the "low-cost" constraint was a factor from the very beginning of the project.[25]

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develop and exploit new technologies in the contexts of enhancing U.S. military capabilities; for example, through applications that promised to address or resolve important military needs or issues, whether formally stated or not; Andriole, ibid.

[21] Earlier, for example, Fossum was exuberant when he saw a demonstration of Field's "Spatial Data Management System" at MIT's Media Laboratory (then called the Machine-Architecture Group). He said that he wanted one for himself, his secretary, and his immediate staff members, and he increased his personal support of the Fields-managed project on advanced information technology for command and control, of which it was a part. Andriole, ibid.; Fletcher, ibid.

[22] While completing doctoral work in psychology at Stanford University, Fletcher had also obtained a master's degree in computer science and had developed a number of successful applications of computer technologies to education and training. He became a member of the Apple Education Foundation in 1978, and through that association had been given a new Apple-II to use in his work. Fletcher, ibid.

[23] Fletcher, ibid.

[24] Andriole, ibid.

[25] Andriole, ibid.; Fletcher, ibid. This is an important point, since such a restriction is very likely to result in a system concept different from that which would follow in the absence of the cost constraint.

CTO was a small office, and the staff members tended to discuss their projects and plans with one another, naming sources they judged capable of developing the various desired enabling technologies. Among those identified as potential sources of the expertise required to develop the Tank Gunnery Trainer were a DARPA contractor, Perceptronics,[26] and its founder and president, Gershon Weltman. Fletcher was introduced to Weltman via the ARPANET, and they communicated about the proposal Fletcher was developing.[27] Fletcher's basic concept was to use the Apple-II to drive the videodisc (a capability that had already been demonstrated), and to overlay computer graphics on the display. The overlaying of the computer graphics was the new technology involved.[28]

Perceptronics was interested. So, before developing an internal DARPA project plan, Fletcher spoke on the topic, first with Weltman, and later with Robert S. Jacobs who joined Perceptronics at about that time.[29] Fletcher's plan won support and the Tank Gunnery Trainer project was initiated in June 1979,[30] and Jacobs began to play an increasingly important role in the development of the Tank Gunnery Trainer.[31] Then, near the end of 1979, Perceptronics successfully overlaid computer graphics on a videodisc image. It was among the first to demonstrate the [illegible] technology--i.e., to accomplish a mixing on a single visual display of digital computer graphics (computer generated images) with analog video images from a videodisc.[32]

Computer image generation (CIG) had been demonstrated prior to this and was being exploited by the Defense training-technology research and development (R&D) community. In 1976, the Advanced Simulator for Undergraduate Pilot Training (ASUPT),

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[26] Perceptronics, Inc., had been a prime element in the development of a "Group Decision Aid" under a DARPA contract managed by Fields.

[27] It is important to note this aspect of the then-current DARPA environment and *modus operandi*. The DARPA project managers were expected to know thoroughly their R&D areas, including all the "players"--i.e., all the persons and firms who had the requisite expertise and capabilities. It was the standard operating procedure for project managers to work collegially with potential or actual "contractors" in the conduct of the work. Many, if not most or nearly all, of the DARPA contracts at the time were "sole source," a situation that ended after 1984 with implementation of the Competition in Contracting Act.

[28] Fletcher, ibid.

[29] Telephone discussion with R.S. Jacobs, Illusion Engineering, Inc., on 21 March 1990. It may be of some interest to note that Jacobs and Weltman brought, respectively, radar and cinematic technology orientations to the work through their family experiences and backgrounds -- orientations that served the SIMNET project well in its later development.

[30] AO 3791, signed 11 June 1979.

[31] Jacobs was later to play a central role in the SIMNET development; Fletcher, ibid.

[32] Andriole, ibid.; Fletcher, ibid.

later renamed the Advanced Simulator for Pilot Training (ASPT), had been installed at the Operations Training Division of the Air Force Human Resources Laboratory (AFHRL/OT),[33] Williams Air Force Base, Arizona. The visual display was a dodecahedron of seven CIG channels (limited to 2500 edges) displayed through special optics (pancake windows) by monochromatic video projectors.[34] In addition, CIG was used in the Visual Technology Research Simulator (VTRS)[35] under development at the Naval Training Systems Center (NTSC),[36] Orlando, Florida, for the Naval Air Systems Command. Its visual display was based on the projection of the CIG image on the interior surface of a dome, with a high-resolution area-of-interest (AOI) inset from a second projector system "slaved" to the head and eye movements of the pilot.[37] The Army's Project Manager, Training Devices (PM TRADE)[38] had a full-mission tank simulator designed to train tank crews under development at Fort Knox, Kentucky; it, the Unit Conduct of Fire Trainer (UCOFT), also used a CIG display.

All such systems were quite costly. For example, during the late 1970's, a single channel capable of producing an adequate CIG visual display was estimated to cost on the order of $2 to $3 million. The relatively high costs were not limited to the development efforts--the estimated procurement costs of the follow-on operational training equipment ranged from the millions to the tens of millions of dollars ($5 million plus for UCOFT, and $30 million plus for ASPT). Even in the R&D community, the concern was growing regarding the projected high costs for the training equipment and the military training community's ability to acquire them in sufficient numbers, once developed.[39]

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[33] Previously the Flying Training Division (AFHRL/FT).

[34] Three additional CIG channels were available, but were reserved for later insertion of a high-resolution inset, the location of which would be driven by the head and eye movements of the pilot in the simulator's cockpit.

[35] See G. Lintern, D.C. Wightman, and D.P. Westra, "An Overview of the Research Program at the Visual Technology Research Simulator," in *Proceedings of the 1984 IMAGE-III Conference*, E.G. Monroe, ed.. Air Force Human Resources Laboratory, Williams Air Force Base, Arizona, 1984, 205-221.

[36] Previously the Naval Training Equipment Center (NTEC).

[37] See D.R. Breglia, A.M. Spooner, and D. Lobb, "Helmet Mounted Laser Projector," in *Proceedings of the 1981 IMAGE Generation/Display Conference II*, E.G. Monroe, ed., Air Force Human Resources Laboratory, Williams Air Force Base, Arizona, 1981, 241-258; also D.M. Balwin, "Area of Interest--Instantaneous Field of View Vision Model," op.cit., 481-496.

[38] Collocated with NTSC in Orlando, Florida.

[39] During the Spring of 1978, Michael Cyrus of AFHRL/OT, who was later to play a principal role in the development of the SIMNET graphics generation system, assisted NTSC to convert its mainframe-based stimulator computer system to a multi-minicomputer architecture, a precursor to the multi-

The concern was reflected at DARPA through Fletcher's emphasis on developing a low-cost item. Specifically, his objectives for the Tank Gunnery Trainer project were to develop a device that would or could be (a) procured in quantity for $10,000 or less each, (b) accessible, for example as a stand-alone "game" in military barracks or dayrooms, (c) motivating, for example in supporting competitive score keeping, (d) of sufficient fidelity to satisfy the training objectives, within the cost constraints, and (e) suitable for documenting training effectiveness in terms of transfer-of-training data. These objectives led to the stipulation of requirements that the device provide (a) the "feel" of the controls like the operational equipment, (b) the "sighting" of the operational equipment's reticle, and (c) the "vision" of a real world visual scene for which scenarios were to be obtained with the cooperation of the U.S. Marine Corps at Camp Pendelton, California.[40]

During the last part of 1979, while discussing the merits of a transfer-of-training study that Fletcher favored (without universal CTO support[41]), an expansion of the initial objectives was stimulated by further consideration of the tank gunner's job and related requirements for training gunners with a device such as the Tank Gunnery Trainer. First, it was recognized that some of the gunner's actions are in response to instructions from the tank commander. So, the thought of representing the commander, for example, by digitally coded instructions programmed into the trainer, was discussed along with the alternate idea of developing a Tank Team Gunnery Trainer. During one of these discussions, a military trainer at Fort Knox said to Fletcher words to the effect, "We have gunnery trainers all over the place. What we need is a way to train a tank platoon." To which Fletcher recalls having responded, "We could do that easily by hooking five [of the Tank Gunnery Trainers] together so that they can interact."[42]

2. Gestation and Planning

During the winter of 1979-80, Fletcher explored with the contractor, Perceptronics, some of the possibilities for developing a Tank Team Gunnery Trainer (TTGT) by

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microprocessor architecture eventually employed in the SIMNET system; personal note to Fletcher from W.S. Chambers, NTSC, 2 March 1990.

[40] Fletcher, ibid.

[41] Fields, who was then CTO Director, did not favor DARPA sponsorship of the transfer-of-training study, arguing that training effectiveness was not a DARPA technology-development function, but rather a Service training-affordability issue. Fletcher, ibid.

[42] Fletcher, ibid.

networking together several Tank Gunnery Trainers--quickly and at low cost.[43] Specifically, the approach discussed was one of adding the necessary capabilities to support a "quick-draw" competition. The concept was that several Tank Gunnery Trainers would be networked to view a single videodisc-generated scene, with the trainees competing to be the first to sight and fire at an "enemy" tank.[44] Thus, although the TTGT concept did not include many of the characteristics of the SIMNET system, it was clearly a step in the right direction on the path towards SIMNET development.

At about the same time, however, Fletcher began planning to leave DARPA. As an early step, he began searching for persons who could possibly replace him and continue the developmental direction initiated by the Tank Gunnery Trainer program. He learned that Jack A. Thorpe, an Air Force officer, had ideas regarding what could be done in training with the interactive battle-engagement networking of such trainers.[45]

Thorpe was just completing a course of advanced military education at the Naval War College. He had served at the Operations Training Division of the Air Force Human Resources Laboratory (AFHRL/OT, Williams AFB) and was familiar with the potentials of computer image generation (CIG) and its application to simulation for flying training.[46] He was also familiar with the high costs associated with large aircraft simulators such as the Advanced Simulator for Pilot Training (ASPT) at AFHRL/OT and the Advanced Technology Visual System (ATVS) at NTSC. As part of his duties in the Life Sciences Directorate of the Air Force Office of Scientific Research.(AFOSR) just prior to his tour at the Naval War College, he had maintained a current appreciation of the technologies that could contribute to the future development of simulators for collective as well as individual training.[47]

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[43] Discussion with A. Freedy, Perceptronics, at IDA on 5 December 1989.

[44] The concept did not extend to an *interactive* one-vs.-one, one-vs.-many, or many-vs.-many battle simulation, but was limited to a many-vs.-"iron horse" paradigm--i.e., many trainee gunners competing among themselves against a computer controlled graphics representation of their firing on a single-view videodisc scene in which "enemy" tanks appeared; Fletcher, ibid.

[45] Fletcher, ibid.

[46] During the mid-1970's, while he was assigned to AFHRL/OT, Thorpe and several of his colleagues had many discussions on, and perhaps actually conceived of, the networking of many low-cost simulators of sufficient fidelity to provide combat-skills training for pilots. Among those included were Don Bustell, Mike Cyrus, John Fuller, Liz Martin, Gary Reid, Rob Reis, and Wayne Waag Telephone discussion with E.L. Martin, AFHRL/OT, on 14 March 1990; and telephone discussion with M. Cyrus, La Jara, Colorado, on 11 April 1990.

[47] Discussion with J.A. Thorpe, DARPA European Office, on 16 October 1989 at Stuttgart, West Germany.

Thorpe had also come to the view that it was wrong to consider flight simulators as substitutes for aircraft to be used for training skills that pilots learned by flying. Rather, simulators should be used to augment aircraft. They should be used to train air-combat skills that pilots could not learn in peacetime flying, but that could be trained with simulators in large-scale battle-engagement interactions. He had proposed this as a 25-year simulation-development goal during the Fall of 1978 in an unpublished AFOSR concept paper.[48]

Thus, before Fletcher left DARPA in the Fall of 1980, he contacted Thorpe and introduced him to the CTO director, Fields, who then set about having Thorpe assigned to DARPA as a replacement for Fletcher. Thorpe joined the CTO staff in January 1981, and started where Fletcher left off--managing the Tank Gunnery Trainer project[49] and developing further the networking of several devices to provide a platoon-level, low-cost Tank Team Gunnery Trainer.[50] He also began developing an expanded proposal emphasizing networking technology--an idea that later became the SIMNET project.[51] His belief was that both the survivability of our friendly forces and the damage they would be able to inflict on enemy forces would be substantially enhanced were we able to provide opportunities for them to enter their first few warfighting battles in the relatively benign environment of a simulation.[52] His concept was to develop and demonstrate the utility of the low-cost, large-scale, battle-engagement simulation technology that would permit such "combat" training--just as he had envisioned earlier, but now aimed at ground troops, not air.[53]

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[48] J.A. Thorpe (Captain, USAF), "Future Views: Aircrew Training 1980-2000," unpublished concept paper at the Air Force Office of Scientific Research, 15 September 1978, available from the author.

[49] The (approximately 100) units that were built by Perceptronics through DARPA for test and evaluation by U.S. and allied military establishments eventually stimulated acquisition, first of devices now known as the "Videodisc Interactive Gunnery System (VIGS)," and later of the "Precision Gunnery Training System (PGTS)"; Jacobs, ibid.

[50] Thorpe had maintained contact with researchers active in the area, including some of his former colleagues at AFHRL/OT. He explored with them his ideas of applying video-game technology for tank gunnery training and telerobotics technology for maintenance training. He actively pursued many of the technologies that showed promise of relevance, not limited to those being developed by the DoD, but also including those being developed by the entertainment and electronics industries. He had set a goal of very low cost per unit in production, and even began to investigate the feasibility of molding a tank "cockpit" that would accommodate a full crew. Martin, ibid.

[51] Freedy, ibid.

[52] Jacobs, ibid.

[53] For example, see A.J. Owens and R.F. Stalder, Jr., *The Adaptive Maneuvering Logic in Tank Warfare Simulation, Final Report* (No. DSI-82-413-F), Decision Science, Inc., San Diego, California, May 1982. The report describes the results of a nine-month effort under DARPA Contract No. MDA903-

"Affordability" was, in Thorpe's view, a core requirement for the system he envisioned.[54] He had experienced the cancellation by the Air Force of "Project 2360," an engineering development effort to prototype a high-resolution, high-brightness, full-field-of-view CIG-based visual system for flight simulators.[55] The reason given for the cancellation was excessive costs--at the time, a single visual system for the proposed simulator was estimated to cost on the order of $30 million, and a single simulator over $35 million, roughly the price of two fighter aircraft. Also, in 1977 the Army had cancelled a similar program for a Full Crew Tank Simulator (Project FCTS) for much the same reason of excessive costs ($18 million). Thus, affordability had been demonstrated to be a major issue in the Military Departments with substantial impact on the development and use of simulators for training.[56]

During the Summer of 1982, Thorpe asked a retired Army Colonel, Gary W. Bloedorn, to help develop, as a DARPA consultant, a network of tank simulators suitable for collective training. Bloedorn promised to pass word of the potential DARPA development to Brigadier General Frederic J. Brown, Jr., then Deputy Chief of Staff for Training at Headquarters, U.S. Army Training and Doctrine Command (TRADOC), Fort Monroe, Virginia.[57] Brown sent a representative, Colonel Harm Stryker, to talk with Thorpe about the proposal. Stryker reported back to Brown that the proposal had merit, or at least potential, for armored-vehicle team training. Brown, who had been notified of his selection for promotion to Major General with a likely new assignment as Commandant of

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81-C-0509 directed toward "the design and development of a computer program for realistic, intelligently interactive tank warfare simulation..." and based on "experience gained in the development of the Adaptive Maneuvering Logic (AML) program for air-to-air and naval combat simulation..." (p. 1).

[54] Thorpe expressed views to the effect that not only would the system have to be of sufficiently low cost to permit the Services to procure the thousands of copies needed for the collective combat-skills training, but also the changes in technology were occurring so rapidly that the Government's buying low-cost, commercially available, off-the-shelf items with a limited life-span would be better than its buying specially developed "mil-spec" items that would last so long that they would be technologically dated before wearing out. Martin, ibid.

[55] Although the engineering development project was cancelled, an advanced development effort, "Project 2363," was continued under an AFHRL/OT-managed contract with the General Electric Company, Daytona Beach, Florida. See R.L. Ferguson, "AVTS: A High Fidelity Visual System," in *Proceedings of the 1984 IMAGE-III Conference*, E.G. Monroe, ed., Air Force Human Resources Laboratory, Williams Air Force Base, Arizona, 1984, 475-485.

[56] Thorpe, 1989, ibid.

[57] Bloedorn and Brown, among others, had authored an Army Training Study that identified problems or needs, certain of which DARPA was trying to address through applicable development of videodisc, microprocessor, and other emerging technologies in the Tank Gunnery Trainer program; Jacobs, ibid.

The Armor School at Fort Knox, Kentucky, indicated a willingness to support the development to the extent that it would address the collective training needs of Armor units.[58]

In the meantime, Perceptronics brought Bloedorn together with Jacobs (a technical staff member working on the Tank Gunnery Trainer) and Ulf Helgesson, an industrial designer from Los Angeles on a consulting retainer. It was agreed that should Perceptronics decide to prepare a proposal for SIMNET development, the three would work together--Jacobs as a member of Perceptronics technical staff, and Bloedorn and Helgesson as consultants. Jacobs would focus on the technology and technical issues, Bloedorn on the military operational and training issues ("the definition of what the simulation system would do"), and Helgesson on the industrial design and human factors issues.[59] These three--Bloedorn, Jacobs and Helgesson--were destined to play central roles in the SIMNET development.[60]

3. Component Development

The SIMNET project was approved by DARPA management late in 1982, and initiated by DARPA early in the Spring of 1983.[61] There were three initial contracts: (a) Perceptronics[62] was to develop the training requirements, and conceptual designs for the vehicle-simulator hardware and system integration,[63] (b) BBN[64] was to develop the networking and graphics technology,[65] and (c) the La Jolla, California, unit of SAIC[66] was to conduct a six-month "lessons-learned" study of Army field-training experiences

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[58] Telephone discussion with G.W. Bloedorn, on 20 February 1990.

[59] Discussion with U. Helgesson, Los Angeles, California, on 12 April 1990; Bloedorn, 1990, ibid.; Jacobs, ibid.

[60] Thorpe, 1989, ibid.

[61] Thorpe, 1989, ibid.; AO 4739, signed 15 February 1983.

[62] See fn. 26.

[63] Telephone discussion with J.M. Levine, Northridge, California, on 6 March 1990; Bloedorn, 1990, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[64] BBN Laboratories Incorporated, now BBN Systems and Technologies Corporation (A Subsidiary of Bolt Beranek and Newman Inc.). BBN had been a principal ARPANET developer, and thus brought to the SIMNET effort its experience with packet switching network technology; see Volume I, Chapter XX.

[65] Bloedorn, 1990, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[66] Science Applications International Corporation.

with armor and mechanized infantry units using the instrumented ranges at the National Training Center, Fort Irwin, California.[67]

Perceptronics produced the first data handbook for the SIMNET development in March 1983.[68] The handbook provided initial data and background information, and it served as a general orientation for the subsequent six-month development study that was scheduled to begin in April 1983. Specifically, the preface to the handbook stated,

> The data and information contained herein describe the M1 Abrams tank, the basic organization that employs the tank, as well as the organic command, control, and communication systems used to employ units; the training, and the logistics attendant to preparing and supporting the employment of the tank.[69]

The second volume of the data handbook, providing data on the M2 Bradley Fighting Vehicle (BFV) and the M3 Cavalry Fighting Vehicle (CFV), was completed in August 1983.[70] It was intended for use in conjunction with the M1 tank data package in providing information on the specific combat systems to be simulated. The preface stated,

> The data and information contained herein describe the M2 BFV and the M3 CFV, as well as the training and logistic burdens/requirements related to field operations of mechanized infantry and reconnaissance units equipped with these weapon systems. Command and control procedures, communications, logistics, troop leading and logistic procedures for M2/M3 equipped units are, for purposes of this development program, identical to those of M1 tank units. For this reason the reader should refer to appropriate sections of the M1 data package, published under separate cover, for information on these topics[71]

This was a highly innovative approach at a time when simulators were typically designed to emulate the vehicles they represented as closely as engineering technology and the available funds permitted. The usual design goal was to reach the highest possible level of physical fidelity--to design "an airplane on a stick," as it were. The SIMNET design goal was different. It called for learning first what functions were needed to meet the training objectives, and only then to specify the needs for simulator hardware. So.

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[67] Bloedorn, 1990, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[68] G.W. Bloedorn, *Large Scale Simulation Data Package, Vol. I: M1 Abrams Tank*, Perceptronics, March 1983(a); also see G.W. Bloedorn R. Kaplan, & R.S. Jacobs, *Large Scale Simulation Data Package*, Perceptronics, March 1983.

[69] Bloedorn, 1983(a), ibid., p. 1.

[70] G.W. Bloedorn, *Large Scale Simulation Data Package, Vol. II: M2 & M3 Fighting Vehicle*, Perceptronics, August 1983(b).

[71] Bloedorn, 1983(b), ibid., p. ii.

selective functional fidelity, rather than full physical fidelity, was SIMNET's design goal, and as a result, many hardware items not regarded as relevant to combat operations were not included or designated only by drawings or photographs in the simulator. This approach also helped minimize costs, thus making possible the design of a relatively low-cost device.[72]

Among those to whom Thorpe briefed the program during the Spring and Summer of 1983, seeking Army support, were the Commandants of The Armor School at Fort Knox, Kentucky, and The Infantry School at Fort Benning, Georgia. Major General Brown, by then Commandant of The Armor School, reiterated his support of the project, and promised the support of the school, provided SIMNET would build armored-vehicle simulators and address Army collective training requirements.[73] By the end of the Summer of 1983, both Armor and Infantry Schools had agreed to participate in validation of the military requirements for SIMNET.[74]

Thorpe's concept for the development was to build an early low-cost prototype--a "60 percent solution" to take into the field as a concrete device to be modified and improved on the basis of informal tests and evaluations.[75] At Perceptronics, Jacobs, having been predominant in the Tank Gunnery Trainer development, was now assigned a principal role in the SIMNET project. He articulated the "rule" that, in lieu of detailed engineering specifications, the government would provide the contractor, Perceptronics, a listing of the "minimum essential" characteristics that the simulators must have.[76] Bloedorn, working as a consultant, provided key information for that listing, and continued to advise the development team regarding armor operational and training doctrine, practices, and issues.[77]

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[72] Bloedorn, 1990, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[73] Bloedorn is credited by Thorpe with having provided the Army field-training and operational expertise that made the difference between success and failure of the SIMNET technology demonstration. Thorpe. 1989, ibid.

[74] Bloedorn, 1990, ibid.; Thorpe, 1989, ibid.

[75] Freedy, ibid.; Helgesson, ibid.

[76] Thorpe, 1989, ibid.

[77] Bloedorn identified the best five missions for which SIMNET should be designed to train as the following: (a) hasty attack, (b) deliberate attack, (c) hasty defense, (d) deliberate defense, and (e) passage of lines. The five missions were broken down into the nine collective skills that are required to perform sixty-two collective tasks. The tasks were associated further with the specific military occupational specialty (MOS) duties of the armored-vehicle crew members. Bloedorn, 1990, ibid.; Thorpe, 1989, ibid.

Thorpe and the development team started the design with identification of the cues that had to be presented to the crew member in order to train specific duties and tasks. Once the necessary cues had been identified, the development team would propose ways of delivering the cues efficiently (i.e., at low cost) and effectively (i.e., for collective training). Only after these considerations were articulated, understood, and accepted by the development team would the "clever technologies" (i.e., hardware) be devised to provide the cues. Such were the behavioral (training) requirements employed as design criteria throughout the development.[78]

To be successful, this behavioral approach required that the scientists and engineers on the development team learn more about how armor units operated and how they were trained. So, during the Fall of 1983, they went to The Armor School at Fort Knox, Kentucky, for field training in close combat heavy skills with actual equipment.[79] Thus armed with this experience, the development team's SIMNET design process became "behaviorally driven." For example, the process required the recognition and provision of the essential touch-and-feel cues in the SIMNET simulators. Input regarding these cues came from a wide variety of persons with relevant expertise--operators, trainers, engineers, and psychologists--many of them on the development team, but others from elsewhere.[80] The design did not concentrate on the armored vehicle, *per se*. Rather, the vehicle simulator was viewed as a tool--a training device that when networked with other vehicle simulators would enhance the training of the crews as a collective, i.e., as a military unit. The major interest was in *collective*, not *individual*, training. The design goal was to make the crews and units, not the devices, the center of the simulations.[81]

Where design options were to be exercised, and there were frequent choices to be made especially regarding the physical fidelity of the simulator, the development team insisted that the decisions be based on the likelihood of obtaining the desired trainee behavior. They asked the question, "What would the trainee do differently," if he has what

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[78] Thorpe, 1989, ibid.

[79] There were three phases in the training: (1) orientation to the vehicles, (2) academic instruction on the concepts and doctrine of armor-unit behavior in battle, and (3) the Armor Officer Basic Course. Bloedorn, 1990, ibid; Thorpe, 1989, ibid.

[80] Thorpe, 1989, ibid.

[81] The training concept was to provide a means of cuing individual behavior, with the armored vehicle being part of the cuing. When individuals and crews reacted, they would provide additional cues to which others would react. Thus, the technology was to play a subservient role in the battle-engagement simulations, making no decisions for the crews, but rather simply and faithfully reproducing battlefield cues. Bloedorn, 1990, ibid.

you want to include instead of what we propose? Where the answer was, "Nothing!" as was frequently the case, the point was usually conceded and the decision made to go with a less-complex (and less-expensive) representation of the actual armored-vehicle equipment. Such was the manner in which SIMNET simulators achieved the design goal of selective functional fidelity, rather than full physical fidelity.[82]

There were other design issues, of course, but these were also resolved in the direction of the behavioral goals. Some of the issues seemed quite controversial at the time. For example, the trainers were developing roles for instructors, and designs for instructor operator stations (IOSs). The behavioral scientists from one of the contractors argued that the presence of instructors, made effective with the use of properly designed IOSs, would be the only way of gaining information regarding what was being learned, by whom, how, and to what level. But the issue, as rephrased by Bloedorn, with the support of General Brown, was "How does a commander at any level diagnose performance deficiencies of his unit and correct them while he is in contact with the enemy?" And since the answer did not provide any "third party" looking over the shoulder of the commander or his troops, they argued that neither should SIMNET. They counselled instead, "Let the soldiers alone. Let the chain of command control its own training."[83] As a result, SIMNET has no "instructors," no IOSs, and no third parties looking over the shoulders of the soldier-trainees. The after-action reviews are conducted by the commanders of the units involved. The cuing feedback during the action is provided by the simulated battle-engagement environment itself, including, of course, the interactions with other elements of the military units taking part in the collective training scenario.[84]

The developmental process was to construct mock-ups of hardware elements that were designed or proposed to satisfy the requirements of providing the proper "touch and feel" of the cues required for training the desired performances, and to work these into the

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[82] Each active display and control in each vehicle simulator remained tied to the performance of a specific task--a function to be trained. There were no superfluous live displays or controls inserted in the simulators simply because the "real" vehicles had them; Bloedorn, 1990, ibid.; Helgesson, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[83] Thorpe, 1989, ibid.

[84] Bloedorn, 1990, ibid.; although arguably included in the concept of "collective" training, it was only later, after actual "field" trials, that the SIMNET development team recognized that SIMNET's "articulation" of command-and-control training provides the larger payoff, not individual armored-vehicle crew training. Thorpe, 1989, ibid.

software logic, from laboratory racks, through plywood foam-core mock-ups, to a fiberglass prototype.[85]

The first SIMNET foam core mockup of the M1 (Abrams) tank was demonstrated at Fort Knox during the Spring of 1984, just about one year after project initiation. At about the same time, the SIMNET concept was demonstrated at the facilities of the Army's principle acquisition agency for simulators and other training equipment--the Army Project Manager for Training Devices (PM TRADE), in Orlando, Florida.[86]

A major crisis had arisen during the early months of 1984 when it appeared that the visual-display and networking architecture being developed by BBN would not support the SIMNET system concept within the limits of the low-cost constraints. Analyses and expert judgments, from both within and outside of DARPA, indicated that the planned use of available off-the-shelf visual-display technology would not support the required scene complexity within the cost, computer, and communications constraints set by the SIMNET goals.[87] DARPA's management, projecting the technology to be inadequate and too costly, was considering abandonment of the project.[88]

However, Thorpe had received a proposal from the Boeing Aircraft Company in Seattle, Washington, for development of a new low-cost microprocessor-based CIG technology for visual displays such as those envisioned for SIMNET.[89] The proposed technology appeared interesting--it promised to meet the scene complexity ("moving models") requirements at acceptably low dollar and computational costs. Also, if it worked, it would permit use of a simpler networking architecture--one that would be less costly in communications capacity and dollar requirements. The proposed technology would use microprocessors in each tank simulator to compute the visual scene for that tank's own "virtual world," including the needed representations of other armored vehicles,

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[85] At each stage of the development, the concrete models of the product were "demonstrated," i.e., put into the hands of the soldiers who worked very closely with the development team, for their reactions and suggestions, which often led to changes (improvements) in the design of the next simulator unit produced. This process provided the necessary input for the success of Thorpe's approach of stopping short of a full-scale emulation of the vehicle with a less complex and less costly device that was good enough to achieve the training objectives desired--a "60 percent solution"; Bloedorn, 1990, ibid.; Helgesson, ibid.; Jacobs, ibid.

[86] Thorpe, 1989, ibid.

[87] Bloedorn, 1990, ibid.; Cyrus, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[88] Thorpe, 1989, ibid.

[89] The new CIG technology was being developed at Boeing by Cyrus (see fn. 39) who had left AFHRL/OT and joined Boeing during the early months of 1984. Bloedorn, 1990, ibid.; Cyrus, ibid.; Martin, ibid.; Thorpe, 1989, ibid.

both "friendly" and "enemy." The network would not have to carry all the information in the visual scenes (or potential visual scenes) of all simulators. Rather, the network transmission could be limited to a relatively small package of calibration and "status-change" information.[90] Thorpe proposed that the then-current contract for development of the networking and graphics technology be terminated or amended, and that the Boeing proposal be funded.[91]

Some were skeptical. They judged the risk to develop the new technology too high. Thorpe argued the case,[92] and won approval to proceed.[93] The stipulation was made that the new technology would have to be successfully demonstrated by the beginning of the next fiscal year, i.e., by October 1984, or the project would be terminated at that time. However, when Thorpe approached Boeing regarding their proposal, they were no longer interested in pursuing the matter. Cyrus then offered to leave Boeing in order to devote his full energies to developing the graphics technology for SIMNET. He founded an independent company, Delta Graphics, to do so. The initial contractor, BBN, continued with responsibility for the network technology, but with the needed change in architecture, i.e., with use of microprocessor-based graphics generators.[94]

A "breadboard" demonstration of the graphics technology was made within the deadline, and in January 1985 a rack-mounted SIMNET-system mock-up with graphics was put together in the Perceptronics office near the DARPA headquarters building to demonstrate the SIMNET *concept* --the concept of a network of low-cost armored-vehicle simulators that could be used for collective training of Army armor and mechanized infantry

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[90] That concept had been demonstrated by ARHRL/OT in the Summer of 1979 with a four-line telephone linkage between a cockpit of the Simulator for Air-to-Air Combat (SAAC) at Luke Air Force Base, Arizona, and a cockpit of the Advanced Simulator for Pilot Training (ASPT) at Williams Air Force Base, Arizona, 60 miles away. The successful demonstration was reported in July 1979 to the Commander of Air Force Systems Command, along with the concept of flight simulators--Combat Mission Trainers (CMTs)--networked together and with Army and Navy simulators to provide realistic air-combat and close-air-support training for Air Force pilots. Telephone discussion with D.K. Meigs (Lt Col, USAF), 3302nd Technical Training Squadron, Keesler Air Force Base, Mississippi, on 19 March 1990.

[91] Bloedorn, 1990, ibid.; Thorpe, 1989, ibid.

[92] In a courageous, and bureaucratically rare, demonstration of his personal commitment to the project and the military need for its development, Thorpe had put his career "on the line" in arguing that he should be permitted to proceed as he deemed best, or be relieved as Project Manager and transferred. Bloedorn, 1990, ibid.

[93] Weltman considers this early DARPA sign-off on the feasibility of the technical approach to be one of four critical milestones in SIMNET development; G. Weltman, personal memorandum to the author on "SIMNET Case History," 2 March 1990.

[94] Bloedorn, 1990, ibid.; Cyrus, ibid.; Thorpe, 1989, ibid.

units. The demonstration included not only the SIMNET plywood-version M1 tank simulator, but also the fire support, logistics support, communications support, and a representation of the Tactical Operations Center. When this was demonstrated to the Secretary of the Army, the Army Chief of Staff, the Vice Chief of Staff, and other high-level Army officials that month, their reaction was positive--sufficiently positive that the Army began to support DARPA's further development of the SIMNET technology.[95]

4. System Development, Networking and Testing

The system design concept was well-established by 1985. SIMNET would consist of local and long-haul nets of interactive simulators for maneuvering armored vehicle combat elements (M1 tanks and M2/3 fighting vehicles), combat-support elements (including artillery effects and close air support with both rotary and fixed-wing aircraft), and all the necessary command-and-control, administrative and logistics elements--for both "friendly" and "enemy" forces. A distributed-net architecture would be used, with no central computer exercising executive control or major computations, but rather with essentially similar (and all necessary) computation power resident in each vehicle simulator or center-nodal representation.[96]

The terrains for the battle engagements would be simulations of actual places, 50 kilometers by 50 kilometers initially, but eventually expandable by an order of magnitude in depth and width. Battles would be fought in real time, with each simulated element--vehicle, command post, administrative and logistics center, etc.--being operated by its assigned crew members. Scoring would be recorded on combat events such as movements, firings, hits, and outcomes, but actions during the simulated battle engagements would be completely under the control of the personnel who were fighting the battle. Training would occur as a function of the intrinsic feedback and lessons learned from the relevant battle-engagement experiences. Development would proceed in steps, first to demonstrate platoon-level networking, then on to company and battalion levels, and later perhaps on to even higher levels.[97]

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[95] Bloedorn, 1990, ibid.

[96] See J.A. Thorpe, "The New Technology of Large Scale Simulator Networking: Implications for Mastering the Art of Warfighting," in *Proceedings of the 9th Interservice/Industry Training Systems Conference, November 30--December 2, 1987*, American Defense Preparedness Association, 1987, 492-501.

[97] See J.A. Thorpe, 1987, ibid.

The system would be developed by applications in three technology domains: (a) the simulators, (b) the computational hardware, software, and networking, and (c) the graphics for the visual displays.[98] The development team contractors for the three areas were Perceptronics, BBN, and Delta Graphics, respectively.[99] Thorpe, as project manager, served essentially as the program's chief executive officer (CEO), matching the contractors' capabilities with the users' interests and needs throughout the program, to the advantage of all.[100]

Each simulator was developed as a self-contained stand-alone unit, with its own graphics and sound systems, host microprocessor, terrain data base, cockpit with task-training justified controls and displays only,[101] and network plug-in capability (Figure 16-1[102]).

Thus, each simulator generates the complete battle-engagement environment necessary for the combat mission training of its crew. For example, each tank crew member can see a part of the virtual world created by the graphics generator using the terrain data base and information arriving via the net regarding the movements and status of other simulated vehicles and battle effects. The precise part is defined by the crew member's line of sight--forward for the tank driver, or from any of three viewing ports in a rotatable turret for the tank commander.[103]

The visual display depends primarily on the graphics generator resident in each simulator. It is a computer image generation (CIG) system that differs in several important characteristics from earlier CIG systems such as the ASPT and VTRS previously discussed. First, it is microprocessor based (vs. large mainframe or multiple minicomputer based), and therefore relatively low in cost (less than $100,000 per simulator visual-display subsystem, vs. more than $1 million per visual channel). Secondly, it is *high in*

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[98] This was the second of the four critical milestones identified by Weltman (see fn. 93); namely, the "...logical subdivision of the program effort into the three technical areas (simulators, computer hardware/software, and vision systems), with the establishment of a program structure able to manage and integrate contributions of the three associated contractors..."; Weltman, ibid.

[99] See AO 5608 and AO 5825, amendments signed 11 and 28 July 1986, respectively.

[100] Freedy, ibid.

[101] As indicated earlier, the design was behaviorally driven using a concept of selective functional fidelity in which those simulator characteristics that were deemed necessary for the desired training are included in relatively high fidelity, whereas those deemed not necessary for training are in low fidelity or not included at all; Bloedorn, 1990, ibid.; Helgesson, ibid.; Jacobs, ibid.; Thorpe, 1987, ibid.

[102] Adapted from Thorpe, 1987, ibid., p. 495.

[103] Thorpe, 1987, ibid.

environmental complexity with many moving models and special effects, but *low in display complexity* with relatively few pixels, small viewing ports, and a relatively slow update rate of 15 frames per second (vs. the opposite with earlier CIG systems and the technology being developed to improve and replace them). The development of the essentially unique graphics generator for SIMNET was a principal factor in permitting the system to meet the low-cost-per-unit constraint of the plan.[104]

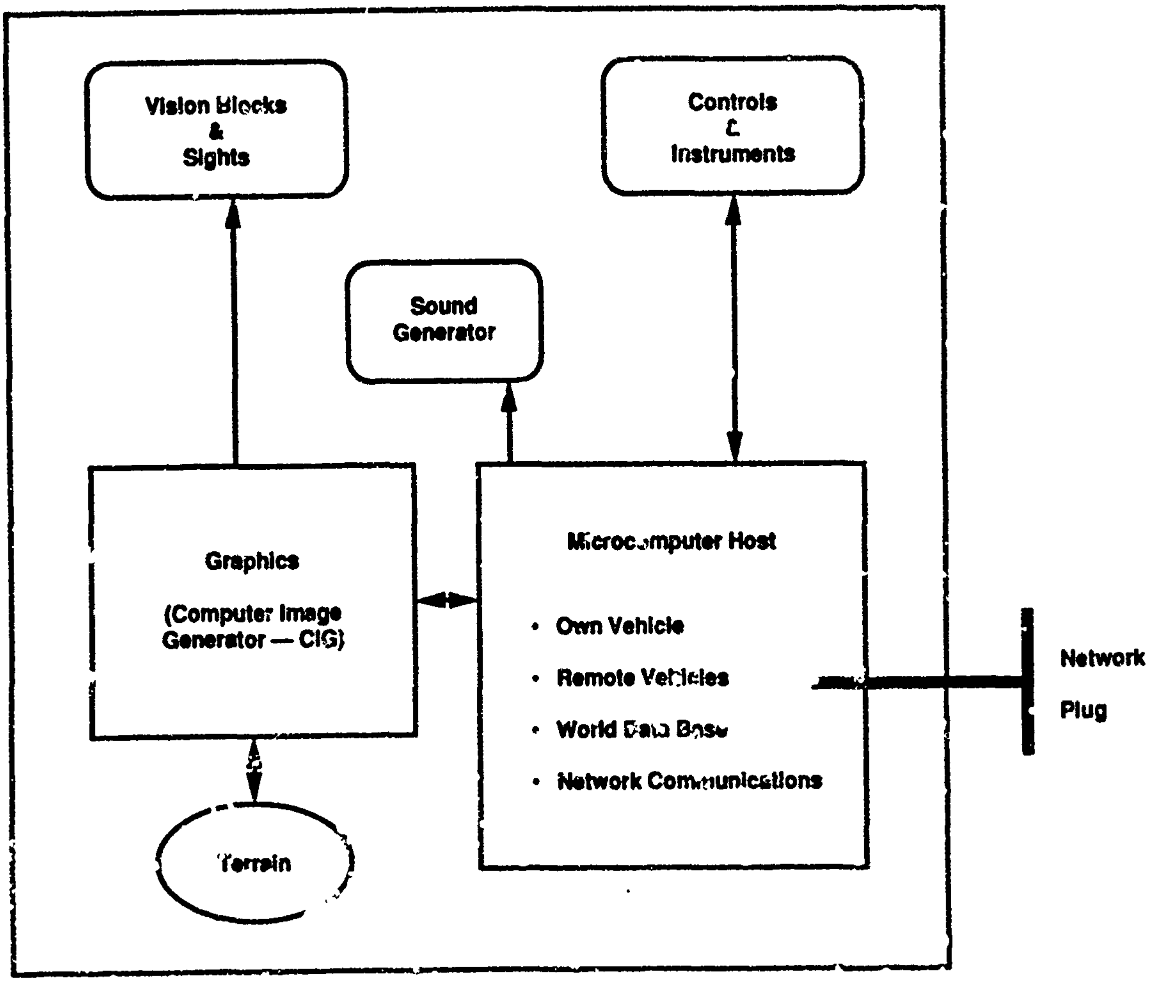

Figure 16-1. Architecture of a Single M1 (Abrams Tank) Simulator in SIMNET

(Adapted from J.A. Thorpe, "The New Technology of Large Scale Simulator Networking: Implications for Mastering the Art of Warfighting," in *Proceedings of the 9th Interservice/Industry Training Systems Conference, Nov. 30 -- Dec. 2, 1987*, American Defense Preparedness Association, 1987, p. 495.)

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[104] See Ferguson, ibid.; and Thorpe, 1987, ibid.

The architecture of the microprocessor-based graphics generator permits anyone or any simulator so equipped to connect to the net. This, combined with the distributed computing architecture of the net, provides an extremely powerful and robust system. New or additional elements can be included simply by "plugging into" the network. Once connected to the net, simulators transmit and receive data "packets" from other simulators or nodes (such as stations for combat-support or logistics elements), and compute their visual scenes and other cues (such as special effects produced by the sound system). Because the data packets need to convey only a relatively small amount of information (position coordinates, orientation, and unique events or changes in status), the communications load on the net and the increase in load with the addition of another simulator are both quite modest. Also, where updating information is slow in coming from another simulator, its state can be inferred, computed, and displayed. Then, when a new update is received, the actual-state data are used in the next frame, and any serious discontinuity is masked by the receiving simulator's automatic activation of a transition-smoothing algorithm. Should a simulator fail, the rest of the network continues without its contribution. Thus, network degradations are "soft and graceful."[105]

SIMNET employs both local area and long haul networks (LANs and LHNs). Thus, it supports a network distribution not only horizontally among simulators or elements of the same or similar kinds, but also vertically among simulated nodes representing the command-and-control, combat-support, combat-service-support, and logistics elements that constitute an entire battle force--i.e., an entire military "collective" committed to engage an enemy force in battle. This kind of battle-engagement simulation includes all the important elements of reality needed to support SIMNET's collective training objective. Further, having been designed to use both LANs and LHNs, SIMNET also permits geographically separated military elements to interact in a common battle engagement over the same simulated terrain. The LAN architecture in SIMNET is a relatively simple application of ether-net technology as shown in Figure 16-2.[106]

The LHN architecture initially employed wide-band land lines capable of joining separated LANs or individual simulators into a common net. Plans called for the LHN eventually to use satellite communications capabilities to expand the flexibility of SIMNET participation. Packet switching protocols, previously developed as part of the ARPANET

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[105] Thorpe, 1987, ibid., p. 495.

[106] Adapted from Thorpe, 1987, ibid., p. 495.

project,[107] were adapted to provide the means for transmitting the data needed by the simulators and other SIMNET nodes to compute the actions taking place in their virtual-world battlefields.[108]

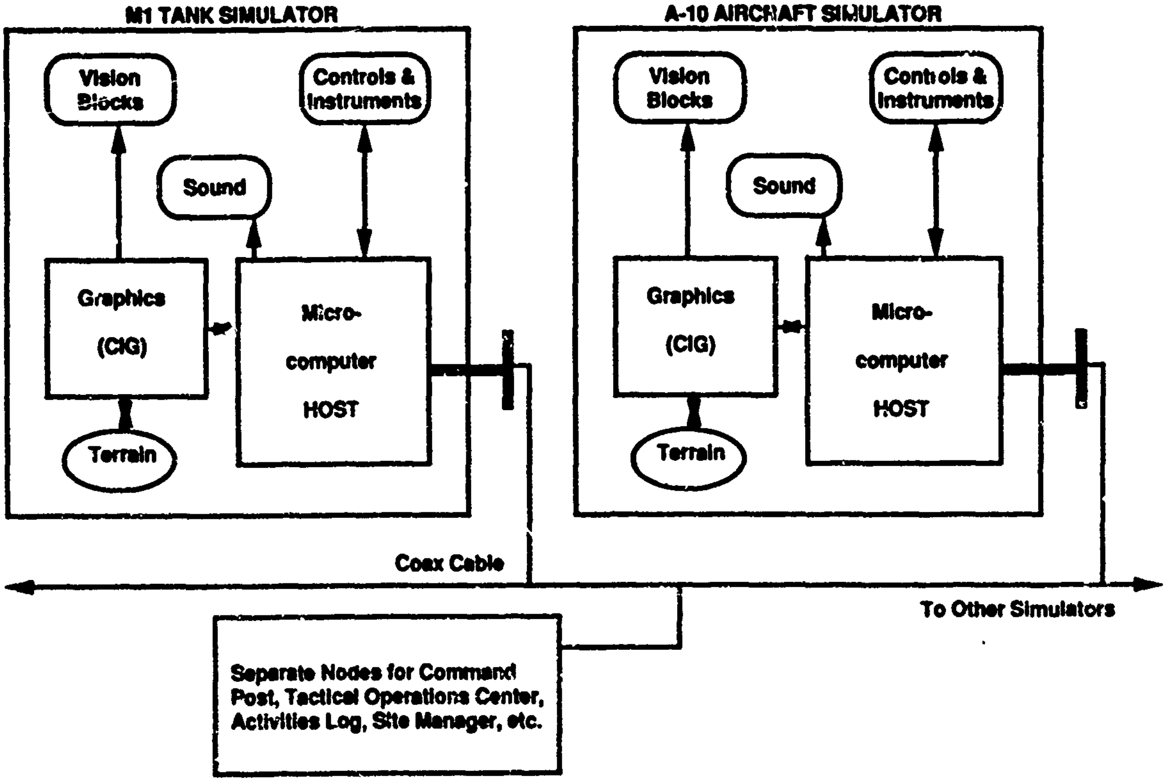

Figure 16-2. Architecture of SIMNET Local Area Network (LAN)

(Adapted from J.A. Thorpe, "The New Technology of Large Scale Simulator Networking: Implications for Mastering the Art of Warfighting," in *Proceedings of the 9th Interservice/Industry Training Systems Conference, Nov. 30 -- Dec. 2, 1987*, American Defense Preparedness Association, 1987, p. 495.)

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[107] See Volume I, Chapter XX.

[108] Thorpe, 1987, ibid.

SIMNET development followed the system design concept and plan. The first two laboratory versions of the M1 (Abrams) tank simulators were completed and tested, then they were networked and demonstrated at the annual convention of the Association of the United States Army (AUSA) during October 1985 in Washington, DC. By May 1986, two "final-version" M1 tank simulators were networked at Fort Knox, and by October 1986 these had been increased to two platoons (eight M1 tank simulators)--including representations of combat support and logistics elements such as the Tactical Operations Center (TOC), supporting artillery (ARTY), close air support (CAS), and the Administrative and Logistics Operations Center (ALOC)--all housed temporarily in Hill Hall at Fort Knox.[109]

There were now a sufficient number of simulators to demonstrate--at least at the platoon level--the collective training capability that the SIMNET system was being designed to provide. Also, the experiences gained through the demonstrations of actual Armor troops using the available simulators provided valuable information that influenced beneficially further development of the additional simulators required for the SIMNET goal of battlion-level training. The developmental approach was one of iterative prototyping that permitted the "lessons learned" from each new SIMNET "field-trial" experience with troops to be incorporated into the next simulator units developed through modifications of the prior designs.[110] Thus, with the flexibility permitted by developmental (as contrasted with production) prototyping, each new addition to the pool of available simulators was essentially an improved version of its predecessor. Where weaknesses were identified or possible improvements discovered, Thorpe and the development team "just backed up and did it right the next time."[111]

As development of the simulators was progressing, attention was also being focussed on the design of a suitable structure in which to house them. The initial SIMNET system concept called for them to be put into trailers (two simulator units per trailer) that could be hauled by semi-trailer rigs from one Army post to another, there to be interconnected with one or more "control-room" trailers or buildings that would supply the

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[109] Jacobs, ibid. Also, these were the two remaining of the four critical milestones identified by Weltman (see fn. 93), "... assembly and test of the first prototype 'in full public view' at Ft. Knox [in May 1986]...," and "...networking of the first four or eight simulators at Ft. Knox [in October 1986], which showed everybody that the rest was just a matter of getting the production cranking -- and, of course, evaluating the full-scale warfighting exercises." Weltman, ibid.

[110] Bloedorn, 1990, ibid.; Cyrus, ibid.; Jacobs, ibid.; Thorpe, 1989, ibid.

[111] Weltman, ibid.

necessary support facilities and connections. However, when Perceptronics' design consultant, Ulf Helgesson,[112] studied the various options and their costs, he found a solution that not only would serve better the SIMNET system requirements, but also would be less costly than the trailers or other options. That solution, which he recommended, called for the construction of a self-contained pre-engineered facility that could be "unbolted," moved, and reconstructed at other sites, with no additional costs except those for suitable foundations.[113]

Since the SIMNET "warfighting" facilities, including the structures for SIMNET-T and SIMNET-D, were project funded, they did not require the long lead times generally associated with the procedures, approvals, and funding lines typical of military construction projects. Helgesson met with, explained the SIMNET project to, and obtained the cooperation and help of the construction, contracting, and engineering offices and personnel at Fort Knox. He also met with local architectural, construction, and supplier firms in the Louisville area to air the facility requirements. Thus, when the construction packages were bid, the firms that responded had information regarding the context as well as the details of the structure they were to erect. As a result, the cost of the SIMNET-T facility erected with steel cables (substituting for piers) under tension below a minimum slab foundation was on the order of $65 per square foot, as contrasted with the $110 per square foot estimated for conventional construction at the time. Of the 33,500 square feet of floor space, approximately 61 per cent (27,500 square feet) is devoted to the simulation "warfighting" bay, with the remainder serving support functions in the front section of the structure. There are single connections to the structure for the water, electricity, and gas that is supplied by the Fort Knox installation, and otherwise the facilities are entirely self-contained, easily maintained, and quite efficient. The move into the SIMNET-T "warfighting facility" took place in February 1987.[114]

SIMNET development progressed rapidly during 1987, with new capabilities coming "on line" monthly. For example, in March 1987 a platoon of four M1 (Abrams)

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[112] Helgesson had worked with Perceptronics' Weltman first in 1960 at a company called "Spacelabs" on space and medical bioinstrumentation. Then, during the mid-1970's, when Perceptronics began to get involved in system development, Weltman called on Helgesson to provide industrial design and human factors consultations on the videodisc-based table-top gunnery trainers, as well as other training and support systems, for DARPA and other customers. Weltman reports that by the time Perceptronics began work on SIMNET in 1983, it was standard practice at Perceptronics to include a strong industrial design input, and Helgesson was brought into SIMNET from the start; Weltman, ibid.

[113] Helgesson, ibid.

[114] Helgesson, ibid.; also, discussion with J. Owens, Fort Knox, on 12 April 1990.

tank simulators (with Range 301 data base) were installed at Grafenwöhr, a USAREUR site in West Germany.[115] In April 1987, a laboratory test of a simulator-satellite-simulator long-haul (40,000 miles) network connection was successful, thus giving promise of eventual implementation of a satellite-based LHN as had been planned. With the addition of two attack (A-10) aircraft simulators for close air support in November 1987, the Fort Knox SIMNET-T "warfighting" facility consisted of 54 SIMNET ground vehicle and aircraft simulators, all networked in the LAN "to play" fully interactively. By the end of 1987, five SIMNET air defense system simulators and two scout/attack helicopter simulators had been added, "time travel" had been demonstrated,[116] a second structure at Fort Knox (the SIMNET-D developmental facility) had been occupied, and the first SIMNET battalion-level battle-engagement training exercises had been conducted.[117]

5. Full System Development, Field Test, Transition, and the Future

As 1987 was drawing to a close, there were general discussions and fears throughout the Department of Defense regarding anticipated cuts in the Defense budgets, including that for SIMNET development.[118] Also, Thorpe had recognized that the SIMNET system, as then currently constituted, was addressing essentially only the training needs of active Army heavy mechanized units. However, he realized that its potential was much greater, and he hoped to expand future SIMNET applications to include Navy and Air Force units--reserve as well as active forces from all four Services--in "joint warfighting" training. Believing that he could benefit from advice on how to expand SIMNET applications, he asked General Paul F. Gorman (USA, Ret)[119] to head a small group of retired senior officers--Admiral S. Robert Foley, Jr. (USN, Ret), General Robert

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[115] The Army used the SIMNET facility at Grafenwöhr for training, and in June 1987, a SIMNET-trained U.S. Army platoon won the 1987 Canadian Army Trophy competition (CAT-87)--the first time that the trophy was won by a U.S. team. See R.E. Kraemer & D.W. Bessemer, *US Tank Platoon Training for the 1987 Canadian Army Trophy (CAT) Competition Using a Simulation Networking (SIMNET) System* (Research Report 1457), U.S. Army Research Institute for the Behavioral and Social Sciences, ARI Field Unit at Fort Knox, Kentucky, October 1987.

[116] That is, SIMNET's ability to provide movement back and forward in time, as well as in space, to permit the viewing of any event in any area of the simulated battlefield using the digitized electronic record of a SIMNET engagement.

[117] Bloedorn, 1990, ibid.; Helgesson, ibid.; Thorpe, 1989, ibid.

[118] SIMNET development was being jointly funded by the Army and DARPA.

[119] General Gorman, who is still viewed as one of the Army's premier trainers, had served as the Deputy Chief of Staff for Training at the Army's Training and Doctrine Command (TRADOC) when TRADOC was first established in the mid-1970's and, immediately prior to his retirement, as Commander-in-Chief of the U.S. Southern Command; Bloedorn, 1990, ibid.

Dixon (USAF, Ret), and Major General George E. Coates (ARNG, Ret)--to assess the potential of the SIMNET system, its then currently available products, and the future developments planned for it.[120]

Gorman and the others visited the SIMNET facilities at Fort Knox, Kentucky, on 10 and 11 December 1987. Their reactions were quite positive and they provided advice as consultants regarding the directions in which they judged the technology should be taken, and how SIMNET could be expanded to address still more of the important combat-relevant tasks on which "collectives" (i.e., crews, groups, teams, and units) needed to train to do well in battle. Gorman carried his support of the SIMNET development to the Secretary of Defense.[121]

> General Jack Vessey [[122]] and I told Secretary Carlucci and Deputy Secretary Taft last week that however the services respond to their budget-cutting guidance, they must not allow them to curtail or to forestall progress being made in training for battle readiness overall, and in joint war-fighting in particular.[123]

Funding support for SIMNET development continued from both DARPA and the Army, and as development proceeded from early 1988, SIMNET evolved more fully into a "warfighting" (training) system. The SIMNET sites were structured to provide the full table of organization and equipment (TO&E) capabilities of all three elements of combat--maneuver, combat support, and logistics. The Army began playing an increasingly active role in planning for the test and transition of SIMNET technology into use.

For example, the Army's Combined Arms Center (CAC) at Fort Leavenworth, Kansas, had formulated the Battle Command Integration Program (BCIP)--a comprehensive training program for the application of advanced automation to the battlefield requirements for command and control. The SIMNET and BCIP development plans appeared to fit together nicely: SIMNET technology would serve as the basis for a comprehensive military simulation that included (a) command modules, (b) a centralized world-class opposing forces (OPFOR) capability, (c) manned SIMNET-level simulations, and (d) automated workstations for semi-automated forces (SAFs). The initial sites would be Forts Knox and Leavenworth, but the system would be capable of expansion by

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[120] Thorpe, 1989, ibid.

[121] Bloedorn, 1990, ibid.; P.F. Gorman, "Battalion Task Force Training with SIMNET," memorandum report for J. Thorpe (DARPA), 15 December 1987.

[122] Former Army Chief of Staff and Chairman of the Joint Chiefs of Staff.

[123] Gorman, ibid., p. 2.

replication of capabilities at other sites. The SIMNET technology was envisioned as ultimately matured and transitioned with follow-on engineering development and procurement "to create a distributed simulation network capable of supporting a 20 Corps exercise with an OPFOR of 40 Corps-sized units." (Figure 16-3[124]).[125]

The vision of a matured and expanded SIMNET-supported BCIP depicted in Figure 16-3 shows some elements partly out of the "SIMNET world" and other elements completely in it (such as the self-contained sites at Forts Knox, Rucker, Benning, etc.). Thus, some elements exist in academic environments, some in real-world tactical environments, and some in SIMNET simulators, workstations, and networks. This longer-term goal presented the development team with both a design constraint and a severe technical challenge; namely, to design the SIMNET command modules so that they would interface transparently with the other, non-SIMNET elements--academic classrooms on the one hand, through SIMNET simulators (wherever located), to Command Posts in the field.[126]

Development proceeded along the lines of the "warfighting" system. By February 1988, the SIMNET facility at Fort Knox had grown to a total of 71 interactively networked simulators on the LAN. In April 1988, battalion-level force-on-force operational exercises with Forward Area Air Defense (FAAD) elements were conducted in the SIMNET facility at Fort Knox, and during the same month, the SIMNET attack helicopter simulators were updated to the next-generation aircraft, and a third SIMNET site was established at Fort Benning, Georgia. During the next month, a major milestone was reached with the successful operation of the long-haul net (LHN) between Fort Knox and BBN Laboratories in Cambridge, Massachusetts. The two CONUS field sites (Forts Benning and Knox) were networked together in June 1988, and BBN's Advanced Simulation Division (the prime contractor and developer of the developmental SIMNET-D capability at Fort Knox) began to support The Armor Center in an evaluation of proposed improvements to the M1A1 Abrams tank.[127] Then, during the next month, July 1988, the third SIMNET

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[124] Adapted from A.L. Gilbert, J. Robbins, S. Downes-Martin, & W. Payne, "Aggregation Issues for Command Modules in SIMNET," paper presented at the *MORIMOC-II Workshop on Human Behavior and Performance as Essential Ingredients in Realistic Modeling of Combat*, Alexandria, VA, February 1989.

[125] Such a simulation would network roughly 200 Divisions, 800 Brigades, and 3,000 Battalions; see Gilbert, et al., ibid.

[126] See Gilbert, et al., ibid.

[127] See R.E. Garvey, Jr., "SIMNET-D: Extending Simulation Boundaries," *National Defense*, November 1989, 40-43.

CONUS site (and fourth total, including the one in West Germany) was activated at Fort Rucker, Alabama, and connected with the others. During the same period, a semi-automated forces (SAF) capability was developed. This capability permits one person at a SIMNET "command module" to orchestrate interactively the battlefield movements of a collective--a unit such as a platoon or company--and all of its assigned vehicles, instead of being limited to the control of a single vehicle alone. The second, third, and fourth USAREUR SIMNET-platoon sites became operational during the summer and fall months of 1989 (at Schweinfurt in June, Fulda in August, and Friedberg in November), and work continued on development of a LHN connecting the CONUS sites with the USAREUR SIMNET facilities. Documentation grew, from both the development team[128] and the Army's tests and evaluations.[129]

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[128] For example, see (1) A. Ceranowicz, S. Downes-Martin, and M. Saffi, *SIMNET Semi-Automated Forces Version 3.0: A Functional Description* (Rep. No. 6939), BBN, 1988; (2) A. Ceranowicz, S. Downes-Martin, and M. Saffi, *SIMNET Semi-Automated Forces Version 3.0: Implementation Issues* (Rep. No. 6940), BBN, October 1988; (3) J.W. Chung, A.R. Dickens, B.P. O'Toole, and C.J. Chiang, *SIMNET M1 Abrams Main Battle Tank Simulation: Software Description and Documentation* (Rep. No. 6323), BBN, January 1987, and Rev. 1, August 1988; (4) M.L. Cyrus, *SIMNET Computer Image Generation System* (Tech. Paper), BBN Delta Graphics, Inc., 1987; (5) S. Downes-Martin, and M. Saffi, *SIMNET Semi-Automated OPFOR: A Functional Description* (Rep. No. 6555), BBN, 1987; (6) D. Friedman, and V. Haiino, SIMNET Network Performance (Rep. No. 6711), BBN, January 1988; (7) R. Garvey, and T. Radgowski, *Data Collection and Analysis: The Keys for Interactive Training for Combat Readiness* (Tech. Paper), BBN, 1988; (8) R.E. Garvey, Jr., and T. Radgowski, "Data Collection and Analysis: The Keys for Interactive Training for Combat Readiness," in *Proceedings of the 10th Interservice/Industry Training Systems Conference, November 29---December 1, 1988*, Orlando, Florida, pp. 572-576; (9) R.E. Garvey, Jr., T. Radgowski, and C.K. Heiden, *SIMNET-D Standing Operating Procedure* (Rep. No. 6929), BBN, October 1988; (10) J. Herman, *A New Approach to Collective Training Simulation: The SIMNET Simulation Formula for Success* (Tech. Rep.), Perceptronics, Inc., 1987; (11) D. Miller, and A. Pope, *The SIMNET Communications Protocol for Distributed Simulation* (Tech. Paper), BBN, 1987; (12) D.C. Miller, A.R. Pope, and R.M. Waters, "Long Haul Networking of Simulators," in *Proceedings of the 10th Interservice/Industry Training Systems Conference. November 29 -- December 1, 1988*, Orlando, Florida, pp. 577-582; (13) A.R. Pope, *The SIMNET Network and Protocol* (Rep No. 6369), BBN, February 1987; (14) A.R. Pope, *The SIMNET Network and Protocols* (Rep No. 6787), BBN, May 1988; (15) A.R. Pope, T. Langevin, and A.R. Tosswill, *The SIMNET Management, Command and Control Systems* (Rep. No.6473), BBN, March 1987; (16) A.R. Pope, T. Langevin, and A.R. Tosswill, *The SIMNET Management, Command and Control Systems* (Rep. No.6473), BBN, March 1987; and (17) A.R. Pope, T. Langevin, L. Lovero, and A.R. Tosswill, *The SIMNET Management, Command and Control Systems* (Rep. No.6473-Rev.), BBN, July 1988.

[129] For example, see (1) B.A. Black, *Review of Activities Supporting DCD Block II Trials* (Memo. Rep. PERI-IK: 70-1r), ARI Fort Knox Field Unit, August 1988; (2) R.E. Brown, R. G. Pishel, and L.D. Southard, *Simulator Networking--Preliminary Training Developments Study*, TRADOC Analysis Command, April 1988; (3) D. Ground, and J.R. Schwab, *Concept Evaluation Program of Simulation Networking (SIMNET)* (Rep. No. 86-CEP345), Armor and Engineering Board, March 1988; (4) R.E. Kraemer and D.W. Bessemer, ibid.; (5) D.W. Pate, B.D. Lewis, and G.F. Wolf, *Innovative Test of the Simulator Network (SIMNET) System*, Air Defense Artillery Board, June 1988; (6) J.R. Schwab, *Innovative Test of Simulation Networking--Developmental (SIMNET-D)*, Armor and Engineering

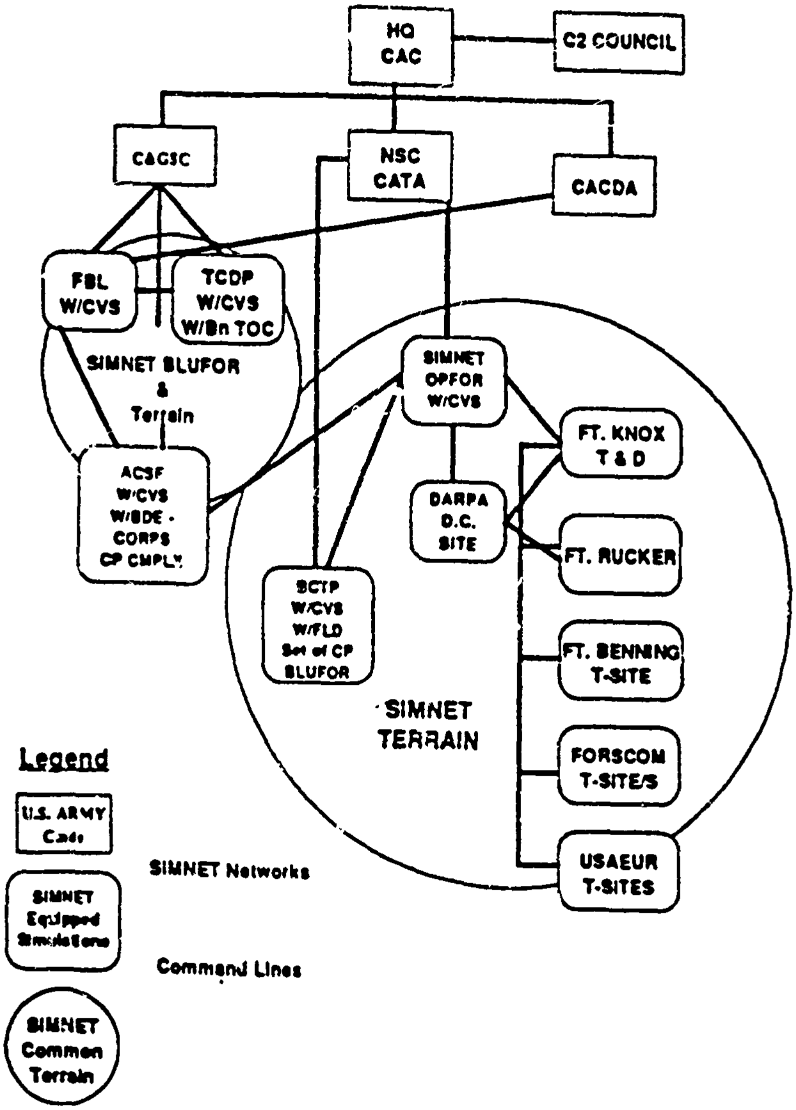
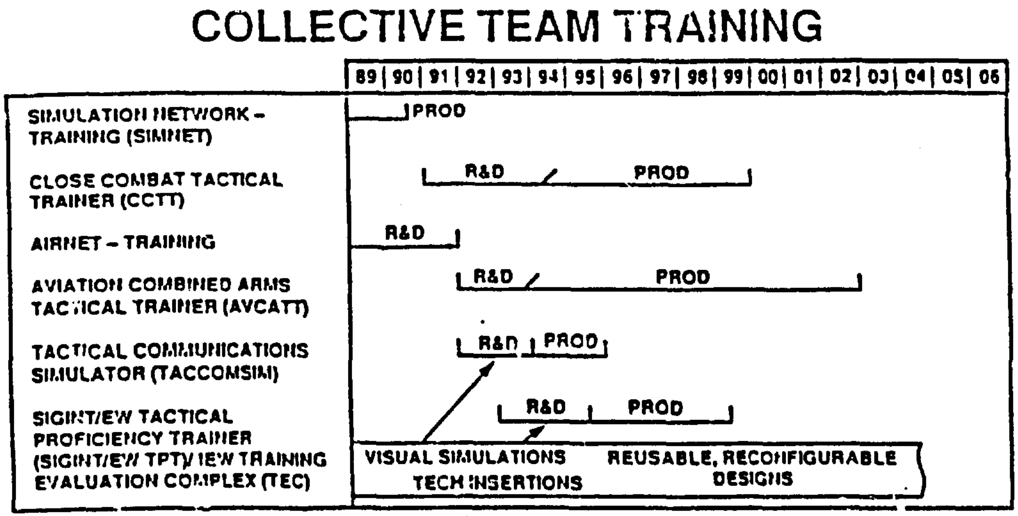


Figure 16-3. SIMNET Simulation in the Battle Command Integration Program (BCIP)

(Source: A.L. Gilbert, J. Robbins, S. Downes-Martin, and W. Payne, "Aggregation Issues for Command Modules in SIMNET," paper presented at the *MORIMOC-II Workshop on Human Behavior and Performance as Essential Ingredients in Realistic Modeling of Combat,* Alexandria, Va., February 1989.)

Board, May 1987; and (7) J.L. Walter, *Post NTSC SIMNET Training Evaluation* (Memo. Rep.), Department of the Army, May 1987.

SIMNET was "completed" and transitioned to the Army starting in October 1989, and as of January 1990, PM TRADE was preparing the necessary documents to be issued during FY 1990 for procurement of the first several hundred units of the Close Combat Tactical Trainer (CCTT) system, the production follow-on to SIMNET. This procurement is to be the first production buy of several thousand planned units. When completed, the planned training system will provide a CCTT (SIMNET-type) training capability at each Army battalion's home base, at an estimated total cost on the order of $1.5 billion. The acquisition plan, as reported by PM TRADE in October 1989, includes provisions for air and ground-vehicle developmental test beds (AIRNET-D and SIMNET-D) intended to "provide materiel developers the ability to try out their ideas prior to issuing doctrinal changes or the bending of metal..." (Figure 16-4[130]).[131]


COLLECTIVE TEAM TRAINING

The collective team training family is the most rapidly growing of the six families. The ongoing SIMNET/AIRNET program under DARPA cognizance will provide some of the necessary technology to network physically isolated locations. These systems are a surrogate wargaming world in which simulators are used as a means of waging unconstrained coalition warfare. They will provide a "combat arena" in which combatants, ranging from the lowest private to the highest commander, can engage in actual warfare without having to consider peacetime safety, environmental, or terrain restrictions. The ground simulators will include the M1 family of tanks, M2 and M3 Fighting Vehicles, FISTVs, and other combat, combat support and combat service support vehicles common to the battlefield. The air simulators will include both scout and attack helicopters. The air and ground test beds (SIMNET D and AIRNET D) will provide combat, training, and materiel developers the ability to try out their ideas prior to issuing doctrinal changes or the bending of metal. Simulations for tactical communications and tactical Intelligence/Electronic Warfare are also under development.

Figure 16-4. Army Project Manager for Training Devices: Projected Plan for Acquisition of Non-System Collective Team Training Devices

(Source: R.J. Lunsford, Jr., *US Army Training Systems Forecast, FY 1990-1994*, Project Manager for Training Devices (US Army Materiel Command), Orlando, Florida, October 1989, p. 14)

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[130] Reproduced from Lunsford, ibid., p. 14.

[131] Lunsford, ibid., p. 14.

The successful development and demonstration of SIMNET's collective-training capabilities have both stimulated new plans and bolstered older efforts to expand this type of computer-based interactive networking for man-in-the-loop, real-time, battle-engagement simulation and wargaming. Perhaps it is too soon to predict with certainty the scope or outcomes of these future efforts, but their immediate directions are fairly apparent.

For example, the SIMNET-D and AIRNET-D capabilities are to be expanded in a new joint Army-DARPA initiative to demonstrate "Advanced Distributed Simulation Technology (ADST)" for use in system development, studies and analyses. This will provide a developmental capability that can be reconfigured to stimulate new design concepts for evaluation in SIMNET-like man-in-the-loop battle-engagement trials. Also, a second conference on communications and network standards for simulator interoperability was held in January 1990 at the Institute for Simulation and Training of the University of Central Florida in Orlando.[132] Industry and Service representatives at the conference agreed to use the SIMNET protocols as the starting point from which to develop further modifications to support the more rapid update rates and additional attributes that would be needed for the net to handle adequately other weapon systems such as faster-flying fighter aircraft and missiles.[133] In a related effort, the Services have agreed to provide continuing funding for the operation of a facility to produce a standardized digital data base of the earth's terrain, including cultural features. This production facility is now scheduled to open under the management of the Defense Mapping Agency (DMA) in May 1991. Industry and the Services are united in seeking to develop the standards and technology to support a data base and simulator-communications net with protocols that will allow simulators of different types and architectures to interoperate--thus permitting man-in-the-loop simulations not only of combined-arms, but also of truly joint-Services warfighting operations.[134]

This combination of cooperative efforts among all the Services and industry marks the most credible assessment of the scope of SIMNET's eventual success. It promises the future availability of a Defense simulation net on which any simulator or wargame can be

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[132] The first conference had been held in August 1989; see J. Cadiz, B. Goldiez, and J. Thompson (eds.), *Summary Report: The First Conference on Standards for the Interoperability of Defense Simulations*, Institute for Simulation and Training, University of Central Florida, Orlando, August 1989.

[133] See K. Danisas, B. Glasgow, B. Goldiez, and B. McDonald (eds.), *Summary Report: The Second Conference on Standards for the Interoperability of Defense Simulations (Vols. I, II, and III* [illegible]stitute for Simulation and Training, University of Central Florida, Orlando, January 1990.

[134] See W.A. Demers, "All Together Now," *Military Forum*, 1989, *6* (#3-Nov/Dec), 38-43.

connected to interoperate with any other simulator or wargame, thereby providing a realistic and valid tool not only for training, but also for the development of concepts and doctrine, the analysis and evaluation of the probable effectiveness of proposed new weapon systems, the rehearsal of combat missions before they are actually undertaken, and perhaps eventually even aiding the management of battles by providing a man-in-the-loop capability of asking the "What if?" questions.

C. OBSERVATIONS ON SUCCESS

Contributions to the successful development of SIMNET can be identified in seven areas, each of which is addressed in this section; namely, (1) needs, (2) objectives, (3) technology, (4) environment, (5) approach, (6) user participation, and (7) people.

1. Recognized Needs Addressed

The pressing need for improvement in collective combat-skills training had been recognized from at least the mid-1970's when the Director of Defense Research and Engineering sponsored a study by the Defense Science Board (DSB) of training technology R&D. The DSB Task Force on Training Technology concluded in its 1976 report that insufficient attention was being given in Defense technology-base R&D to collective training--i.e., to the training of military crews, groups, teams, or units (CGTUs).[135] A second DSB study, that of the 1982 Summer Study on Training and Training Technology, reached essentially similar conclusions.[136] They specifically addressed the need for realistic battle-engagement simulation as follows:

> The next issue is that of putting, as well as one can, wartime realism into simulation. Many wartime actions are too dangerous for peacetime practice; many cannot be duplicated at all. Simulation offers the potential to explore and define, and to a degree, experience that which prudence prevents actually practicing[137]

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[135] The Task Force suggested that increases in team training R&D could lead to substantial improvements in the efficiency and effectiveness of both the training and the performance of military CGTUs; see Defense Science Board, *Summary Report of the DSB Task Force on Training Technology*, February 1976, pp. xi and 36-37.

[136] They wrote, "... Unit level training is considered of vital importance. Investments should be made now in implementing on-the-shelf technology to enhance our on-going training efforts. We are convinced that great possibilities exist for new enhancements in the future. New methods and devices will be needed to meet this need...;" Defense Science Board, *1982 DSB Summer Study Briefing Report for Training and Training Technology*, 26 July--6 August 1982, p. 47.

[137] Defense Science Board, 1982, ibid., p. 79.

From its very beginning, the SIMNET project sought to address recognized Service needs for collective combat-skills training. During the 1980's, these needs became even greater, especially for the Army, as more stringent restrictions were placed on the opportunities for conducting large-scale operational exercises, the traditional means of military collective training. In addition, there was growing recognition and concern regarding unfilled needs for more frequent and effective combined-arms and joint-Services training at all levels.[138]

The recognition of these needs, and of SIMNET's potential for addressing them, was one element contributing to its success. Specifically, because SIMNET promised to provide the Army with an effective capability for collective battle-engagement training of heavy mechanized units, at an affordable low per-unit simulator cost, its development was supported in substantial and critical ways by the Army.[139] The other Services have been reluctant to support SIMNET, viewing the system as primarily aimed at addressing Army (and not their) collective training issues, but this has begun to change, and in 1990 there are indications of increasing Navy and Air Force acceptance of SIMNET or SIMNET-like technology adaptations to meet some of their collective training needs, especially in combined-arms and joint-Services scenarios.

2. Realistic Objectives Established

The objective of armored-vehicle simulators that could be networked to provide a means for collective combat-skills training, with sufficient visual scene complexity to simulate the appropriate complexity of battle-engagement scenarios, at relatively low unit costs to permit the acquisition of a number sufficient to impact training (and, therefore, readiness)--a simple, yet promising concept, capable of being articulated clearly and understood quickly--was a second area that contributed to the successful execution of the SIMNET project.

The emphasis on affordability led to the objective of low-unit cost being stated clearly and forcefully up front, and this, in turn, established the necessary mind set for success. That is, it placed constraints on the system concept, approach, and design without which the SIMNET development very likely would have failed.

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[138] For example, see Defense Science Board, *Report of the DSB Task Force on Computer Applications to Training and Wargaming*, May 1988.

[139] For example, of the total of about $214 million spent on SIMNET-T, AIRNET, and SIMNET-D, DARPA provided about $33 million, or slightly over 15%, and the Army provided the remainder; discussion with L.L. Mengel (Colonel, USA), on 12 April 1990.

Moreover, Thorpe maintained throughout a "matching [of] the level of expectation to the level of reality,"[140] and saw to it that all concerned--Army users, engineers, psychologists, trainers, etc.--were often reminded that SIMNET's goal was to achieve a reasonable (acceptable, affordable, feasible, and usable) solution to the critical collective-training issue, and that the SIMNET solution would be achieved, not with a "perfect" simulation of mechanized vehicles, but rather with a simulation that would be affordable and "good enough."

The establishment of realistic objectives, including the low-cost constraint to address the affordability issue, was a second element contributing to SIMNET's success. The objectives were easily understood, and, if attained, SIMNET technology promised to provide a realistic way for the Army to address its collective training needs, at least in the area of its most difficult and expensive heavy mechanized units. The concept of a network of simulators that permitted entire units to train by "experiencing the fog of war" in realistically simulated interactive battle engagements with "live" opposition forces was both understandable and attractive; it generated Army support for SIMNET.

3. Feasible Technologies Identified

The critical computational, imaging, and networking technologies were actually, or at least potentially, available for further development and integration into the SIMNET system. Moreover, they were "fitted" well to the SIMNET objectives. The objectives were not new; they had been discussed and articulated elsewhere at least from the mid-1970's, but the critical enabling technologies were not then available. Thorpe and the SIMNET development team recognized that the rapid advances being made in the relevant technologies were providing the capabilities that made feasible the development of SIMNET during the 1980's.

It is true that once demonstrated, the SIMNET technology appears relatively simple and easy to understand. It appears innovative, but not especially revolutionary; after all, there are many computer-graphics based video games in the marketplace. However, this is not to imply that there were no risks involved. For example, the development of the graphics generator--with sufficient visual-field complexity to support SIMNET's battle-engagement collective training mission, and to do so within the cost (dollar and time)

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[140] Fready ibid.

constraints--represented an extreme in technological risk, essentially equivalent to the development of a critical enabling technology.

The identification of feasible technologies was a third element contributing to the successful development of SIMNET. It is to the credit of Thorpe and the development team that those critical and enabling technologies required for successful execution of the SIMNET project were identified, developed, and applied successfully.

4. Risk-Tolerant DARPA Environment

The DARPA environment at the time, including the then-current *modus operandi* in which project managers were expected to know thoroughly their R&D areas, including all the "players," i.e., all the persons and firms who had the requisite expertise and capabilities, certainly contributed to the project's successful execution. It was the standard operating procedure for project managers to work collegially with potential or actual "contractors" in the conduct of the work and to some extent in the development of the concept, the identification of the relevant enabling technologies, and the specific and innovative applications to which it could contribute. The typical operating mechanism was that of a *"development-team"*,[141] and many, if not most or nearly all, of the DARPA contracts at the time were "sole source," a situation that essentially ended after 1984 with implementation of the Competition in Contracting Act.

This risk-tolerant environment at DARPA in the early to mid-1980's, including its rapid-prototyping persuasion, and pervasive scientific and management culture, was a fourth element contributing to SIMNET's successful development. In fact, much of the success of the SIMNET project can be attributed to the DARPA culture--a culture that not only permitted support of high-risk projects that showed promise of compensatingly high potential payoffs, such as SIMNET, but also fostered rapid prototyping. The SIMNET project flourished in this environment, for it required not only the acceptance and support of its high-risk development, but also a tolerance and supporting infrastructure for the rapid prototyping it needed for Army support.

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[141] The "development-team" mechanism appears particularly well suited to the kind of high-technology, advanced-research projects, like SIMNET, for the development of which DARPA has been notably successful. Of other projects it has been said that they "... could not have been completed with any agency other than DARPA with its close, patient, two-way-understanding, working relations with the developer...;" Fredy, ibid.

5. Iterative Approach Adopted

A rapid-prototyping iterative approach was taken to SIMNET development. Nothing in the design phase was set "in concrete." No detailed engineering specifications were written, but rather goal-oriented functional specifications were used, with those based on a thorough front-end analysis with heavy user impact on the articulation of what had to be trained--i.e., on the military training "requirement." Then the procedure was to build a mock-up as rapidly as possible, expose it to many different people with relevant expertise--Army tank personnel, both operational and training, psychologists and engineers, developers and users--and on the basis of their reactions, comments, and advice, modify the design before building the first prototype, try it out, revise the design for the next unit, etc.--in short, iterate the design on the basis of experience and lessons-learned from working with concrete objects, not merely concepts on paper.

The rational iterative-prototyping developmental approach adopted was a fifth element contributing to the success of the SIMNET project. It was consistent with Thorpe's "60 percent solution" and "not-forever" principles, which recognized that trying to develop a "perfect" product would extend the development time substantially, would likely fail, and even to the extent that it was successful would leave the military user with very expensive, but technologically outdated equipment "that would last forever." Rather, the approach was to buy, wherever possible, off-the-shelf commercially available components that might not meet "mil-spec" constraints or last as long, but that could be obtained more quickly and much less expensively. In addition, and even though relatively inexpensive, SIMNET's use of such constituents provided it with state-of-the-art, yet proven, high-technology components and parts.

6. Reliable User Support Obtained

In part because of the prompt demonstrations of concrete "products" instead of the more usual "notional" viewgraphs with "artist's conceptions" of a product, and in part because of the iterative and rapid prototyping approach instead of the typical detailed engineering specifications and 10-year acquisition cycle, SIMNET promised early implementation of products that would address specific Army collective training requirements with new (not outdated) technology. High levels of the Army hierarchy were convinced of SIMNET's potentially high payoff in "readiness," and were assured of user influence (understanding and approval) of the SIMNET systems--both SIMNET-T for training, and SIMNET-D for the development of concepts and doctrine. There were extensive SIMNET demonstrations at each stage of its development to very high levels of the Department of Defense--the Office of the Secretary of Defense and all three Military Departments. As a result, the Army provided "user support," from the very top--the Secretary of the Army, as well as the Army Chief and Vice Chief of Staff--and that resulted in broad and welcomed "user" participation and cooperation in the development, as well as in the funds for SIMNET-T totally.

The reliable user support obtained, not only in funding, but also in cooperative participation in the development and testing of the system, was a sixth element contributing to SIMNET's successful development. Of the $214 million spent on its development, approximately 85 percent was provided by the Army and 15 percent by DARPA. DARPA transitioned the SIMNET-T facilities in their entirety to the Army beginning in October 1989. The SIMNET-D facilities form the basis for a follow-on joint development of the Advanced Distributed Simulation Technology project.

7. Resourceful People Engaged

The SIMNET development was blessed with the "right" people throughout, including, but not limited to, development team members (e.g., Bloedorn, Cyrus, Helgesson, Jacobs, Miller, and Thorpe), and others representing DARPA, the Army, and other elements of the Department of Defense (e.g., Ambrose, Brown, Coates, Dixon, Fields, Foley, Gorman, Thurman, and Vessey). SIMNET could not have been rapidly prototyped and transitioned without the kind of "top-down" user support it enjoyed. If it had obtained only the "bottom-up" advocacy typical of the Planned Program Budget System (PPBS) used by the Service laboratories and acquisition agencies, SIMNET might never have been approved as a DARPA project. The people were committed and dedicated to the successful development and implementation of SIMNET. They were resourceful and able to handle well each of the many crises. They *believed* in the goal of an affordable, effective network of simulators for the collective battle-engagement training of U.S. forces. They were confident that they could do it.

These observations are consistent with Thorpe's assessment of the three most important contributors to the successful development and transition of SIMNET; namely, the *concept*, the *support*, and the *staffing*. The *concept* was that of a product directed at an acknowledged need, and was based on knowledge of a technology (or enabling technologies) capable of being developed for implementation within reasonable cost and time constraints. The *support* came from persons in positions sufficiently high in the relevant hierarchies to help "make it happen," and was obtained through many high-level briefings that communicated the concept in concrete terms.[142] The *staffing* was the responsibility of the project-management team, which saw to it that all administrative requirements were met in timely and correct form, including the planning, monitoring, and execution not only of all technical, but also of all fiscal and other management aspects of the project.[143]

The resourceful people engaged in the SIMNET project--those among the developers, the managers, and the supporters--constitute a seventh (and most important) element contributing to the successful execution of the SIMNET project. Of these, the most predominant essential ingredient to account for its success is the contribution of the SIMNET project manager, Thorpe. Without his concept, commitment, determination, technical expertise, willingness to accept risk, and steadfast pursuit of the means to bring the SIMNET concept to concrete reality and operational test, the SIMNET project would have faltered many times over and perhaps even failed, if it even were to have begun. Thorpe's ability to work with others and to communicate his vision and articulate his assessment of the benefits that would result from collective battle-engagement training also contributed directly to the success of the project. He is cited as having exhibited throughout the project a judicious exercising of considerable skill in managing ideas, people, and contracts. This assessment is a conclusion based on the independent statements of many persons.[144] It is yet another instance of a lesson-learned by DARPA many times over: good people are the most important of the necessary ingredients to success in its business.

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[142] Thorpe considers high-level (General or Flag Officer) support "absolutely essential" for successful development and implementation of warfighting training systems like SIMNET; Thorpe, 1989, ibid.

[143] Thorpe, 1989, ibid.

[144] Bloedorn, 1990, ibid.; Fletcher, ibid.; Freedy, ibid.; Jacobs, ibid.: Levine, ibid.; Martin, ibid.

XVII. VLSI: ENABLING TECHNOLOGIES FOR ADVANCED COMPUTING

A. INTRODUCTION

From J.C.R. Licklider's 1963 vision of developing man-computer interaction technology (see Volume I, Chapter XIX), several DARPA programs evolved which are covered in different chapters but should be seen as part of a broader program effort. His man-computer interaction concept evolved over the years into several major program thrusts. Among the first were the development of MAC (Volume 1, Chapter XIX), ARPANET (Chapter XX) and precursor network and timesharing programs, and Artificial Intelligence (Chapter XXI) in the late 1960s and early 1970s. Next came the VLSI program, beginning in 1977-78, followed by the Strategic Computing Program (SCP) in 1982-83. Developments from each of these earlier programs fed into the later programs, sometimes incorporated into them and sometimes continued in parallel. For example, a number of the new computer architectures developed with VLSI program support are now being pursued within the SCP while the VLSI program continues in other directions. This account covers the main VLSI technologies launched by 1982-83 when the SCP began.

VLSI was only one of several programs that came to contribute to a broader, coordinated effort known as Strategic Computing. These included DARPA programs to develop software, applications (e.g., imaging and sensing), program languages, operating systems, and educational systems. The educational systems were intended to instruct researchers how advances in various segments (e.g. operating systems) might apply to the work that an individual might be doing in his or her particular segment of activity (e.g., applications).

The VLSI program came about because, although there were lots of creative ideas germinating in the academic community, progress was limited because resources to develop them and practical means to implement and test them were lacking. Initially the program was rather ad hoc. At the outset of the VLSI program there were several related streams of activity going on. Implementation of experimental device designs through MOSIS was an early and key component (see Chapter XVIII of this volume.) In the mid-1970s the few facilities for implementing VLSI designs in silicon limited the researchers who could try out their concepts by building and testing actual devices and systems. MOSIS, for the academic community, was analogous to providing printing presses for the masses.[1] Its availability opened the floodgates for new ideas to pour forth. One of its early side effects was to stimulate development of all kinds of semiconductor design tools, including CAD, simulators, testing and characterization, and others needed for advanced production technology. As these developed there came a virtual explosion of device and computer architecture ideas. In 1982-83, DARPA pruned these numerous new architectural directions back to a handfull of the most promising basic types, and swept them into the SCP in order to develop them in a coordinated and focused way.

B. BRIEF OVERVIEW

The U.S. computer technology environment of the mid-1970s was characterized by (1) a tapering off in the rate of improvement in computer performance as the marginal costs rose and marginal gains from extending prevailing technologies declined; (2) extensive insulation of commercial microelectronics firms, concentrating on their own proprietary developments, from academic communities which were limited in their access to advanced equipment and industry technologies; and (3) exponential growth in the cost of equipment and of implementing device design, as industry concentrated on incremental efforts to pack more gates and transistors into semiconductor devices. It was widely realized that:

> ...university engineering and computer science departments were getting shut out of much of the microelectronics revolution because they couldn't afford the equipment necessary to manufacture silicon chips. Even those universities that could afford some equipment could never keep up with the rapidly advancing state of the art.[2]

It was in this environment that DARPA originated the VLSI program. Through his relations with the academic community going back to the early 1970s, Dr. Robert E. Kahn was aware of both the technology potentials of work being done at academic centers of excellence in computer science, and of the cost and limits placed on their ability to implement, validate, and demonstrate their work because of the proprietary practices of industry.[3] The VLSI program was undertaken specifically to revitalize creativity in the academic community, which had played an important role in earlier computer and

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[1] Interview with Dr. Stephen Squires, Chief Scientist, DARPA ISTO, October 19, 1990.

[2] "Homebrew Chips," by John Markoff, Phillip Robinson and Donna Osgood, *BYTE*, May 1985, p. 363.

[3] During this period, Kahn advanced from Chief Scientist to Deputy Director of DARPA's Information Processing Techniques Office (IPTO) in 1976 and became Director of IPTO in November, 1979.

semiconductor developments but which had a declining role by the mid-1970s due to its increasing distance from technology developments in industry.

The VLSI program began formally in 1978. With the arrival of Dr. Robert Fossum as Director in that year, DARPA front-office support for academic research in information technologies and efforts to get additional funding for it increased, which encouraged new initiatives in this field. As the program evolved, the VLSI initiative was to include design tools, systems architecture, microelectronic device implementation and fabrication systems, and semiconductor material programs.

C. TECHNICAL HISTORY

1. Program Origins

Academic research in semiconductor technology had suffered from declining funding from defense sources in the mid-1970s. The pressures of the Vietnam conflict had shifted DARPA's focus in the early 1970s toward projects with relatively more direct applicability to near-term defense requirements than previously. That trend, plus the end of the conflict in 1975, and the pursuit of on-going priorities reduced DARPA attention and funding for broadly based academic research in computer sciences. In January 1974, J.C.R. Licklider was brought back to DARPA to head IPTO. Although he maintained a keen interest in computer sciences, he was unable to persuade George Heilmeier, who became DARPA Director in January 1975, to put new money into broad research in this field. The latter instead favored continuation of service-related projects already underway,[4] particularly since IPTO's overall budget had fallen from a peak of about $40 million in the early 1970s, to the low $30 millions by 1975.[5] Heilmeier focused new initiatives in the information sciences on artificial intelligence projects.[6] Overall IPTO funding for computer sciences research continued to decline through 1975. By the time Licklider left DARPA in August 1975, the potentials of VLSI for generating major improvements in computer capabilities had become increasingly evident to Dr. Kahn, who had followed this field at DARPA since 1972. He felt that greatest opportunities lay in pursuit of VLSI and

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[4] On-going programs included a variety of testbed activities with the armed services such as a packet radio project, and other efforts to produce system prototypes of interest to the services.

[5] Interview with Dr. Robert E. Kahn, August 7, 1990.

[6] In the information field, to advance the use of artificial intelligence and networking technologies in military command and control operations IPTO in 1976 took on the ACCAT project (Advanced Command and Control Architectural Testbed). See Vol. I, Chapter XXVII, ACCAT.

concluded that if academic research did not begin developing VLSI technologies it could miss out on the whole next phase of semiconductor technology advances.

To determine what might be done to reverse this prospect, in July 1976 DARPA commissioned the RAND Corp. to evaluate the scope for research that it might support.[7] The three authors, Ivan Sutherland, Carver Mead, and Thomas Everhart, were each expert in different but related aspects of microelectronics and computer science. Their report, submitted in November 1976, argued that current microcircuit technology was rapidly approaching limits both in feature sizes, imposed by the wavelength of visible light, and in fabrication precision, imposed by silicon substrate stability. The authors recommended new approaches in several areas which they calculated could provide order-of-magnitude improvements in integrated circuit and computing performance. After reviewing six technology areas and the research on-going in each, they recommended that "relatively modest investments of $500,000 for several years in each of four selected target areas would produce a highly leveraged payoff." In their view, while it was understandable in competitive terms for industry to concentrate on incremental improvements (e.g., in memory size), DARPA, they argued, should support efforts to gain order-of-magnitude improvements because of the more massive computing capabilities required by defense systems in such fields as target recognition and signal processing. Specifically the report recommended efforts to (1) push rapidly the fabrication and design of simple circuits toward the smallest possible feature sizes; (2) understand the system design implications of very-large scale integrated circuits; (3) measure limits of dimensional stability in silicon substrates and mask materials; and (4) predict optimum feature, die, and wafer sizes.[8]

This report was instrumental in prompting Kahn to develop and push for initiation of a DARPA VLSI program. Moreover, to have any chance of getting increased funding for this field into a budget already almost fully committed to on-going programs, a new program departure would be needed. By mid-1977 Kahn prepared an internal position paper proposing a VLSI program as a major DARPA technology "thrust." As he conceived it, the VLSI program would emphasize three main objectives: (1) submicron design; (2)

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[7] I.E. Sutherland, C.A. Mead, T.E. Everhart, *Basic Limitations in Microcircuit Fabrication Technology*, RAND Corporation Report No. AD-AO35149, Santa Monica. Cal., Nov. 1976, 58 pages, prepared under DARPA Contract No. DAHC15-73-C-0181. ARPA Order 1891.

[8] The September 1977 issue of the *Scientific American*, dedicated to microelectronics, had an article by Sutherland and Mead. ["Microelectronics and Computer Science," by Ivan E. Sutherland and Carver A. Mead, p. 210-229.] The article explained how changed relationships in costs between logic and wiring had opened up revolutionary opportunities in computer architecture; it described how more standardized design techniques would permit development of parallel processing machines with major gains in computing efficiency.

semiconductor fabrication; and (3) computer architecture and design.[9] As the last of these components evolved, it in turn came to draw on three streams of research inputs: (a) creation of standard, simplified design rules which freed researchers from having to deal with numerous different proprietary implementation systems; (b) development of scalable design systems to permit implementation of designs at smaller scales as more condensed implementing technologies became feasible; and (c) simplification of the whole design process through improved computer-aided design to make it quicker and cheaper.[10] Because of time and resource limitations, the overview of VLSI enabling technologies in this chapter is limited to those developed under IPTO's direction, and does not report on semiconductor materials and fabrication technologies supported by DARPA's Defense Materials Office (now the Defense Science Office).

In program terms DARPA's VLSI program would support two main salients: the development of *infrastructure* needed to facilitate learning, implementation and propagation of VLSI technologies, and research of key academic centers on actual *VLSI technologies.*

Infrastructure. As the VLSI program developed, it had four main *infrastructure* components: (1) use of ARPANET to facilitate propagation and implementation of new technologies; (2) development of a fast turnaround facility to implement semiconductor device technologies in silicon, (3) support for expanding VLSI courses and design technologies (e.g., computer-aided design) at academic institutions, and (4) projects to advance semiconductor materials and fabrication technologies.

Dr. Kahn recalls envisaging early in DARPA's VLSI program the need for an economic way for the academic research community to get chips fabricated easily and inexpensively to test their design ideas in silicon. The idea took further shape in a pivotal conversation Kahn had with senior DARPA colleague Arden Bement, who, as Director of the Defense Materials Office, managed semiconductor material and fabrication technology projects for DARPA. When Kahn floated the idea of a fully automated chip factory, Bement countered that DARPA should instead promote development of a device research facility to produce experimental device designs in support of university research. As a computer scientist, Kahn foresaw, as an extension of this idea, the even greater value of a fast-turnaround fabrication facility that could produce semiconductor devices from univer-

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[9] Many of the latter two of these objectives were managed throughout the VLSI program by DARPA's Information Processing Technologies Office. Responsibility for semiconductor fabrication technology was assigned to DARPA's Defense Materials Office.

[10] Interview with Duane Adams on May 30, 1990.

sity designs at low cost. As it happened, a timely means of satisfying this idea soon emerged in the work of researchers in California, which allowed DARPA to support their efforts rather than having to initiate an independent solution.

The insistence, by existing industry silicon fabrication facilities, on keeping their fabrication design rules proprietary had resulted in a welter of different commercial rule systems, which effectively made it prohibitive for most academic researchers to implement their designs through these fab lines. Only a few universities could afford their own fabrication facilities. Among academicians Kahn had known from the 1960s was Ivan Sutherland of CalTech,[11] through whom he met CalTech's Professor Carver A. Mead. Over many years Mead had developed an exceptional range of industry contacts and access, which provided him detailed knowledge of fabrication lines around the country. In the early 1970s Mead pioneered in identifying the physical limits of semiconductor *scaling*, thus opening up the challenge of how to exploit the remaining potential for increasing chip density and complexity. He also pioneered in the instruction of students in state-of-the-art MOS/LSI (large-scale integration in metal-oxide silicon) circuit design, as then practiced by the leading integrated circuit semiconductor producers. Mead used his access to these industrial fabrication facilities to have student circuit design projects implemented in silicon.

In the mid-1970s Bert Sutherland joined Xerox Palo Alto Research Center (PARC) in Palo Alto, California, at about the same time as his brother Ivan went to CalTech. The brothers were keenly interested in developing the potential of computer-aided device design, and to that end came to foster a collaboration between Lynn Conway, a computer architecture expert at Xerox PARC, and Carver Mead at CalTech, with his device design expertise. In 1975 the Mead-Conway collaboration began with work on structuring and simplifying the then *ad hoc* MOS/LSI design methods used by industry leaders. Through this collaboration, Mead and Conway simplified, standardized, and improved the teachability of available VLSI design methods. This Mead-Conway collaboration also led to development of the DARPA-supported MOSIS system for fast, low-cost implementation of researcher chip designs in silicon. [See Chapter XVIII for details.] Linked to participating academic institutions mainly via ARPANET, MOSIS became the main infrastructure component of the VLSI program. MOSIS remains to this day an active, vital part of the infrastructure supported by DARPA for academic microelectronic research.

Mead-Conway's simplified design rules and methods also provided the essential ingredient for the development of computer-aided design (CAD) tools for VLSI layouts that

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[11] Sutherland was DARPA's Director of (IPTO) from mid-1964 to mid-1966.

the Sutherland brothers had hoped for. The first of a series of such design tools, known as ICARUS, came in 1976 from the work of Douglas Fairbairn at Xerox PARC, together with James Rowson at CalTech, which incorporated the Mead-Conway simplified design system.[12] This VLSI layout design program, run on the Xerox Alto computer, was a valuable tool in new courses on VLSI design at Stanford, and was quickly put to use by researchers such as Jim Clark at Stanford, who used ICARUS in developing his famous geometry engine with DARPA funding. In 1978-79 DARPA also underwrote the development of a program at the Miller Institute of the University of California for step-level improvement in microelectronic device layout. From this emerged CAESAR, an interactive VLSI layout editor, written in C (a high-level compiler language), which runs on a VAX computer using a Berkeley version of the UNIX operating system originally developed by AT&T's Bell Labs. Caesar produces CIF (CalTech Intermediate Form) files which are the medium used for the MOSIS fast-turnaround microchip fabrication program. Caesar contributed directly to the development of the two VLSI reduced-instruction-set computers RISC and MIPS (see VLSI Illustration A following page 17-35); the needs of these device design research programs in turn provided the motivation for developing Caesar beyond its then-experimental state into a more powerful tool.[13] A later, more advanced UC-B design technology, MAGIC, became even more widely used and is said to have been the basis for several CAD systems, including those commercialized by the firms Cadence, Daisy, Valid Logic and ViewLogic. (See J below.)

Technology. On the technical side, IPTO had received numerous unsolicited proposals from academics for research to extend applications of current commercial piece-parts to new types of systems. Seeing such proposals as offering only marginal potentials for improvements, Kahn preferred to enable types of academic research that he felt promised greater potential. Kahn 's initial concept of the program anticipated achieving the RAND report's vision of a two-order-of-magnitude leap from the 5µ feature-size-world of *semiconductor devices* in the late 1970s to a submicron world early in the 1980s. As his concept matured, Kahn shifted emphasis beyond submicron device feature sizes toward a broader agenda of order-of-magnitude improvements in *computer capabilities*, with

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[12] Fairbairn in 1980 founded and published *LAMBDA, The Magazine of VLSI Design*, with assistance from Rowson as Consulting Editor; Conway became a Contributing Editor in 1981. This magazine served as one of the main early communication channels for the "VLSI community" during the several years of its existence.

[13] Interview with Prof. John Ousterhout, May 7, 1990.

particular attention to new computer design and architectures.[14] In addition, rather than attempting to divine which proposals had the greatest potential or chance of success, IPTO's main support criteria would be the persuasiveness of the individual proposals, combined with the record of excellence and achievement in computer sciences of the proposing institutions and principal investigators.

During 1977 from the abundant unsolicited proposals seeking DARPA funding for VLSI programs from the best centers, a number were selected and readied for signature when the new DARPA Director, Dr. Robert Fossum, arrived in January 1978. In 1978-1979 DARPA funded roughly a dozen VLSI programs covering widely varying aspects of VLSI technology, at centers such as CalTech, Carnegie-Mellon University, Jet Propulsion Lab, MIT, Mississippi State, North Carolina, Stanford, University of California (Berkeley), and the University of Utah. IPTO favored proposals broadly drawn to cover a range of related research in a general direction under the supervision of a principle investigator (PI).

DARPA did not "invent" or originate VLSI research. Industry had already begun to implement VLSI technologies and rich potentials had also begun to develop in the academic community by 1975. However, DARPA did enable and "exponentiate" development and implementation of VLSI technologies with its funding of academic research. Among other forces, the synergy of the Mead-Conway collaboration quickly extended beyond device design, to generate new principles for computer architecture. Their simplification and standardization techniques rapidly led to widespread use of their design rules, first as course materials, and subsequently as a book, *Introduction to VLSI Systems,* published by Addison-Wesley Publishing Co. in 1980. This Mead-Conway book had a major impact on the academic research community as soon as the first draft chapters began to be used in courses at several universities in 1978. In addition to new vistas in chip design and computer architecture, these design rules also spurred development of a rich variety of

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[14] VLSI program emphasis on academic research contrasted with the VHSIC program supervised by DoD's Director for Defense Research and Evaluation (DDR&E). The latter program reportedly stressed near-term results with direct military application, and focused on pushing beyond the then-state-of-the-art in industrial semiconductor technology to new frontiers. At least one very prominent industry official publicly criticized the VHSIC concept as a case of government diverting resources to do what industry could do better; by contrast he privately supported the VLSI concept as bringing new approaches and resources to the table. Kahn emphasizes that there were no relationships, trade-offs, or choices made between the two programs, even though for a brief time at its beginning a few in the Pentagon were interested in possible DARPA management of the Design, Architectures, Simulation, and Test (DAST) portion of the VHSIC program for R&AT (Research & Advanced Technology).

related supporting technologies including checking, testing and characterizing subtools, graphics editors, and simulators.

According to Robert Kahn, one of the most powerful projects DARPA ever funded was developed early in the VLSI program. It originated with a modest proposal to DARPA by Dr. James Meindl of the Center for Integrated Systems, Stanford University, to combine specialized memory, logic, and communication functions then done on sep devices, and to build individual devices containing integrated systems. Kahn saw in the proposal the germ of a more complex and ambitious project and urged Meindl to consult Stanford's leading computer architect, Forest Baskett.[15] The result was a proposal that DARPA funded for development of a computer workstation for the Stanford University Network. The SUN workstation, subsequently commercialized when designer Andreas Bechtolsheim and others founded Sun Microsystems, Inc., in 1982, has led development of the fastest-growing segment of the computer market in the late 1980s. (See VLSI Illustration B: The SUN Workstation, page 17-B-1)

The range of technologies supported by the VLSI program is illustrated in section 2c below.

Program management. Dr. Robert Kahn conceived and gave initial shape to the VLSI program, with particular emphasis on innovative computer architecture and device design and simulation. Then-Lt. Col. Duane Adams became DARPA's first VLSI program manager in September 1977. He launched the program with considerable organizational and managerial skills and enthusiasm for its objectives. After Adams became Deputy Director of IPTO, DARPA brought in Paul Losleben from the National Security Agency (NSA), who became VLSI program manager in July 1981. Losleben brought to the program an increased emphasis on the mechanics and processes of semiconductor technology. Drawing on his experience and comprehensive knowledge of semiconductor technologies gained at NSA, Losleben's special contributions were to impart added momentum to MOSIS plans to include CMOS technology in its service, and greater emphasis on testing for quality assurance in semiconductor fabrication efforts. The semi-annual principle investigator meetings, initiated by Adams and carried on effectively by Losleben, were instrumental in spurring dissemination of VLSI technology developments, stimulating cooperation, and shaping future research directions. From 1986 through 1988 the program manager was Dr. William Bandy, who was succeeded in 1988 by Col. John

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[15] Baskett had extensive previous experience at Xerox PARC before going to Stanford in about 1978.

C. Toole. Table 17-1 provides a timeline of DARPA, ISTO, and VLSI directors and managers.

In management of the program Kahn and his VLSI program managers maintained open, non-restrictive policies and requirements which (a) did not limit research to military or defense applications, (b) did not require classification of results; and (c) did not restrict publication of results.[16] These freedoms were, from all indications, very important in making the program attractive to academics, especially in the immediate post-Vietnam period by which time opposition to academic participation in Defense programs and classified research had become a *cause celebre* at many universities.[17]

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[16] In this respect also the VLSI program differed from VHSIC, which was subject to limitations imposed by the ITARS, operated on a classified basis, and did not call for unclassified publication. However, there was sharing of research results at the staff level between the two programs.

[17] A detailed description and evaluation of general DARPA management practices can be found in: *TECHNOLOGY TRANSFER at The Defense Advanced Research Projects Agency: A Diagnostic Analysis*, Ronald G. Havelock and David S. Bushnell, Technology Transfer Study Center, George Mason University, Fairfax, Virginia, December, 1985, 79 pages, produced under DARPA contract MDA 903-64-K-033K.

Table 17-1. VLSI--Time Lines

	ADMIN	DDR&E	DARPA DIR	IPTO/ISTO	VLSI[a]	MOSIS[b]
1966	Johnson		C. Herzfeld	R.W. Taylor		
1967			E. Rechtin			
1968		J. Foster				
1969	Nixon			L. Roberts		
1970						
1971			S. Lukasik			
1972						
1973						
1974	Ford	M Currie		J. Licklider		
1975			G. Heilmeier	D. Russell		
1976						
1977	Carter					
1978		W.J Perry	R. Fossum			
1979				R. Kahn		
1980					D. Adams	
1981	Reagan	D. Hicks	R. Cooper		P. Losleben	
1982						
1983		G. Delauer				
1984						D. Cohen
1985			R. Duncan	S. Amarel		
1986					W. Bandy	
1987		R. Duncan		J. Schwartz		G. Lewicki
1988			R. Colladay			
1989	Bush		C. Fields	B. Boehm	J. Toole	
1990		C. Herzfeld		C. Piña		

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a. Program Manager
b. MOSIS Director at ISL

Table 17-1. VLSI--Time Lines (Cont'd.)

BSCC / IPTO / ISTO DIRECTORS

BSCC (Spring 1963 to Fall 1964)		BEGAN	DEPARTED
J.C.R. Lickider		Mar. 1962	Spring 1964
IPTO			
Sutherland		Fall 1964	Summer 1966
Robert W. Taylor		Fall 1966	Mar. 1969
Lawrence Roberts		Mar. 1969	Sept. 1973
Alan G. Blue (Acting)		Spring 1974	Summer 1974
J.C.R. Licklider		Jan. 1974	Aug. 1975
Col. David Russell		Sept. 1975	Aug. 1979
Dr. Robert E. Kahn	Aug. 76 (DD)	Nov. 1979	Sept. 1985
Dr. Saul Amarel		Sept. 1985	April 1986
ISTO			
Dr. Saul Amarel		May 1986	Sept. 1987
J. Schwartz		Sept. 1987	Sept. 1989
Barry Boehm		Nov. 1989	Present

VLSI & MOSIS PROGRAM MANAGERS

	DATES OF SERVICE	
	BEGAN	DEPARTED
VLSI MANAGERS		
Lt. Col. Duane Adams	Sept. 1977	June 1983
Paul Losleben	July 1981	Oct. 1985
AUTOMATION TECHNOLOGY MANAGERS		
Dr. William Bandy	March 1986	Nov 1987
John Toole	Dec. 1988	Present
MOSIS DIRECTORS AT ISI		
Danny Cohen	Jan. 1981	1983
George Lewicki	1983	Feb. 1990
César Piña	March 1990	Present

Table 17-1. Continued

EVOLUTION OF INFORMATION SCIENCES TECHNOLOGIES OFFICE (ISTO)

OFFICE TITLE	DATES COVERED	FIRST DIRECTORS
Behavioral Sciences Command & Control Research Office	Spring 1963 to end-summer 1964	JCR Licklider
Became		
Behavior Sciences Office	Fall 1964	Lee Huff
	1966-1969	Cody Wilson
and	1969	Davis Bobrow
Information Processing Techniques Office	Fall 1964	Ivan E. Sutherland
	Summer 1966	R.W. Taylor
	Fall 1969	Roberts
VLSI Program Originates	Late 1977	Robert Kahn
Strategic Computing originates	1983	
Engineering Applications Office	Nov. 1984 to Feb. 1985	
Information Sciences Technology Office	May 1986	S. Amarel

At the same time, the ultimate objective of the program was to maintain or enhance the U.S. computer technology edge for what it might contribute in defense applications. To limit the chances of important computer technology advances diffusing rapidly to actual or potential foreign adversaries, there was a general understanding in the VLSI program that investigators would delay for roughly a year the open publication of VLSI research papers; meanwhile the results would be circulated quickly within the U.S. VLSI principal investigator community.[18] In addition, participation in research and informal sharing of results by foreign nationals was generally discouraged according to researchers contacted.

2. Early Years of VLSI Program.

The number of institutions participating in the program numbered at least eight in the first two years, featuring diverse programs at well-established centers of excellence such as California Institute of Technology (CalTech), Carnegie Mellon Institute (CMU), Massachusetts Instituite of Technology (MIT), MIT's Lincoln Laboratory, Stanford, and

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[18] This paragraph is based largely on comments by Dr. Robert E. Kahn in an interview on 8/7/90.

the University of California (Berkeley). These contractors were supplemented by some specialized work done by the Jet Propulsion Laboratory at the University of Southern California, and by Xerox's Palo Alto Research Center (PARC). The semiannual VLSI Contractors meetings also included representatives from IBM, Texas Instruments, the University of Southern California's Information Sciences Institute (home of MOSIS), the National Security Agency, and National Bureau of Standards. DARPA funded both solicited and unsolicited proposals. IPTO would grant funding blocks for two, three, or more years (usually for three-year periods) to designated principal investigators for support of research within broadly defined objectives. This approach permitted PIs to allocate funds flexibly within the program to support the most promising research initiatives consistent with program objectives.

a. DARPA Program Precursors

As DARPA's VLSI program got underway, it addressed mainly new technology areas in which major breakthroughs and multiple-order-of-magnitude changes might be realized. Nevertheless it did have some indebtedness to the accomplishments of earlier ARPA programs. Specifically, ARPANET proved pivotal in the propagation, sharing, and implementation of VLSI technologies. Without ARPANET the development of the fast turnaround system for fabricating and testing new devices for new system concepts – MOSIS – would have developed more slowly if at all. ARPA's complementary relationship with the National Science Foundation (NSF) was also of central importance, as the NSF funded some of the costs of MOSIS and other components of the overall effort to strengthen the VLSI community at the universities. The experience and lessons learned from earlier ARPA support of ILLIAC IV with its emphasis on parallel processing structures and techniques gained new prominence from the potentials opened up by VLSI development of new computer designs and advancement of the new microprocessor technology.

b. State of the Academic Art

Part of what made IPTO's VLSI program concept both possible and powerful was the existence of rich veins of academic research relevant to program objectives. Among the more obvious and important areas of exploration which DARPA found to support was the effort that Carver Mead, later joined by Lynn Conway, had underway in the area of VLSI design methods. Their book, *Introduction to VLSI Systems*, also included important contributions by Charles Seitz and several others. A rough inventory of the academic state-of-the-art at the time the DARPA VLSI program began in January 1978 can be gauged from the program of a major Conference on VLSI, organized by Carver Mead at CalTech a year later: by January, 1979, a wide variety of work was underway (but laboring under funding handicaps) in fields such as submicron fabrication, design tools (including silicon compilers), self-timed logic, VLSI device and circuit design (including microprocessor and memory design and management), and computer architecture, including early work on tree machine structures.

c. Early Program Content

DARPA's Annual Reports did not apply the VLSI title to this program until the FY 1982 issue. Available annual reports give only the sketchiest indications of program content in the 1979-81 period. For FY 1980 and FY 1981, apart from references to materials efforts not covered by IPTO, the only notations that appear to outline some VLSI program activities were:

> FY 1980: Smart Processors: We have initiated research in the area which invokes both materials science and information processing technology. The materials effort is focused on properties of materials, submicron lithography techniques, and fundamental VLS design considerations. Information processing research is concerned with computer-aided design, implementation and testing of VLSI chips containing very large numbers of components made possible by advanced submicron manufacturing techniques.[19]
>
> FY 1981: Advanced Technology Seed Efforts:...Initiatives to establish advanced technologies for VLSI circuits are increasing with the establishment of new device design capabilities and fast turnaround fabrication services on the ARPANET, and novel directed energy processing and lithographic techniques for fabricating submicron size electronic circuit elements.[20]

Under Kahn IPTO management was strongly "enablement-oriented" in philosophy. In light of the breadth of new frontiers opened by VLSI, it resisted the temptation to specify in advance (and thus possibly to restrict inadvertently) the content of the program. Based on earliest available records, from the semiannual VLSI contractor meetings for 1980, the following were the major thrusts in the early years of the VLSI program.

-- Implementation: The MOSIS fast turn-around silicon implementation facility provided brokerage services to facilitate fabrication and testing of experimental device designs (ISI/USC). Wafer Scale Integration was an early program to promote integration technology in order to increase speed, to reduce power

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[19] P. I-19, DARPA annual report for FY 1980. Underlining is in the original document.

[20] P. I-15, DARPA annual report for FY 1981.

requirements, and to simplify bonding and packaging. DARPA also supported research in the development of improved fabrication technologies such as the Stanford Fast Turn-Around Facility (SFTAF).

-- Design Methods & Tools: Availability of MOSIS and the breakthrough potential of VLSI technology helped to spawn a wealth of design methods and computer-aided design (CAD) technologies. Among them were the CAESAR and MAGIC--general design tools from UC (Berkeley), which provided the basics for numerous design tools later commercialized, as were DAEDALUS, a graphics design editor developed at MIT, LISPIC, an interactive design database also from MIT, and SIMS, the Stanford Smart Image Memory System.

-- Test and Simulation Tools: Also supported was development of a number of important simulators essential for testing and supporting design work, including simulators for device-level (GEMINI, at Stanford), circuit (SPICE), switch (MOSSUM), and process (SUPREM and BIRD) simulation. Still other DARPA-supported developments included tools for device characterization (TCAP) and imputation of schematics (DRAW).

-- Computer Architectures: Among the earliest efforts were the UC Berkeley development of RISC I and RISC II architectures (begun in 1979 under David Patterson), and of the Stanford MIPS architecture (begun in 1980 under John Hennessy). Both were general purpose designs aimed at achieving much more efficient interaction between computational, storage, and communications units within a device structure. VLSI opened the door to microprocessors on a chip. Combining memory with logic and other components within devices lead to designs for parallel and pipelined operations linking fairly simple microprocessors with cache memories, registers, and other device refinements that promised order of magnitude improvements in processing efficiency and speed. Numerous variations of parallel processing approaches for **general purpose computation** quickly flowed from the combination of VLSI design methods and reduced-instruction-set computer architectures of RISC and MIPS. Early development of connection machine, tree machine, cube machines (Hypercube and later Cosmic Cube), and butterfly designs, were supported by the DARPA VLSI program at MIT, CalTech, and Bolt, Beranek, and Newman (BBN) respectively. For special purpose applications, at CMU, DARPA funded **systolic array (WARP) architecture,** of special interest for signal processing and other analog applications with heavy floating point operation requirements. At UC Berkeley, DARPA supported **symbolic processing architectures** such as SOAR and SPUR. All these approaches represented revolutionary departures from the general industry emphasis of the mid-to-late 1970s which was still focused on advancing the density of gates on a chip.

-- Specialized Devices: New preoccupations with computing efficiency in turn generated requirements for specialized devices to meet the special needs of parallel and pipelined processing flows. Resulting from DARPA support in this area were accomplishments in routing and message-passing devices such as the TORUS routing chip, and the MOSSAIC-A and MOSAIC-C fine-grained message-passing chips (CalTech), timing devices such as PLATO (programmable logic array timing oscillator (Stanford), analog-to-digital converters developed under Paul Grey from UC-Berkeley, and the CORDIC micro-programmed hypercomplex signal processor from Stanford.

e. Program Evolution and Progress

By FY 1982 and 1983 annual reports began to reflect more fully the scope of VLSI-related work already supported by DARPA, and formally used "VLSI" as the program title. VLSI research, only one of eight programs under "Information Sciences and Communications," had the third-largest budget of these, for the whole of which $93.3 million was requested:[21]

Table 17-2. Illustrative VLSI Technologies and Commercializations

TECHNOLOGY	INSTITUTION/LEADER	COMMERCIALIZATION
I. ARCHITECTURES		
A. RISC Architectures		
RISC I, II	UC-B, David A. Patterson	SPARC, Sun Microsystems
MIPS	Stanford, John Hennessy	MIPS Computers, Inc.
B. Parallel Processing Architectures		
Connection Machine[a]	MIT, W. Daniel Hillis	Thinking Machines, Inc.
Tree Machine	CalTech, C. Mead, C. Seitz	None
Cosmic Cube	CalTech, Charles Seitz	iPSC (Intel)
Non-Von (tree machine)	Columbia U.	?
Butterfly switch	BBN	In comm'l production
MOSAIC C (multicomputer)	CalTech, Charles Seitz	Intel
WARP[b]	CMU, H.T. Kung	iWARP (Intel)

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[21] This amount funded programs in the Defense Sciences Office as well as the IPTO programs which are the main focus of this chapter.

[a] Early chip designs were developed with VLSI program; bulk of program support funding supplied by Strategic Computing Initiative program (SCI).

[b] High-performance parallel system architecture based on programmable systolic arrays. Early chip designs were developed with VLSI program funding; bulk of program support funding supplied by Strategic Computing Initiative program (SCI).

Table 17-2. Continued

TECHNOLOGY	INSTITUTION/LEADER	COMMERCIALIZATION
II. DESIGN (continued)		
LINK	CMU; H.T. Kung	?
C. Symbolic Processing Architectures		
SPUR (symbolic & RISC)	UCB, David A. Patterson	?
SOAR (symbolic)	UC-B, David A. Patterson	?
AI coprocessor	Syracuse	?
II. DESIGN		
A. Design Stations		
Cochlea (neural network analog)	Cal Tech	Synaptics, Inc.
Retina (neural network analog)	Cal Tech	Synaptics, Inc.
SUN (networked)	Stanford, Forest Baskett	Sun Microsystems, Inc.
Geometry Engine (graphics)	Stanford, Jim Clark	Silicon Graphics, Inc.
B. Design Tools		
Caesar	UCB, Ousterhout	public domaine
Magic	UCB, Ousterhout	Multiple[c]
LISPIC (interactive design database)	MIT	n.a.
Daedalus (interactive graphics editor)	MIT	n.a.
C. Simulators		
Mossim (switch simulator)	UCB	n.a.
Gemini (device simulator)	Stanford	n.a.
Bird (2-D process simulator)[d]	Stanford	n.a.
D. Testing & Characterization		
TCAP (device characterization)[e]	Stanford	n.a.
DRAW (imputes schematics)[f]	Stanford	n.a

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[c] Valid Logic, Viewlogic, Mentor, Daisy, and Cadence all have products essentially based on the MAGIC concept.

[d] Computes impurity profiles in silicon; coupled with GEMINI, it evaluates test structures.

[e] Modular system for measuring device characteristics and extracting CAD model parameters for SPICE.

[f] Software allows direct output of SPICE input information.

Table 2. Continued

TECHNOLOGY	INSTITUTION/LEADER	COMMERCIALIZATION
III. SPECIALIZED DEVICES		
A. Routing, Message-Passing Devices		
Torus routing chip	CalTech	n.a.
CRRESE[g]	Jet Propulsion	n.a.
B. Timing Devices		
Plato (timing oscillator)	Stanford	n.a.
C. Analog-to-Digital Converters		
CMOS A/D	UCB, Paul Grey	Microlinear Corp
A/D (High speed pipelined)	UCB, Paul Grey	n.a.
D. Signal Processors		
CORDIC[h]		
IV. IMPLEMENTATION, TESTING AND EVALUATION		
CIF (Cal. Intermediate Format)	CalTech	public domain
MOSIS	USC/ISI	US-2, Orbit[i]

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[g] MOSFET matrix for transistor parameter extraction, sampler for propagation delay measures.
[h] Microprogrammed "hypercomplex processor" serves wide variety of signal processing needs.
[i] See this volume, page 18-31, paragraph 10.

FY 1982: Very Large Scale Integration (VLSI) Research. The VLSI research program is developing methodologies, innovative architectures, and computer-aided design and process simulation tools to exploit VLSI technology. Custom VLSI chips are being designed and fabricated to explore innovative architectures. The goal is to develop VLSI systems with a million or more gates on a chip that represent fundamental advances in processing capability. Fundamental research on critical silicon VLSI fabrication processes will provide scientific insight and lead to increased circuit yield and reliability. The circuit design and fabrication times and the cost of providing custom VLSI chips for military systems will be significantly reduced through the use of network-based design methodologies support systems, and process simulation aids being developed under this program. Various innovative architectures such as the tree machine and the geometry engine are being explored to exploit VLSI technology, to achieve orders of magnitude greater processing capabilities than current LSI techniques permit....A new computer architecture called a

> tree machine is being developed for highly parallel computations, and a working version will be demonstrated in FY 1982.[22]
>
> FY 1983: Very Large Scale Integration (VLSI) Research. The VLSI program is developing design methods, innovative computing architectures and computer-aided design, and test/simulation tools to make VLSI technology readily accessible to a much broader community of digital system implementers than had been possible before. A key step in this effort has been decoupling the logic design from detailed consideration of the physics of ICs through development of process-dependent design rules that are not tied to any single fabrication line....The circuit design and fabrication times and the cost of providing custom VLSI chips for military systems will be significantly reduced through the use of network-based design methodologies, support systems, and process simulation aids being developed under this program. Various innovative architectures such as multiprocessor systems, language-oriented architectures, and high performance special purpose systems are being explored to exploit VLSI technology.[23] A new multicomputer architecture called a "tree machine" will be developed for highly parallel computations, and a working version is being demonstrated in FY 1982. A high performance graphics system that utilizes a custom "geometry engine" chip is being built. Research is on-going and will continue in the development of VLSI design tools, languages, and systems to aid in synthesizing designs with a million or more gates. In FY 1983, research will continue into the development of highly parallel architectures, including both the processor architecture and the interconnect structure. Techniques from artificial intelligence research will be incorporated into the design systems to assist in managing the complexity of large designs. Fast turn-around fabrication will be provided to the designers, including both NMOS and CMOS technologies and minimum feature sizes of 3 microns.

From 1978-83 the VLSI program generated prolific activity in new computer architectures and related supporting design and simulation tools; thereafter attention shifted to other VLSI activities. In 1983, as plans for the SCP evolved, the most promising architecture projects for computing breakthroughs were shifted to the SCP. While presented as a major new technology initiative, much Strategic Computing Program (SCP) content in fact involved further development of technologies initiated with VLSI program funding, such as the WARP systolic array processor, the Butterfly machine, and the Connection Machine.

By 1984 the VLSI program shifted mainly to programs at the semiconductor device level. With the launch of the Strategic Computing Program, the Information Science and Technology Office (IPTO) was reorganized into a Computer Systems branch with responsibility for the SCP, an Automation Technology branch with responsibility for VLSI program, and a Systems Integration branch. Main components of the post-1983 VLSI Pro-

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[22] P. I-63-64, DARPA annual report for FY 1981.

[23] Pp. III-14 thru-16, DARPA annual report of FY 1983.

gram were: (1) computer-aided design and manufacturing technology; (2) test and evaluation tools; and (3) implementation and testing technologies. The latter includes (a) ongoing support of the MOSIS fast turnaround silicon implementation facility which provides ever more advanced fabrication technologies, now at the submicron level, along with an experimental effort in gallium arsenide fabrication; and (b) continued support of the SFTAF program at Stanford.

D. COMPUTER ARCHITECTURES: OVERVIEW

Arguably the most important breakthroughs in computer power and efficiency produced by DARPA's VLSI program have come in computer architecture. Because of the exceptional achievements that sprang from DARPA support of architectures, a brief description of main accomplishments in this area is included here.

Beginning in 1978 DARPA funded work in computer architecture at several major academic institutions. Behind this effort was a concern that the complexities and costs of achieving further miniaturization in microelectronic device design--and thereby greater computing power--posed growing barriers to progress in computing and might limit or slow gains in computer power and efficiency, if current technologies alone were pursued.

Among defense applications DARPA anticipated for a new generation of computers were such computationally intensive uses as signal processing and interpretation, strategic target planning, aerodynamic simulation, artificial intelligence, image and speech recognition systems, robotics, and high performance graphics.

Industry's main approach to improving computing power in the mid-1970s was to invest in incremental reductions in feature size and increases in microcircuit complexity. With the advent of the first commercial microprocessors in 1974-75, industry worked to combine more and more logic and memory power into this device, creating an ever more powerful "computer-on-a-chip." *Basic Limitations*, RAND's report to DARPA in 1976, reasoned that this approach neglected the possibilities that greater gains in computing power might be achieved by improving computer architecture.

The VLSI program sought new computer architecture approaches to break free of these impending limits. At the same time, DARPA support for development of semiconductor tools and for quick-turnaround chip fabrication made possible vital enabling capabilities that greatly facilitated the ability of the research community to develop new computer architectures. These design and fabrication tools started to appear in 1976, and in quick succession thereafter a virtual explosion of new computer architectures appeared.

Dr. Stephen Squires, current Chief Scientist of ISTO, recalls that in the early 1980s IPTO kept a chart of new architectures that eventually ballooned to at least 50 new ideas. By the time the Strategic Computing Initiative (SCI) came along in 1982-83, the truly promising among these had been culled to a handful, which were absorbed into the SCI so they could be developed in a more focused and better-coordinated way. The four with greatest potential for major impact on future computing are: (1) RISC; (2) parallel processing; (3) systolic arrays, and (4) symbolic processing.

1. RISC Architectures

RISC architectures developed from observations that in current microprocessor technology a tiny fraction of components were busy while the great majority were idle most of the time. In general, RISC architectures aim at improving computing efficiency by breaking down the logic, memory, and communication functions of the microprocessor and linking them in ways that maximize the efficiency of interaction between the three components. RISC architectures have proven so significant that they receive more detailed attention in two illustrations of VLSI technology at the end this chapter. The first treats the origins and impact of RISC architectures that DARPA supported, and the second highlights the Sun Workstation which owes much of its commercial success to its incorporation of a RISC-based architecture.

2. Parallel Processing

A second broad direction supported by DARPA has been to encourage innovative, aggressive computer architectures using existing components. Many architectural variations have focused on various forms of parallel processing, ranging from a few to massive quantities of microprocessors operating in parallel. At the outset of the VLSI program DARPA supported several research projects on scalable parallel processing, which included the Cosmic Cube, developed under Professor Charles Seitz at CalTech, the Tree Machine (also at CalTech), the Butterfly developed by Bolt, Beranek, and Newman, the Non-Von at Columbia University, and the Connection Machine at MIT. At the upper end of the range in extent of parallelism, is the Connection Machine, a massively parallel architecture now available with 65,625 microprocessors. Its producer, Thinking Machines, Inc., claims to have become the second largest U.S. producer of supercomputers, within seven years of its founding. (See VLSI Illustration C at page 17-C-1.)

Computer history records limited use of processors in parallel before 1979, including the work of Seymour Cray. Only with the availability in the early 1980s of new design and implementing technologies assisted by DARPA did research in parallel processing grow rapidly and in literally dozens of directions. For the architect, the main challenge was (a) to develop parallel structures that would optimize the speed and efficiency of interactions between logic and memory functions and (b) to devise communication linkages to produce that efficiency. Where RISC architects sought to achieve efficiencies by incorporating within the microprocessor structure the best possible juxtapositions of cache memory, registers, message routers, and logic units so that they would interact in the most efficient way, parallel architects sought to use separate processors in communication (interconnect) structures that would achieve those kinds of efficiencies.

Differing configurations used for chaining processors together (the "interconnect structure") give names to the differing architectures employed that are literally descriptive of the structures, such as the tree, cube, and butterfly machines. To illustrate several of the most significant directions in parallel architectures supported by DARPA under the VLSI program, three are singled out for brief description here--the Cosmic Cube, the Tree Machine, and the Connection Machine. Then two special-purpose variations on parallelism --the programmable systolic array and symbolic logic machines--are described.

a. The Cosmic Cube

The hypercube topology has become the most popular architecture for large-scale parallel computers. It was first demonstrated through the work done under the direction of Professor Charles Seitz at CalTech, supported by DARPA. A major objective of this design is to achieve maximum interconnection between many processing nodes, with the shortest wiring distances and fewest transit points between nodes. The cube approach originated in research on connection pathway design in 1978-80 by two CalTech graduate students, Sally Browning and Bart Locanthi. Its first hardware demonstration was realized in the winter of 1981-82 in a two-cube "Cosmic Cube," and was elaborated to a six-dimensional, 64-node version in 1983. An article describing this approach, "The Cosmic Cube," by Charles L. Seitz, *Communications of the ACM,* January 1985, has become a standard reference on hypercube architectures. The hypercube topology has the advantages of minimizing the number of wires and connecting nodes through which messages must pass, and of allowing scalar expansion beyond what most parallel architectures permit. The prototypes developed at CalTech were used extensively in scientific applications at CalTech in high energy physics, quantum chemistry, fluid mechanics, structural mechanics, and seismology research. The CalTech research has been influential in extending the application of hypercube technologies by others. By 1987 there had been at least five commercial computers based on hypercube topologies, including the iPSC and iPSC-VX computers developed by Intel, the NCube/ten by NCube of Beaverton, Oregon, and the System 14, of Ametek, Inc., of Arcadia, California.

The Cosmic Cube and the Connection Machine share certain similarities but their differences are also instructive. Both are highly concurrent, hypercube architectures, have open-ended expansion potentials, use a front-end host computer for ease of programing and for any serial processing an application may require, and depend heavily for their functional effectiveness on the development of sophisticated operating system software. A fundamental difference is that the Cosmic Cube is a multiple-instruction multiple-data (MIMD) machine, which relies on a more complex microprocessor (the Intel 8086) which in present designs has a small number of nodes (64).[24] By contrast the Connection Machine is a single-instruction multiple-data (SIMD) machine with nodes numbering from 16,256 to 65,565 nodes, and a custom 4-bit serial processor, 16 of which are integrated into a single chip.[25]

b. The Connection Machine

The massively parallel Connection Machine, which in its latest configuration offers 65,536 microprocessors, is the most revolutionary of the approaches to parallel processing funded by DARPA under the VLSI program. This approach originated in an effort to simulate the way information is believed to be processed by the human brain. This structure involves thousands of processors each interacting concurrently with data and each other. The interconnect structure lends itself particularly well to signal, and flow processes, and simulation uses in which vast quantities of events interact with each other. It has also been developed to run on Lisp and other languages used in symbolic processing. Its technical origins, commercialization, and technology impact are treated in more detail in VLSI Illustration C at page 17-C-1.

c. The Tree Machine

A highly concurrent architecture using multiple processors and memories connected as a binary tree for highly parallel computations, this architecture is based on a design and

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[24] In 1985 CalTech and the Jet Propulsion Lab developed a 64-node 80286-based machine, the Mark II, and in 1986 a 1024-node hypercube with a 68020 CPU and custom vector processor.

[25] In MIMD machines, multiple instruction and data streams flow to different combinations of processors; in SIMD, individual instructions flow simultaneously to all processors which operate on multiple data streams.

algorithms developed by Sally Browning at CalTech, and implemented under the direction of Professors Carver Mead and Charles Seitz. No commercial applications have been identified in the course of this survey.

d. The Butterfly

A 256-processor architecture which scales linearly for various important defense computer applications, the Butterfly was developed by Bolt, Beranek & Newman of Cambridge, Mass., under a DARPA contract. It takes its name from the butterfly-like nature of its connection structure. It's first commercial production model came out in 1986. It uses the Motorola 68020/81 chip as its CPU. This multi-function architecture proves well suited for both numerical and symbolic processing. It has been commercialized.

3. Systolic Arrays

Systolic array processing is a high-performance, special-purpose design concept involving pulsed processing of data which permits order-of-magnitude simplification of microprocessor and computer system design. Its structure is one of synchronous cells that perform fixed sequences of computations with fixed patterns of communication. "In a systolic system, data flows from the computer memory in a rhythmic fashion, passing through many processing elements before it returns to memory, much as blood circulates to and from the heart."[26]

Professors H.T. Kung and C. E. Leiserson of Carnegie Mellon University first introduced the term and the concept.[27] Their initial work was funded by DARPA, with supplemental funding available later from the National Science Foundation and the Office of Strategic Defense Initiative. The concept addresses the fundamental issue most commonly faced by VLSI architecture designers -- how to overcome the inefficiencies and delays inherent in vector computers and their serial processing of data. The initial systolic array concept represented a type of solution intermediate between multiple-instruction multiple-data (MIMD) designs using limited numbers of processors of moderate to high complexity, at one end, and the massively parallel structures of comparatively simple

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[26] *Why Systolic Architectures?*, monograph by H. T. Kung, Department of Computer Science, Carnegie-Mellon University, Pittsburgh, Pa., 15213, November 1981, p. 1.

[27] H.T. Kung and C.E. Leiserson, "Algorithms for VLSI Processor Arrays," *Introduction to VLSI Systems*, C. Meand and L. Conway, eds., 1980, Addison-Wesley, Reading, Mass., Section 8.3, pp. 271-292. For a basic overview, see H.T. Kung, "Why Systolic Architectures?", *Computer*, Vol. 15, No. 1, January 1982, pp. 37-46.

individual processors such as the Connection Machine, at the other end. A single-instruction, multiple data (SIMD) architecture, the systolic array uses pipelining controlled by a global clock synchronization, which permits parallel processing of data in pulsed cycles of "admission" and "expulsion" combined with onward flows in which the output from one processor is pipelined forward to become the input to be operated on in the next.[28] The advantages of this technology are optimized by use of a large number of a few types of processors. The design costs and other disadvantages of building such a special- rather than general-application machine are partially offset by the modular structure and repetitive components of this design. Early implementations were optimized by designing processor arrays to correspond closely to the algorithm suited to the particular application required:

> Typically, a systolic array can be thought of as an algorithmically specialized system in the sense that its design reflects the requirements of a specific algorithm.[29]

Building such a special-purpose machine may be an economically viable solution only for a few major, widely used, and standardized applications such as signal and image processing. Initially considered a "special purpose" architecture, more advanced implementations have achieved greater breadth and flexibility of use, either through hardware mechanisms to permit reconfiguring interconnect patterns between processors and thereby modifying computing topologies, or through software that permits rerouting of data and instruction flows to match the differing algorithms associated with different computational problems. Among early experimental designs was the WARP, a systolic array developed by H.T. Kung at Carnegie Mellon University, and produced by General Electric. Because it was *programmable*, it permitted programmed reconfiguration of computing elements to adapt to differing computing requirements of varying applications.

Systolic design is especially advantageous when the pattern or generation and use of data involves regularity and uniformity. For these reasons, this architecture proves particularly effective in managing signal and image processing, pattern recognition, language recognition, and other analog applications with heavy floating point operation requirements. It also has matrix arithmetic, and relational database, and artificial intelligence applications (neural network simulation). Among its earliest defense-specific applications have been target recognition, along with radar and IR signal processing.

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[28] Like the Connection Machine, systolic arrays are usually designed for attachment to a host computer.

[29] José A.B. Fortes and Benjamin W. Wah, "Systolic Arrays--From Concept to Implementation," *Computer*, July 1987, p. 15(1).

The first commercial systolic array processor chip, the Geometric Arithmetic Parallel Processor (GAPP) was developed by NCR in conjunction with Martin Marietta Aerospace Corp. and was introduced in October 1984. Applied to real-time use in target recognition, systolic processing proved effective in feature extraction and matching applications, performing at speeds 100-250 times faster than on a conventional sequential minicomputer. By 1987 six semiconductor producers offered commercial microprocessors, including four U.S. (Texas Instruments, Analog Devices, National Semiconductor, and INMOS) and two Japanese (NEC and Fujitsu) producers. The iWARPA, resulting from collaboration between Carnegie Mellon University and Intel Corporation, represents an order-of-magnitude improvement over the initial WARP design, and provides a greatly expanded range of applications. In 1990, Intel completed design of a *general-purpose* 64-chip parallel-processing systolic array system (iWARP) funded by DARPA, which represents one of the most advanced commercial implementations of systolic array processing to date. Another is the Saxpy Matrix-1 general purpose systolic array computer.[30]

4. Symbolic Processing

Symbolic processors are designed to perform rapid parallel computations operating on symbols rather than numbers. DARPA's objective in supporting symbolic processing research is to speed up critical operations in machine-intelligence programs, such as pattern-matching and unification (e.g., for retrieval from data bases, rapid-reasoning from maps, and operations on semantic memories).

Symbolic processing has different requirements and characteristics from numeric processing. Computers designed for numeric processing generally are inefficient at meeting symbolic processing requirements. Because of DARPA's special and long-standing interest in Artificial Intelligence, expert systems, and man-machine interaction, a research focus on symbolic processing has had a high priority in its VLSI architecture programs.

A multiplicity of approaches has developed in symbolic processing, including language-based, knowledge-based, and intelligent interface machines (for speech and pattern recognition, image processing, and computer vision applications). Examples of DARPA-supported architectures within the three broad typologies and the related sub-categories are shown in Table 17-3.

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[30] See the July 1987 issue of *Computer* magazine, which devotes an entire issue to systolic array topics.

Table 17-3. Illustrative Symbolic Architectures[a]

A. Language-Based Machines

List-processing (LISP)	Prolog machines	Functional programming
Spur (UC-B)[b]	Parallel Inference Machine[c]	DataFlow Multiprocessr[c]
Symbolics 3600 series[b]	Parallel Inference Engine[c]	Rediflow
Lamda (Lisp Machines Inc.)[b]	Programmed Logic Machine (Acquarius) (UC-B)[b]	ALICE
ALPHA (Fujitsu)[c]		C-Lisp Machine[c]
Xerox 1100 series	Tamura Machine[c]	ZAPP
Tektronix 4400 series		Formal Functional Programming (UNC)[b]
TI Explorer		

B. Knowledge-Based Machines

Semantics networked	Rule-Based	Object-based	Neural Networks
Connection Machine (MIT)[b]	Non-Von[b]	SOAR (UC-B)[b]	Boltzmann machine
NETL	DADO[d]	iAPX 432 (Intel)	Neural circuits
Thistle (CMU)[b]	PSM	Dragon	
SNAP (USC)		FAIM-1	
		AI-32	

C. Intelligent-Interface Machines

Speech Recognition	Pattern/Image Processing	Computer Vision
Harpy (CMU) [b]	Cytocomputer	WARP (CMU)[b]
Hearsay-II	PIPE (Natl Bur. of Stnds)	Butterfly (BBN, Inc.)[b]
Dialog Systems 1800	Pyramid (U.Wash. Seattle)	VICOM-VME
NEC DP-100[c]	Tospics	
IBM Natural Task	Pumps	
	Zmob	

Among symbolics programs that received noteworthy DARPA support were:

(1) UC-Berkeley, which, under Professor David Patterson conducted a research project known as SPUR (Symbolic Processing Using RISC). Its goal was to develop a Lisp-based multiprocessor that could run common Lisp at least an order of magnitude faster than existing conventional workstations. Subsequently UC-B's Patterson applied RISC NMOS microprocessor technology to an exploratory programming language called Smalltalk-80, in its SOAR program (Smalltalk on a RISC).

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[a] From "Computer Architectures for Artificial Intelligence Processing," by Kai Hwang, Joydeep Gosh and Raymond Chowkwanyun, *Computer*, January 1987, pp. 19-27.

[b] Denotes architectures developed with direct DARPA support or commercializations that benefited from DARPA-supported research.

[c] Developed in Japan

[d] Columbia University

(2) MIT which developed the Connection Machine to operate using Lisp and Smalltalk, explicitly to assure its capability for symbolic processing, in addition to its numeric processing capabilities.

E. OBSERVATIONS ON IMPACT

When DARPA began to shape its VLSI program in 1977, it mainly drew on developments that were in formative stages at several "centers of excellence" in computer science (CS) and electrical engineering. An early participant in the VLSI program sees as a major factor in its success that Dr. Kahn and VLSI managers did not try to impose any preconceptions or content constraints on the program, but acted catalytically to encourage development of a VLSI community and to depend upon synergy within the community to generate the main directions of the program.[31]

Nor was DARPA the only source of funding for VLSI research. The National Science Foundation, Office of Naval Research, and other Federal and defense organizations were also involved. However, since 1978 DoD, and DARPA in particular, have been the dominant funding source for experimental computer science in U.S. universities:[32]

> According to *The Nation*, the DOD controls 71% of all federal funds for academic CS research compared to 45% a decade ago. More than 80% of the federal money going to the Big Four computer science universities--Berkeley, CMU, the Massachusetts Institute of Technology and Stanford University--comes from the military.
>
> According to the Project on Funding Policy in Computer Science, part of the Association for Computing Machinery's Special Interest Group on Automata and Computability Theory (SIGACG), DARPA's budget for university computer science research grew from $14.8 million in fiscal year 1980 to $94.3 million in FY 88–that's nearly 340 percent in constant dollars.
>
> Back then [five or 10 years ago], DARPA was doing things like preserving what are now mainstream technologies. "There are parts of the computer industry that wouldn't exist without DARPA" says Waters [Richard Waters, professor of computer science, MIT.]
>
> There have been some significant commercial benefits from its [DoD's] mission-oriented research, such as...automatic design of very large-scale integrated circuits (VHSIC). Without DARPA funds, Thinking Machines

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[31] Telephone interview with Lynn Conway, October 4, 1990.

[32] "U.S. Computer Research's Basic Dilemma," by Willie Schatz, *DATAMATION*, December 1, 1989, pp. 44-47.

> Corp. wouldn't exist, nor would the Cambridge, Mass.-based company's Connection Machine.
>
> DARPA's dollars also spawned iWarp, a system architecture for various high-performance parallel systems ranging from special purpose systolic arrays to general purpose distributed memory computers.
>
> DARPA neither interfered with nor micro-managed the CMU team during the iWarp project, which was developing an architecture for various high-performance parallel systems. Neither did the agency attempt to involve the iWarp team in any military projects or classified research.
>
> "Only DARPA money made this possible," CMU's Gross [Thomas Gross, professor of computer science, Carnegie Mellon University]. The SCI money allowed us to take these ideas and make them real."

With regard to the impact of DARPA funding on the high payoff area of computer architectures, there comes this testimony: "Parallel processing has come as far as it has largely because farsighted funding by the Government and industry of many university-based projects has lead to an impressive number of commercial endeavors spanning a wide variety of architectures."[33] In the examples cited in this Chapter, the funding source has been primarily and in many cases preponderantly DARPA.

One of the most beneficial aspects of the DARPA's early VLSI program was its practice of supporting proposals which were broadly defined and which provided scope for follow-up on promising directions as they emerged and for dropping or reducing others as they ran into limitations or dead ends. Following passage of the Competition in Contracting Act (CCA) of 1984, it became necessary for DARPA to publish announcements to encourage multiple proposals, which required DARPA to define proposal objectives in a much more precise and limiting way in order to make them "bid-able." In addition, it has become necessary to "compete" proposals to attempt to get the most economic results. During our interviews of academic researchers about their experiences with the VLSI program, several contractors praised DARPA's policies in the management of the VLSI program, and volunteered their contrasting discontent with the changes introduced by the CCA as it affects this type of research. In their view the CCA has greatly increased the costs and burdens of pursuing DARPA funding, making the effort less feasible and productive, and reducing the attractions of DARPA as an organization with which to contract research. Former IPTO officials have also observed with regret the

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[33] "Advanced Computer Architectures," by Geoffrey C. Fox and Paul C. Messina, *SCIENTIFIC AMERICAN*, October 1987, p. 74.

deleterious impact of the Act on DARPA's ability to structure its research objectives and funding in ways that have been particularly productive in the past.

As Dr. Stephen Squires, present Chief Scientist of DARPA ISTO, puts it:

> It was remarkable that in contrast to corporate powerhouses such as Xerox PARC, which was unable to transition the Alto into a commercial personal computer, and AT&T which was unable to transition UNIX to a workstation environment, and IBM, which failed to transition RISC into a viable commercial product, a few separate individuals without any corporate backing or experience, were able with DARPA funding assistance to commercialize UNIX, VAX-like workstations and RISC-based computers that became highly successful commercial technologies of Sun Microsystems and MIPS Computer Systems.
>
> On the importance of SUN: "Researchers were mostly all used to working on VAX in multi-user systems. ARPANET provided that environment. But most didn't like having to share a system--would rather have their own dedicated system. Some of the early VLSI work that DARPA funded aimed at developing UC-Berkeley as a primary substrate or node of the ARPAnetwork specially to service the VLSI work that DARPA was sponsoring. At UC-B DARPA funding helped Bill Joy develop a transitional version of UNIX that could serve to operate an individual work station. Meanwhile at Stanford, DARPA was funding Andreas Bechtelsheim's work to develop a workstation to be attached to a network to permit advanced computing linked to a central computer. When Bill Joy and Andy Bechtelsheim teamed up, they joined Joy's version of UNIX to the workstation hardware developed by Bechtolsheim, to produce Sun Microsystems workstations. Sun workstations then represent the achievement of the researcher's dream--the equivalent of a personal VAX."[34]

DARPA budget documents do not provide a separate breakout for funding allocated to VLSI from 1977 to the present or even identify the broader category within which the funding was provided. Relevant funding categories for FY 1978 to 1980 include:

	Office	FY 78 Act.	FY 79 Est	FY 80 Est.	FY 81 Est.
IPTO	Advanced digital	5.1	6.1	8.3	9.4
DSO	Electronic Sciences	9.2	10.7	10.9	11.7

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[34] Interview with Dr. Stephen Squires, Chief Scientist, DARPA ISTO, October 19, 1990.

F. TECHNOLOGY ILLUSTRATIONS

Of the main new directions supported by DARPA, three of the most significant technology accomplishments of the VLSI program were: (1) RISC; (2) multicomputer systems, (the Sun workstation); and (3) the Connection Machine (Danny Hillis, MIT). Brief illustrations of DARPA's influence on these technologies follow.

ILLUSTRATION A: RISC ARCHITECTURES

A. BRIEF OVERVIEW

In 1978 current commercial technologies were producing improvements in speed which had slowed to an estimated 20-30 percent yearly. DARPA's new VLSI program sought new approaches to break free of these impending limitations.[35]

Of different architecture approaches DARPA supported for quantum improvements in computer architecture, two were variants of reduced instruction set computer (RISC) architecture. These provided important gains in microprocessor efficiency and performance, and gave rise to widely accepted commercial applications that are still expanding rapidly. Within two years of the conclusion of the two RISC programs in 1984, the *computer industry* had announced products based on RISC, and soon semiconductor firms began producing RISC processors which claimed a two- to five-fold performance advantage over other computers using the same technology,[36] and gave workstations capabilities roughly equivalent to those of minicomputers. Combined into networks with specialized file servers, RISC-based workstations are also increasingly becoming an alternative approach to mainframe-based systems.

It is estimated that systems based on RISC architectures gained at least 16 percent of the computer workstation market in 1989[37], which in turn is one of the fastest growing segments of the computer market.[38] Most major U.S. and foreign semiconductor and computer firms have incorporated RISC-based systems into their product lines for both defense and commercial applications. "In 1990 it is hard to find a computer company without a RISC product either shipping or in active development."[39]

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[35] Based on interview comments by Lt. Col. John Toole in March, 1990.

[36] Patterson and Hennessy, op. cit., p. 395.

[37] Ibid.

[38] "What's Taking the Risk out of RISC," by Bob Francis, *DATAMATION*, January 15, 1990, pp. 61-64.

[39] Patterson and Hennessy, op. cit., p. 190.

B. TECHNICAL HISTORY

The *roots* of RISC architecture predate the VLSI program. Seymour Cray used multiple processors in parallel in early versions of his supercomputers. Independent of DARPA, in the late 1970s IBM developed an experimental machine, the 801, based on statistical analysis of computer operations which revealed the inefficiencies of serial operations by monolithic logical processing elements. However, little was known about the effort at IBM, which did not commercialize the approach, and IBM designs did not influence the work of later computer architecture designers.[40] Cray's work did however influence the ideas of Forrest Baskett in his supervision of the Stanford MIPS program.

DARPA's VLSI program directly capitalized on recommendations of a 1977 Rand report by directly supporting academic research into improved computer architecture.[41] As DARPA's program was getting underway, the Mead-Conway book on simplified and standardized design rules and methods, applicable both to device and computer design, greatly stimulated and facilitated efforts to develop new architectures. Such architectures included use of multiple processors, typically in parallel mode; associated cache memories to link logic-data operations more closely; compilers and registers to facilitate these operations; and pipelining to direct the flow of particular operations to particular processors to optimize efficient use of logic processors and to minimize data processing delays.

Of the new architectures, RISC designs originated in efforts to analyze the flow of computer operations to determine which processor elements were most frequently used,[42] and in what sequences, and then to restructure linkages to achieve more efficient interactions. The main advantages of these designs are that (1) since most *logic* elements in traditional architectures and instruction configurations do nothing a very high percentage of the time, there was enormous room for improvement in their duty cycle; and (2) "with the greatly reduced cost of logic circuitry, it became economic to duplicate computation functions and deploy them geometrically close to the data elements on which they operate." Such architectures involve use of multiple processors and their conduct of logic operations in parallel rather than the traditional serial flows.

A key technique used to achieve this result is the pipelining of instructions so that they flow to the microprocessor in a sequence and timing pattern aimed at maximizing use of memory and logic. The principal early efforts in RISC development concentrated on

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[40] See Hennessy and Patterson, op. cit., p. 188-189.

[41] See VLSI Overview, footnote 5.

[42] I.e., logic, memory, and communications elements.

development of RISC microprocessors that incorporated all three components. The first Sun workstation was an early example of the application of a RISC-based microprocessor to enhance the power of the workstation, which has ultimately given it computer power equivalent to a minicomputer. As work in parallel processing architectures progressed, under DARPA sponsorship, multiple RISC microprocessors have in turn been incorporated into parallel computing structures.

RISC architecture introduced fundamentally different design principles from the then-established machine principles, now referred to as CISC, or complex instruction set computers. The new principles are: (1) keep functions simple; (2) microinstructions should not be faster than simple instructions; (3) microcode is not magic or better; anything that can be done in a microcoded machine can be done in assembly language in a simple machine, and is simpler to change; (4) simple decoding and pipelined execution are more important than program size; and (5) compiler technology should be used to simplify instructions rather than to generate complex instructions. These principles were applied with some differences at Stanford and Berkeley.[43] However, both MIPS and RISC machines depart from the previous practice of linear instruction processing, employing instead "pipelined" instructions (see chart). DARPA funded the research at both of these institutions.

At the University of California, Berkeley, Dr. David A. Patterson and colleagues developed a program called RISC (for "reduced instruction set computing"). The purpose of the project was to use parallel processors closely linked with memory and communication circuits to increase computer speed and efficiency. The Berkeley group produced the RISC I and RISC II computers.[44]

> In 1980, Patterson and his colleagues at Berkeley began the project that was to give this architectural approach its name. They built two machines called RISC-I and RISC-II. Because the IBM project was not widely known or discussed, the role played by the Berkeley group in promoting the RISC approach was critical to the acceptance of the technology. In addition to a simple load/store architecture, this machine introduced register windows--an idea that has been adopted by several commercial RISC machines. [45]

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[43] The description of RISC in this and the two following paragraphs depend mainly on: David A. Patterson, "REDUCED INSTRUCTION SET COMPUTERS," in *COMMUNICATIONS of the acm* (Association for Computing Machinery), January 1985, Volume 28, No. 1, pp. 8

[44] The RISC II was designed by Manolis Katevenis and Robert Sherburne.

[45] From John L. Hennessy and David A. Patterson, *Computer Architecture, A Quantitative Approach*, 1990, p. 189.

In 1987 Patterson, as a consultant, assisted Sun Microsystems, Inc., in developing a new form of RISC called scalable processor architecture, or SPARC, to incorporate RISC architecture into its workstations This approach developed a hardware solution for making more efficient use of registers, by having enough registers to keep all the local scalar variables and all the parameters of the current procedure in registers. Based on licensing rights to RISC-II, SUN acquired SPARC architecture rights from UC-Berkeley.[46] In addition to designing its own devices and workstations, SUN has also licensed the SPARC chip for production by a number of major system houses, hoping thereby to make its technology and devices the industry standard for RISC. See VLSI Illustration C on Sun that begins on page 17-B-1

At Stanford, Dr. John Hennessy and colleagues developed their variant of reduced instruction architecture, producing a chip and computer known as MIPS. MIPS depends on a combination of (1) redesign of micro devices and associated simplification of microprocessor design, (2) transfer of a number of hardware functions to software, and (3) restructuring of computer systems to take advantage of more efficient device design and associated software. This architecture emphasized pipelining data flows to parallel processors. It aimed at achieving mainframe-level performance at the VLSI processor level, and supercomputer performance through a VLSI-based parallel processing structure. Stanford advanced the state-of-the-art in compiler technology to maximize the use of registers.

Persuaded of the potential for applying this approach commercially, Hennessy and colleagues at Stanford founded MIPS Computer Systems. MIPS has licensed five major chip producers to produce devices based on its technology,[47] and licensed five others to use its architecture in production of their own computers.[48]

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[46] According to Dr. Patterson, the ability to transfer SPARC to commercial applications was crucially dependent on the open architecture of the UNIX system, developed by Bell Laboratories of AT&T (phone interview. April 27, 1990).

[47] Integrated Device Technology, Inc. (IDT), Performance Semiconductor Corp., LSI Logic Corp., NEC of Japan, and Siemens (FRG).

[48] Both Sun Microsystems and MIPS Computer Systems have licensed their particular versions of RISC technologies to a growing array of first and second rank industry leaders. As of early 1990, the score card read:

SPARC: AT&T, Fujitsu, ICL, LSI Logic, Philips, Texas Instruments, Xerox

MIPS: DEC, Honeywell-Bull, Nippon Electric Corp. (NEC), Tandem, Silicon Graphics.

Independently, Motorola and IBM have developed their own RISC or RISC-like microprocessors.

ILLUSTRATION B: THE SUN WORKSTATION

A. TECHNOLOGY ORIGINS[49]

By 1979-80 DARPA was funding a wide variety of separate VLSI efforts at Stanford and the University of California, Berkeley (UC-B). From these two programs a number of pieces ultimately came together in commercial ventures. The Sun workstation is one of the most dramatic and successful. In its commercial manifestation, the Sun workstation is a story of the progressive adaptation and integration of an array of VSLI-origin technologies into a computer architecture and system that has become today one of the fastest growing segments of the world computer market, with average annual increase in computer power per dollar currently averaging over 30 percent yearly.[50] Founded in February, 1982, Sun Microsystems, Inc., has become an "international powerhouse" with $2.5 billion in sales.[51]

The original SUN project and its commercial offspring incorporate numerous technologies which in varying degrees owe their origins or development to DARPA initiatives--the workstation itself, computer-aided design tools, high quality graphics display, UNIX operating system extensions,[52] and "RISC" architecture. These are all technologies developed by or based largely on DARPA-supported programs, mainly at Stanford University and the University of California at Berkeley.

Earliest DARPA recollections of project origins revolve around a proposal of Stanford's Dr. James Meindl to build microelectronic devices that integrate systems on chips. In 1979, Meindl requested DARPA funding for that purpose. DARPA's Robert

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[49] Much of the information on which this section is based was obtained through interviews with Andreas Bechtolsheim, Vice President of Sun Microsystems, Inc., on December 4, 1990, Dr. Alan Bell at Xerox PARC on December 6, 1990, and Vinod Khosla of Kleiner Perkins Caufield & Byers, Palo Alto, Cal., on May 9, 1990.

[50] Sun's continuing commercial success despite the vulnerability of its open architecture has depended on its keeping its competition "perpetually off balance with a barrage of new products." See "Sun's Sizzling Race to the Top," by Stuart Gannes, *Fortune*, August 17, 1987.

[51] "Carol Bartz: star is still rising for hard-driving Sun executive," *PC Week*, Vol. 7, #35, September 3, 1990, p.134(2).

[52] UNIX is a registered trademark of AT&T Bell Laboratories.

Kahn recalls encouraging him to broaden the concept by cooperating with Stanford's foremost computer architecture specialist, Dr. Forest Baskett.

B. TECHNICAL HISTORY

1. Hardware Development

Forest Baskett of the Stanford Computer Systems Laboratory was a co-principal investigator along with John Hennessy for a wide-ranging program of research under the DARPA VLSI program. Both were faculty members in the Stanford Computer Sciences (CS) Department.[53] Baskett's interests ranged over a broad array of VLSI and computer technologies. As did many other Stanford CS faculty and researchers, Baskett had close working relationships with Xerox Palo Alto Research Center (PARC), where many innovative computer system developments were underway. Baskett was intrigued by the Xerox Alto, the first personal computer or intelligent single-user workstation, with its high-quality graphics and networked capabilities.[54] The Alto was developed for Xerox internal use, provided to individual PARC researchers, and was net-worked throughout the PARC facility near Stanford via Ethernet. It was the first application of the Ethernet network system and had the first mouse and laser printer.[55] The Alto illustrated the potentials for distributed advanced computing power that individual researchers might expect to have more broadly available in the future.[56] Xerox donated ten Alto's to Stanford. Although Ethernet and its network services were invaluable, the Alto, by 1980 already six years old, was limited in its potential for science and engineering applications, both because of the limitations of its *16 bit*-central processing unit (CPU) and because of a proprietary

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[53] In the early 1980's this department was merged with Electrical Engineering to become the Computer Sciences and Electrical Engineering Department.

[54] Baskett had extensive previous experience at Xerox PARC before going to Stanford in about 1978.

[55] *Computer Architecture, A Quantitative Approach*, by David A. Patterson and John L. Hennessy, 1990, p.560.

[56] The Alto was developed by Xerox in 1974. At PARC, the Alto's were networked together via the Xerox Ethernet. Other local area networks at that time involved dumb terminals linked to mainframes and minicomputers by ad hoc communications, which permitted terminals only to talk to each other and transfer files and programs, and to use central mainframes on a *time-sharing* basis. The Alto represented the first single-user computer, an intelligent workstation with significant independent computing power, networked by comprehensive communications software and protocols. With its 64k memory and 16-bit addressability, it brought roughly the capability of the minicomputers of that time to the desk of the individual researcher, along with bit-mapped graphics, a mouse, on a network. Networked services transparent to the user included database and file servers, electronic mail, and printing.

operating system that made it hard to develop programs to adapt it to the emerging range of specialized scientific and engineering requirements.

Fortuitously, commercial components were becoming available that made it feasible to develop independently and at low cost a more versatile and powerful Stanford workstation, largely from off-the-shelf components.[57] The new Motorola 68000 appeared in 1979-80 and was the first microprocessor to have a *32-bit* CPU--a major advance for managing complex scientific and engineering applications.[58] Baskett envisaged single-user workstations that would combine the Motorola 68000 microprocessor with a newly available wide-screen cathode ray tube (CRT) display produced by Ball. Xerox was willing to share the specifications of its proprietary Ethernet to permit networking of workstations around the campus and connection to Stanford's PDP-11 and VAX 780 minicomputers. These were the main building-blocks of what was to become the Stanford University Network (SUN), as it took shape in Baskett's mind. SUN was to be the means by which Baskett hoped to put on Stanford research desks single-user minicomputers powerful enough to manage the complexities of current scientific and engineering research as stand-alone units, yet concurrently linked by Ethernet to each other and to university mainframes and databases. In a Stanford report to DARPA in mid-1979 Baskett formally proposed creation of the Stanford University Network "designed to connect systems that span the spectrum for computing needs from large timesharing systems to personal computing systems." It was to be sponsored as a separate project within the DARPA VLSI program at Stanford. He saw its promise as a powerful new tool for leveraging research in science and engineering, particularly in a wide variety of computer-related VLSI research, including computer-aided chip and hardware design, computer-aided engineering, and development of new computer architectures.[59]

To implement the project, for hardware development Baskett turned to a young Austrian-born graduate student in electrical engineering at Stanford, Andreas (Andy) Bechtolsheim, and tasked him to design a SUN "modular personal computer system

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[57] A similar project, dubbed the "NU machine" was undertaken at MIT about the same time.

[58] The other leading microprocessor then available was the Intel 8086 which offered only 16-bit addresses that severely constrained its utility for application to scientific and engineering tasks.

[59] The workstation project was in reality more an engineering than a research project, but its broad potential as a powerful tool for VLSI work, foreshadowed by the Alto, combined with the flexibility and initiative allowed to principal investigators under DARPA's program management style at that time, made it possible to incorporate this project as an integral part of Stanford's VLSI program under Baskett.

designed for the network," to be produced from available commercial components.[60] The workstation would be based on the Motorola 68000 microprocessor, and would be designated the SUN 68000. The two envisaged that the system architecture would involve (1) Ethernet-based stations, (2) centralized file servers and data bases, and (3) remote large-scale computing resources.[61] Because the workstation was to be used mainly in technical applications, the graphics system and display technologies were particularly important. High resolution graphics display, graphical input, and high-speed manipulation of raster images, included high-speed frame buffer updating though hardware innovations, were priorities. Among the main applications initially contemplated were computer-aided circuit design automation for the VLSI project, development of more powerful design tools, and advanced text processing. Since high quality graphics display would be particularly important for scientific and engineering applications, Baskett also engaged in the SUN project a graduate student in computer sciences, Jim Clark, who was working on a high-speed graphics engine for generation of graphics displays.[62] Clark and M.R. Hannah also developed an image memory processor for the workstation. Another key player was Dave Cheriton who brought to the project special skills in network connectivity and operating system software design and programming.[63]

Engineering design tools from industry were available only on commercial terms that were too rich for university budgets. However, thanks to the power of Alto workstations and computer-aided design software newly available from DARPA-sponsored academic sources,[64] Bechtolsheim was able to complete design of the first workstation within one year of long days and many late nights--a task that, until these new tools became available, would have been considered far too expensive, ambitious, and labor-intensive for a single engineer or even team of engineers to accomplish. Bechtolsheim's personal efforts were funded under a DARPA VLSI research project, with component and material

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[60] Bechtolsheim relates his recollection of an informal seminar Baskett held for graduate students at which he provided a show-and-tell of the available components including the 68000 and the Ball CRT.

[61] DARPA-MDA-903-C-680. See "The SUN Workstation, Hardware Overview," by Andreas Bechtolsheim and Forest Baskett, Computer Systems Laboratory, Stanford University, November 12, 1980.

[62] Development of a VGT--a video graphics terminal--was another priority VLSI project effort under Baskett's sponsorship, which he later pursued commercially with Clark. See footnote 20.

[63] Stanford lacked expertise or detailed familiarity with UNIX which was emerging as the dominant software operating system for multitasking and network operations.

[64] UC-Berkeley had recently begun to share its "MAGIC" advanced CAD software, developed under DARPA sponsorship.

costs from bits and pieces of funding that Baskett pulled together from various project sources, since the SUN was designed to serve all aspects of the VLSI program.[65]

2. Software and Operating Systems

By 1980 Stanford had several Digital Equipment Corporation (DEC) PDP-11 and two or three VAX 780 minicomputers with around 20-30 users on each. DEC promised Baskett that it would modify its proprietary VAX VMS operating system to accommodate the needs of the SUN workstation. Soon, however, doubts arose about whether the VMS could or would be modified to meet SUN needs.

As originally configured, the SUN at Stanford consisted of Ethernet, with its networking software that linked Stanford's ten or so Alto workstations, its DEC VAX minicomputers, and its DEC PDP-11's, along with the new SUN workstations. The Ethernet operating system would provide not only station-to-station communications, but would also add for the first time such network services as file, database, and printer management--until that time only available on the Xerox PARC network. UNIX was available at Stanford only as an alternative operating system on its PDP and VAX minicomputers, and did not include network management and service capabilities, and thus did not figure in original SUN plans. A key component of the project was to develop network software that would interface effectively with the VAX/UNIX operating system. One challenge was to develop software to provide multiple display windows--a particularly valuable new capability for scientific and engineering applications.

The UNIX system, developed by AT&T Bell Labs, was specifically designed for multi-tasking.[66] Bell Labs made the system available freely to universities, with the intent of seeing it become the industry operating system standard for multitasking. Software for the UNIX, because it was written in "C", a high-level language, proved especially easy to adapt and extend to new processing and networking environments and applications. DARPA welcomed the potentials of UNIX as an open architecture, and fostered its further

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[65] The overall university research environment fostered by DARPA in the late 1970s and early 1980s was considered an important factor in fostering projects such as the SUN; while it was not VLSI work per se, the workstation was seen to be an enabling tool of great potential value for numerous aspects of VLSI work; similarly DARPA's style of allowing principal investigators considerable latitude in defining VLSI projects provided the kind of flexibility for decision-making that was important for Stanford's ability to launch and implement the project quickly and efficiently.

[66] By multitasking we refer to the management of the computer central processing unit (CPU) or microprocessors in a way that permits the computer to process several tasks simultaneously. Introduction of this technique represented a major advance in the efficiency and utility of computer

development and broader application at the University of California, Berkeley (UC-B). Bill Joy was the principal developer, having launched in the late 1970s a version known as the BSD 4.0, followed not long after by the 4.1, which was widely used in university computer circles. By 1980 Joy was working on 4.2 BSD, which was to become the first version of UNIX to be extensively used in industry.[67]

One of the first major accomplishments of the UC-B UNIX effort under DARPA sponsorship was to develop a version of UNIX as an open architecture alternative to the VMS.[68] By 1980 this UNIX was available on Stanford PDP-11's and VAX minicomputers. UC-B also undertook to expand UNIX so that it could provide networking services. However, since there was no UNIX expertise available at Stanford, the first SUN proposal and report did not contemplate use of UNIX as an operating system for either the workstation or for the network.[69]

Bechtolsheim observes that while the 68000 microprocessor gave the workstation a quantum advantage in computing power over the comparatively weak PC's then emerging, the real power of the workstation was to come later from application of the UNIX network-based operating system software, as developed by Bill Joy and his colleagues at Sun Microsystems, Inc.,[70] with its capability to provide network services.

3. Integration and Adaptation

Bechtolsheim then began to integrate the work of the collaborators and to produce the hardware board that combined the 68000 microprocessor, graphics display engine, network interface, and other essential ingredients. However, he discovered that the 68000 did not incorporate a memory management unit (MMU). He was able to design around the gap by producing an independent MMU composed of eight chips designed by the project team. He also found that the 68000 lacked instruction restarts needed to achieve "virtual

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operation over the previously dominant timesharing mode that involved batched serial processing of tasks.

[67] It was also compatible with the new "reduced instruction set computing" or RISC architecture being developed at UC-B by Joy colleague David Patterson; this compatibility was to facilitate the incorporation into the Sun workstation of an adaptation of RISC architecture -- SPARC -- that Sun introduced in April 1989.

[68] VMS (Vax Management System) is a product of Digital Equipment Corporation.

[69] At that time, the DEC VMS operating system was not designed to provide networking services but rather functioned to manage multitasking on DEC minicomputers.

[70] Bechtolsheim emphasizes that operating systems change gradually over 10-20 year periods, and have a much more powerful and long-lasting influence on computing than does the hardware.

memory" operations--a problem Motorola worked out when it came out with its 68010 -- the chip finally used in the first SUN workstations distributed at Stanford. Once the first prototype SUN workstation was completed and successfully demonstrated in early 1981, the project team undertook an initial output of workstations for distribution to priority sites. By the end of 1981 the project had distributed roughly twenty workstations around the Stanford campus, at an estimated cost of $10,000 each. Each provided computing power approaching that of a $100,000 VAX 780 at about a tenth of the cost.

4. Commercialization

With regard to other aspects of DARPA's role, Bechtolsheim recalls that as VLSI program technologies reached useful stages, Bob Kahn and others from DARPA actively encouraged their commercialization. He understood DARPA's view to be that only through commercialization could the technology availability, viability, and cost be brought to a level where it could be widely and inexpensively available to universities. Thus in the latter half of 1981 Bechtolsheim was able to determine from DARPA and from Stanford that he would be legally and otherwise at liberty to attempt to license the workstation board for commercial applications. He began VLSI Systems, a company in which he was the sole participant. His hope was to license the workstation board technology broadly enough that it would become the standard for workstation design. Some eight small start-up companies submitted letters of intent to license, but Bechtolsheim concluded that all lacked either the funding or vision to covert the board's potential into a commercial success. Moreover, Apollo computers had come out with a commercial workstation, which created great urgency if SUN were to compete in this new market.

Around the end of 1981 he received a call from a young "venture entrepreneur," Stanford MBA, Vinod Khosla, who read about his company and technology in a venture capital magazine and was impressed by its promise. A meeting of Bechtolsheim with Khosla and his close friend and fellow Stanford MBA Scott McNealy ensued. Convinced of the advantages of the Sun design over that of the sole competitor then in the market, the three quickly developed a business plan. One important objective of the plan was to convert to UNIX as the Sun operating system to take advantage of both its multiuser, multitasking, and networking advantages. Both Khosla and Bechtolsheim were familiar with the work of Bill Joy at UC-Berkeley in extending UNIX to these new and more powerful applications, and favored an effort to get him to join in their new venture. Bechtolsheim knew that others had tried and failed to lure Joy into commercial enterprises, and doubted their prospects, but Khosla proposed to make him an offer Joy could not refuse. They did, and succeeded. Joy had been striving to promote the Berkeley version of UNIX, BSD version 4.2, as the industry standard. Sun's business plan appeared to offer a meaningful mechanism for doing that.

Vinod Khosla brought to the venture his access to venture capital--he had been raising capital for and co-founded Daisy Systems, to sell computer-aided engineering (CAE) systems for designing electronics. Scott McNealy had several years experience as manufacturing manager for Onyx Systems, a computer firm.[71] Bechtolsheim brought the hardware knowhow, and Joy the software expertise.[72] On January 15, 1982, first meetings began with venture capital firms. By February 15 agreement on funding had been reached with two firms and initial funding of $2.5 million was agreed on; within a few months a total of four venture capital firms had agreed to provide a total of $4.5 million in start-up capital. Its first product, the Sun-1 workstation was launched in 1983. Sun also found that numerous other companies spawned by Stanford and Berkeley computer technologies were among its first and best initial customers.

DARPA then provided a critical assist to the launching of Sun by extending funds to a number of academic institutions to permit them to acquire workstations for their own institutional users and networks. According to Khosla, academic institutions (particularly the University of California at Berkeley, Stanford, and Carnegie-Mellon) accounted for roughly 80 percent of the orders received by Sun in its first year of business, thanks to this DARPA funding.

One of Sun's first tasks was to incorporate a new operating system. The Stanford SUN workstation design still relied on the Ethernet operating system. Sun's first commercial product, the SUN 1, provided major improvements in stand-alone computing

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[71] McNealy in 1984 became the chairman and Chief Executive Officer of Sun, and Bechtolsheim the Vice President of Technology. Joy is Sun's Vice President of Research and Development. Khosla, who left Daisy to join Sun, was its first chairman and CEO until retiring in 1985. He is now with the venture capital firm of Kleiner Perkins Caufield & Byers in Palo Alto, Cal.

[72] While Forest Baskett was the original sponsor of the SUN project, his primary interests were in graphics displays and reduced instruction set computing (RISC) technologies. He did not participate in the formation of Sun Microsystems. In the mid-'80s, he served as Digital Equipment Corporation project leader for development of its experimental RISC processor. In 1986 he became Vice President for Research and Development of Silicon Graphics, Inc., Mountain View, Cal. Baskett's support of an extraordinarily wide range of project activities was extolled by former students at a 25th reunion of Stanford computer science graduates in November 1990.

Bechtolsheim was also in touch with Stanford colleague Jim Clark, who was at work on the "geometry engine." Clark was an ardent proponent of three-dimensional graphics, whereas Bechtolsheim believed that two-dimensional graphics would be adequate for the general applications for which he expected to market the SUN. Thus the two proceeded in different directions. Clark founded Silicon Graphics, Inc., in the mid-1980s, where he was joined by Baskett in 1986.

power, with this 32-bit 68010 microprocessor, but was not converted to UNIX. Bill Joy and four colleagues achieved the conversion to a UNIX workstation and network operating system in 3-4 months. Bechtolsheim argues that the open UNIX system deserves credit for having created an immense and rapidly growing user pool as a result of its easy application to networks and to new computing architectures and operating environments.[73]

The next major VLSI-related progression at Sun was the incorporation of RISC architecture into its workstations. In 1983, when rumors circulated about APPLE coming out with the Macintosh, Bechtolsheim and Khosla saw the need for a step-level advance in Sun workstation technology. By 1985, DEC and Hewlett-Packard were also beginning to make inroads into Sun's market share, and Steve Jobs, with his recently-founded Next Inc. planned to enter the market with an advanced desktop computer. They looked again to academic research labs for ideas, and quickly became convinced that the faster processing speeds and greater computing efficiency made possible by the new RISC architecture could become an important means for maintaining and improving Sun competitiveness. Bechtolsheim talked first with Stanford colleague John Hennessy who, starting in 1981 under DARPA sponsorship, had developed a Stanford version of RISC architecture, called MIPS. However, by 1985, Hennessy, believing that sale of MIPS chips would not be enough to sustain a commercial venture, had organized a company which he envisaged would produce its own computer--a decision which precluded cooperation with Sun.[74]

Bechtolsheim and Khosla then turned to David Patterson, at UC-B, who led the design and implementation of the reduced instruction set computing architecture and the RISC-I, perhaps the first risc computer, as well as the RISC-II and subsequent generations. Patterson agreed to serve as a consultant and assisted Bechtolsheim in development of the SPARC workstation, a derivative of RISC-II.[75] The resulting commercial product was a particular form of RISC called scalable processor architecture,

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[73] DEC reportedly found that about one-quarter of its VAX users were operating their systems on UNIX in preference to using the DEC proprietary VMS (VAX Management System) provided with the equipment.

[74] Hennessy took a one-year leave of absence from Stanford to concentrate on commercialization of MIPS. As it developed, the firm that he co-founded, MIPS Computer Systems, now mainly sells and licenses its own risc chip design, having licensed the technology to DEC, NEC, Siemens, Tandem, Honeywell-Bull, and Silicon Graphics, Inc. It has also developed a multiprocessor workstation, the Iris Power Series, designed under the leadership of Forest Baskett. Hennessy is Chief Scientist at MIPS, but also remains on the faculty at Stanford.

[75] SUN initially had tried also, unsuccessfully, to hire Skip Stritter from Stanford because of his experience with the 68000; six months later, Stritter assisted John Hennessy of Stanford with the founding of MIPS Computer Systems, to produce another RISC-based computer.

of SPARC.[76] Sun's SPARC chip, which replaced the Motorola 68010 chip originally used, was quickly incorporated into next-generation Sun workstations which were first shipped in 1987.[77]

Gaining top management acceptance of the need for the SPARC workstation (dubbed Sparcstation 1) involved extraordinary efforts by Bechtolsheim, supported by Khosla, which are chronicled elsewhere.[78] The ultimate result, Sun's first *true desktop* work-station, with its efficient, high-speed low-cost leap over previous PC's and workstations, has been Sun's best seller, expected to account for an estimated 75 percent of its unit shipments in 1990.

In addition to producing its own workstations, Sun has also licensed SPARC for use by a number of major system houses, hoping thereby to make its technology and device design the *de facto* industry standard for RISC-based computers. According to Khosla, another reason for licensing has been that Sun began with a proprietary position in only one of the three technology bases on which its product depends--the architecture. It depends on others for the process technologies and for the actual fabrication of its chips.

C. OBSERVATIONS ON SUCCESS

DARPA's impact on computing via its support of the Stanford University Network extends well into the commercial life of the Sun workstation. DARPA's main *direct* contributions to the feasibility of the Sun development were its support for:

- the work of Bechtolsheim and Baskett on workstation hardware;
- CAD and other enabling tools that equipped Bechtolsheim to accomplish engineering design that would have been unimaginable in previous years;
- enhancement to open operating systems, particularly UNIX, that provided great ease of extension and adaptation to new computer architectures, multiprocessing environments, and ancillary input and output devices;
- Bill Joy's UC-B work in his multiple enhancements of the UNIX operating system;

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[76] According to Prof. Patterson, the ability to transfer SPARC to commercial applications was crucially dependent on the open architecture of the UNIX system, initially developed at the Bell Laboratories of AT&T (phone interview with Patterson on April 27, 1990).

[77] Patterson continues to support Sun technology development as a day-a-week consultant.

[78] See "Who's News: Sun's Success Doubly Sweet for Designer," by G. Pascal Zachary, *Wall Street Journal*, May 29, 1990, p. B8.

- funding of first-year workstation orders by academic institutions, aiding Sun's successful entry into the commercial market;
- development of new computer architectures, particularly UC-B's RISC architecture, which entered Sun's enhanced workstation via Patterson's SPARC architecture that now gives Sun a *true desktop workstation* with minicomputer capabilities;
- new display technologies, particularly the work of Jim Clark on the geometry engine, which contributed to Sun development of a high-resolution display terminal suitable for engineering and scientific applications.

Less obviously, "If DARPA had not been available, university researchers would have had to use 'free' equipment from companies like Digital and IBM to do their research. DARPA funding of research was essential in providing an ability to make independent choices."[79] (As seen in the next Chapter, "MOSIS," availability of a quick, inexpensive DARPA-supported fabrication service was also instrumental in early development of experimental RISC chips.)

From a DARPA viewpoint, the SUN project had special significance. As noted in the VLSI overview, former IPTO Director Kahn considers it one of the most powerful programs funded early in DARPA's VLSI program. Kahn saw in the modest "system-on-a-chip proposal of Jim Meindl the germ of a more complex computer project and the project was in fact broadened accordingly, with remarkable result

In a still broader sense, *DARPA efforts fostered development of new technologies that proved able not only to compete with the technologies of industry leaders but in some cases to challenge them for leadership.* This process involved two stages:

- By adapting RISC-II to develop and incorporate SPARC, Sun posed a challenge to a technology of IBM, which had developed its own reduced-instruction-set computer, the 801, in the late 1970s,[80] but made no effort to market it in spite of its initial lead.[81] RISC technology has provided an additional step up in the power of workstations and personal computers which have become increasingly viable as alternatives to or accessories of minicom-

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[79] Interview with Vinod Khosla of Kleiner Perkins Caufield & Byers, Palo Alto, Cal. on May 9, 1990

[80] See VLSI Program - An Overview, Section C, pp. 25-26.

[81] Introduction of a RISC-based machine would presumably have provided increased computing power, affecting the price structure of current lines of mainframes. "Begun in the late 1970s, the IBM project was the first to start but was the last to become public....The 801 was an experimental project, but was never designed to be a product." Op. cit., Hennessy and Patterson, p. 189.

puters for a growing range of applications;[82] demand for workstations is said to have grown at roughly at 70 percent annual rate in 1985-88, faster than any other market segment except possibly supercomputers.[83] Almost all computer and chip fabricators have now found it commercially necessary to produce RISC-type chips.

- As workstations have achieved minicomputer power and then networked with specialized servers, they have in fact become a significant challenge to mainframe producers as well.[84]

A tribute to Sun's effectiveness as a challenger to established mainframe producers is provided by IBM Chairman, John Akers, who, in particular respects, "compares IBM unfavorably" to Sun:

> "Let's use Sun as an example," says Ankers. "It brings performance to the market at a very fast clip and has been able to do that better than anyone else. That's why they're doing so well: People like performance improvements at what's seen as a reasonable price. So if IBM wants to be successful vis-a-vis Sun, we have to do what they're doing at least as well...to even have a chance to be even with them."[85]

Bechtolsheim's view is that DARPA sponsorship and support of open systems and open architecture approaches has accounted for some of its most exceptional successes. These efforts came at a time when industry was preponderantly committed to closed proprietary systems. This closed orientation has had three types of consequences:

- In general it tended to focus investment unduly or even exclusively on efforts at the margin to upgrade, elaborate and extend existing technologies and systems, and to perpetuate proprietary systems at the expense of R&D for innovation and new technologies, and the development of open systems.
- To the limited extent that industry leaders have invested R&D in development of new technologies, it tends to constrict introduction of technology breakthroughs by industry, which could have the effect of undercutting current revenues or shortening the market life of existing profitable lines. A relevant example is the IBM 801, a risc-type computer from the late 1970s that was

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[82] As early as 1986 with the introduction of its Sun-3/200 series, Sun's workstation was said to provide DEC VAX 8600 capabilities at roughly a fourth the cost.

[83] "Workstation game too early to call," by Kristina Sorensen, *Digital Review*, July 11, 1988, p. 106(1).

[84] "Rethinking the Computer: With Superchips, the Network is the Computer," *Business Week*, November 26, 1990, pp. 116-124.

[85] As quoted in "IBM's Real Challenge is to Stop Reinventing the Wheel," by Michael Schrage, *Washington Post*, Nov. 16, 1990, p. C13.

never commercialized. A vitally important exception was AT&T's policy of keeping its UNIX operating system architecture open and available.

- It has encouraged start-ups and spin-offs not committed to existing products and technologies to develop and commercialize new technologies.

Bechtolsheim praises DARPA's role in the third of these areas through its VLSI and successor computer and microelectronics programs. First, by concentrating on developing research potentials at the universities, DARPA supported an environment which had some of the most advanced application requirements, and was unconstrained by commitments to existing technologies. Second, by emphasizing and abetting development of open architectures and non-proprietary core technologies, DARPA generated powerful catalytic and symbiotic forces that spurred cross-fertilization of technology development in the academic community and resulted in an amazing array of new technologies. Third, by promoting both open systems and networking of *technologies*, in combination with an emphasis on commercialization of their *applications*, DARPA fostered broad and even mass availability of these new technologies, produced economically because of commercial economies of scale, to the point that industry leaders have had to respond with their own adaptations or alternatives.

Bechtolsheim observes that over a period of years in the early and mid-1980s, the computer industry was investing roughly $250-300 billion in R&D, but preponderantly focusing these funds on proprietary systems and closed architectures. He estimates that, by contrast, DARPA may have invested less than one percent of that amount, but with greater benefit for the United States than all of industry's investment combined. He contends that today's workstations, with their minicomputer-equivalent computing capabilities and leveraged power via network connectivity, have done more than any other new technology to maintain and even advance U.S. competitiveness in the worldwide computer market. That market is basically flat, but within it workstations are a fast-growing segment.[86]

It is particularly noteworthy that the challenges to industry leaders and contributions to competitiveness have often come from small start-up companies founded or co-founded by academic faculty and graduate students, and are often based on little more than academically developed technologies and venture capital. In the view of DARPA's former

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[86] Thinking Machines, Inc., co-founder and chief scientist Danny Hillis argues that fastest growth is in highly parallel computers, specifically supercomputers.

IPTO director Bob Kahn, Sun Microsystems is perhaps the best example. Bechtolsheim gives DARPA much of the credit for making these achievements possible.

ILLUSTRATION C: THE CONNECTION MACHINE

A. TECHNICAL HISTORY

In 1979, Danny Hillis was diverted from his initial plan to study neurophysiology at M.I.T. by a professor who suggested that he might learn more about how the mind works by pursuing studies of artificial intelligence (AI). In so doing Hillis came to consider the gross short-comings of existing computers in simulating human intelligence in spite of processing times estimated to be 1,000 times faster than neurons in the mind.[87] He focused on the deficiencies of computer manipulations of information *serially* through central processors--the traditional von Neumann computer architecture. The mind by contrast is believed to use massive numbers of processors in *parallel*, achieving much faster and more complex results than those achieved by computers. Hillis' approach to computer architecture takes its inspiration from the human brain in attempting to replicate the brain's massively parallel processing of information. By 1982 this approach and its special potentials for application to problems involving immense volumes of data had become broadly apparent within the MIT AI program. Even before Hillis had completed his dissertation on "The Connection Machine"(CM), supporters of his efforts had become persuaded that its promise should be tested in the commercial market, and private investors raised over $7 million to launch it as a commercial venture. Thinking Machines, Inc., was founded in 1983, and by the time Hillis had converted his dissertation into a book in 1985, the company had sold its first Connection Machine. Five years later, Thinking Machines has sold over 50 machines, leased ten more and describes itself as the second largest supercomputer producer in the United States.

DARPA's role was pivotal in several aspects of this evolution. Not long before Hillis began to develop a detailed formulation of the CM concept, DARPA had provided a grant to the M.I.T. Artificial Intelligence program under the direction of Professor Patrick Winston. Hillis submitted a proposal for funding his CM development as part of a broader research program to be undertaken with DARPA funding.

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[87] While the mind improves the quality and speed of its output as it acquires added information, the von Neuman serial-processing computer architecture becomes slower at processing increased data volumes.

However DARPA's influence on CM development in fact considerably predated this 1983 funding grant, one of the earliest under its Strategic Computing Program. These earlier contributions are the ones that originated with DARPA activities under the VLSI program. As a graduate student, Hillis was first exposed to the potentials of quick silicon implementation of projects through his awareness of the work of M.I.T.'s Guy Steele on the SCHEME chip which was first executed through one of the quick-turnaround fabrication projects organized for academic users by Lynn Conway and colleagues at Xerox PARC in 1979-80. Once the successor to this multichip effort, the MOSIS quick-implementation service--became available through DARPA's efforts, access to it became part of the critical time path which brought Hillis' work so quickly to the commercialization process which began in 1983 with the establishment of Thinking Machines, Inc.[88] It is Hillis recollection that the first chip designs planned as components of the CM were fabricated in an early run--possibly the third--in 1980, MOSIS' first year of operations . In quick order, he had fabricated through MOSIS the initial processor, dynamic memory, and routing chips. More important to the graduate student was that the fact that DARPA IPTO Director Robert Kahn had made one of the early grants under the VLSI program to Principal Investigator Patrick Winston of the AI program at M.I.T. Funding for Hillis' dissertation work on the CM came from that DARPA grant. Hillis also attributes to DARPA the general ambiance of creativity and excitement over the potential the VLSI program fostered in the academic community at that time, as colleagues had the opportunity to work on an array of related chip and computer activities.[89]

As Hillis' self-described "crazy idea" for reconfiguring computer architecture into massive parallelism came to capture the imagination of others, professors and colleagues began to contribute to various aspects of its development. In late 1982, even before his dissertation on the CM was complete, "the project had grown so big" that Hillis and supporters accepted that its further development would require resources beyond those available through M.I.T., and actions were initiated to form a company and to raise financing. Thus for a time in 1982-83 Hillis was concurrently completing his dissertation and co-founding Thinking Machines, Inc. The complex of potentials that massive parallelism foreshadowed necessitated solving a wide array of problems created by this new

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[88] See Chapter XX, VLSI Implementation: MOSIS.

[89] In his book acknowledgments, Hillis specifically mentions "Craig Fields, who knew it was the right thing....Bob Kahn, who supported the machine through its development.... Steve Squires, for support, ideas, and enthusiasm....the Defense Advanced Research Projects Agency and the Naval Electronic Systems Command for support of the construction of the prototype under contract #N00039-84-C-0638."

approach. Hillis' intellectual debts to colleagues whose work was also supported in various ways by DARPA and who contributed to meeting these challenges are catalogued in two pages of credits in the introduction to his 1985 book based on his dissertation.[90] Major assists included initial programming, program language development, help with invention of data parallel algorithms, and inspiration for the idea from the thesis of a fellow student.

The CM then participated in late 1982 in the transition to the Strategic Computing Program by becoming one of the early beneficiaries of SCP funding. While DARPA did not contribute directly to the financing that launched Thinking Machines, Inc., its agreement under SCP to purchase the first Connection Machine for $4.5 million was an important assist to raising the $7 million from the private sources that provide its initial financial base. The DARPA progress payments became the first cash flow for the new company which culminated in delivery to DARPA of the first machine in 1984. Other key developments in commercialization of the Connection Machine are noted in Table17-C-1.

Table 17-C-1: Key Dates in Connection Machine Commercialization

DATE		Action	Elapsed Time[a]
1983	(first half)	Founded company	0
1985		Delivered 1st prototype	2.5 years
1988		Sold and delivered > 30 systems	5.0 years
1989	(Nov. 28)	$12 million contract from DARPA Development of Tera-Ops machine	6.5 years
1990		First machine sold to Japan	7 years
1990	(As of October)	Total: sold & delivered > 50 systems	7.5 years

a. From preceding event.

B. OBSERVATIONS ON SUCCESS

Hillis' appraisal is that DARPA's role involved several streams of contributions which converged at varying points to contribute to the development of the CM and its subsequent commercialization. DARPA's role did the following.

- It created the overall environment of intellectual stimulus that was to give rise to a wide variety of new ideas about computers and human-machine interaction.

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[90] W. Daniel Hillis, "The Connection Machine," The MIT Press, Cambridge, Mass. 1985. The dissertation on which it was based received the ACM "Distinguished Dissertation" award for 1985.

- It funded work of specific colleagues who originated ideas and support that contributed to CM development.
- It made possible the MOSIS service which provide rapid realization of experimental chip designs and greatly accelerated CM commercialization.
- By block grants to the MIT Artificial Intelligence program and the specific CM component, it provided the financing for the CM dissertation.
- Its even earlier interest in AI made possible the existing state of development of that program at MIT, which provided expertise and inspiration for Hillis' work.
- Then under the SCP, DARPA's agreement to purchase the first CM was instrumental in helping TM co-founders to assemble the financing for commercialization.

Hillis suggests that DARPA funding was highly leveraged in that its commitment to purchase the first CM was the key to TM's ability to raise five times DARPA's commitment amount --the total of funding that ultimately went into development of the first machine.

On a broader scale, Hillis believes that the new technology gave the United States its sole remaining lead in supercomputing over Japan since in his view Japan has now drawn even or possibly even ahead of the United States in serial processing technology. Hillis identifies the main advantage of current CM technology as being the "data parallel programming" feature which gives the ultimate efficiency to massive parallel architectures. He believes that TM can maintain its lead, citing its participation in one of DARPA's latest program initiatives--the Terraops (trillions of machine operations per second), which aims at a 1,000-fold improvement in processing speeds. To get to this level will require further major improvements based on massive parallelism. Getting the necessary increments in computing power requires new concepts in communication flows between processors that will leave behind the hypercube-type structures that are at the core of the present Connection Machine.

XVIII. VLSI IMPLEMENTATION: MOSIS

A. BRIEF OVERVIEW

MOSIS the Metal Oxide Silicon Implementation Service[1] is a key enabling component of DARPA's comprehensive VLSI (very large scale integration) technology initiative which took shape in the late 1970s.[2] MOSIS provides a fast turnaround system whereby researchers can obtain limited runs of custom and semicustom microelectronic devices of their own design within roughly four to ten weeks at limited expense. In addition, the system facilitates the educational and human resource objectives of the VLSI program: it obviates the need for researchers to have direct access to fabrication equipment, or to face the complexities of arranging their own fabrications, by providing access to a qualified multivendor base through a single interface.

As microelectronic circuitry moved below two-micron feature sizes in the late 1970s, further miniaturization threatened to "hit the wall[3]" as complexity of design, limitations of available materials, and increases in the cost of fabrication equipment and runs stretched the known potentials and increased the cost of further marginal improvements. The VLSI program stimulated new approaches that could break out of these impending limits. As it evolved, the program took on four main directions: (1) computer architecture and system design; (2) microelectronic device fabrication process, (3) education and human resource development in microelectronics and computer sciences, and (4) fast-turnaround design fabrication, testing, and evaluation.[4]

Since beginning operation in 1980, MOSIS has managed a growing volume of device fabrication (from 258 projects in 1981, rising to 1,880 in 1989 after a decline in 1986-1988), in an expanding array of device technologies (nMOS devices from 1980-

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[1] Implementation, in its MOSIS formulation, includes "merging [chip] designs into a starting frame, converting design data into a patterning format, making masks, processing [silicon] wafers, dicing the wafers into chips, and mounting and wire-bonding the chips into packages", as defined by Lynn Conway in *The MPC Adventures: Experiences with the Generation of VLSI Design and Implementation Methodologies*, Lynn Conway, Xerox, Palo Alto Research Center, 1981.

[2] VLSI technology roughly defined involves devices with from 10,000 to 1,000,000 transistors or gates.

[3] Quoted from an interview with Dr. Paul Losleben, September 29, 1989.

[4] Interview with Col. John Toole, ISTO, March 26, 1990.

1984, moving toward full CMOS from 1985-1989 (see Table 18-1); adding printed circuit boards in 1984, with gallium arsenide chip service planned in 1990, at steadily decreasing feature sizes (from 5μ in 1980 to 1.2μ by 1989, with 0.8μ envisaged shortly). MOSIS serves users at more than 360 institutions throughout the United States, via ARPANET[5] and other E-mail services. Advances in MOSIS services offered are stimulated by close relations between MOSIS staff, users, DoD/DARPA, commercial vendor communities, and the VLSI research community.

Through ARPANET[6], DARPA first provided access to MOSIS to the DARPA VLSI project community and to DoD contractors, but extended its use in 1982 to the National Science Foundation (NSF) and affiliated educational institutions, and in 1984 to qualified commercial users.[7] In 1982 DARPA and the NSF also agreed to foster further expansion in the use of MOSIS, as NSF undertook the administration of MOSIS services for approved educational uses. MOSIS has facilitated the work of DoD contractors, as well as DARPA-sponsored and academic researchers at a growing array of institutions.

More generally, MOSIS has proven to be a key mechanism by which DARPA and NSF have expanded and fostered the VLSI community, thus broadly and powerfully enabling a great profusion of developments in VLSI technologies. The greatest overall value of MOSIS is said to be its contribution to the broader thrust of the VLSI program as a whole. For the growing community of institutions and researchers participating in this program, MOSIS was the indispensable mechanism by which researchers could quickly test their designs in silicon, and develop devices that became the components of new electronic systems. It played a crucial role in making economically feasible and accelerating a process by which the VLSI community could develop, test, and share its technology advances, particularly among universities.

More than two dozen major and hundreds of lesser device and computer design developments, which are shaping new computer directions and performance capabilities for

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[5] The telecommunication network established by ARPA in 1969 to serve the defense and research communities. Since 1989 called INTERNET. See Volume I, Chapter XX.

[6] University users were also able to access the MOSIS silicon brokerage service through TELENET (a commercial offspring of ARPANET) or CSNET.

[7] Extension to commercial users was expected to reduce government costs of MOSIS support, and to bring down costs to users generally, via better rates from suppliers through larger, more frequent runs.

Table 18-1. MOSIS Projects 1981-1989

TECHNOLOGY	Size	Layers	Type*	1981	1982	1983	1984	1985	1986	1987	1988	1989	TOTALS
NMOS	5μ	1M	D	238	441								679
NMOS	4μ	1M	D	20	283	1199	1035	234	18				2789
NMOS	3μ	1M	D		63	56	162	439	309	131	20		1180
CMOS	5μ	1M	D		22	45							67
CMOS	3μ	2M	D					949	1113	887	710	231	3890
CMOS	3μ	1M	A			22	437	106	146	83	5		799
CMOS-SOS[1]	4μ		D					62	11				73
CMOS	2μ	2M	D						71	225	396	615	1307
CMOS	2μ	2M	A								185	934	1119
CMOS	1.6μ	2M	D						15	70	86	55	226
CMOS	1.2μ	2M	D								27	45	72
TOTALS				258	809	1332	1634	1790	1683	1396	1429	1880	
GRAND TOTAL													12,201

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*D: digital, A: analog (2P)

[1] Silicon on saphire

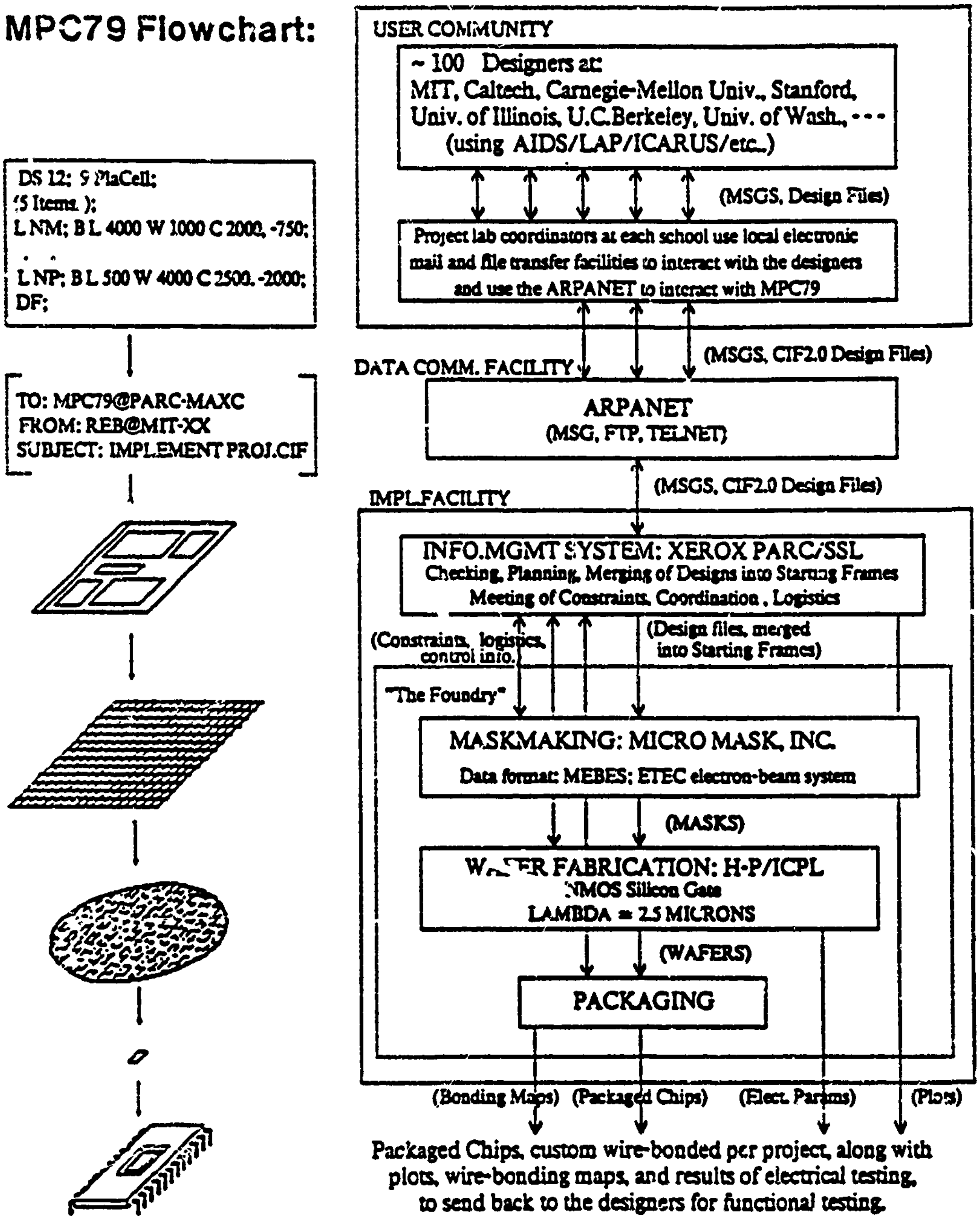

Figure 18-1. Projects Fabricated Through MOSIS

the 1990s, virtually owe their existence to MOSIS (See Section C below). Many of these devices led to or became part of systems that were successfully commercialized, often with obvious defense applications. Just two among new concepts of foremost importance in which MOSIS' role was crucial were the reduced instruction set computer (RISC) architectures from UC-Berkeley and Stanford, and the wide array of microprocessors for parallel processing, such as the massively parallel "connection machine," the MOSAIC homogeneous multiprocessor, and a variety of systolic array processors. The dominant view of those contacted who were at research institutions in this early period is that without MOSIS, few of the many rich VLSI technology advances from non-commercial institutions in the early 1980s would have taken place.[8] (See Table 18-5 below)

B. TECHNICAL HISTORY

1. Technology origins

In about 1977, as he began the early shaping of what was to become the DARPA VLSI program, Dr. Robert E. Kahn, DARPA's Director of the Information Processing Techniques Office (IPTO) first considered the idea of a fully automated semiconductor device (chip) factory. However, he revised this notion after discussions with Arden Bement, then director of DARPA's Defense Materials Office, who debated the practicality of an automated chip line, countering that a better route would be to set up a research lab to produce quickly new chips designs from DARPA-sponsored researchers, a concept of which Kahn became increasingly persuaded. DARPA had begun to fund a growing array of university research which would hopefully lead to new chip designs. Kahn realized that would be important for DARPA to facilitate direct testing of these designs in silicon in some prompt and inexpensive way. By happenstance, in 1978 he learned of efforts in California which might lead to that kind of capability. DARPA was able to encourage *initial experimentation* with this approach, first by authorizing use of ARPANET as a channel for forwarding designs from remote and multiple sources to a centralized mechanism for implementation in silicon, and second, by its support of research projects which had designs approaching the implementation and testing stages. Fortuitously,

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[8] This chapter focuses on MOSIS as a key enabling capability for those VLSI developments. Chapter 17 documents specific device DARPA development research in new microelectronics architectures, particularly parallel processing and RISC.

Kahn's perception of the need and his initial support for development of such a system in California provided successful ingredients for what was to become the MOSIS system.[9]

The origins of what was, through later DARPA sponsorship, to become the MOSIS technology can be found in seminal work of Carver Mead of the California Institute of Technology and Lynn Conway of the Xerox Palo Alto Research Center (PARC) in the latter half of the 1970s. In the early 1970s Mead conducted a series of courses in integrated circuit design at CalTech, based on the industry state-of-the-art in MOS LSI design. Then in 1975 Mead and Conway, through the intermediation of Sutherland brothers Bert (at Xerox PARC) and Ivan (at CalTech) began a research collaboration to restructure and simplify design methods to make them more accessible and more powerful for computer system designers. That collaboration evolved into the book they co-authored, *Introduction to VLSI Systems*, published in 1979, which, in its pre- and post-publication versions, had an immediate, broad, and profound impact in stimulating interest and effort in VLSI design.[10,11] Their book emphasized standard design methods and simplified scalable device design rules.[12] Pre-publication chapters of their book were used to train instructors and to teach courses first offered in 1977-78 at CalTech, UC-Berkeley, Carnegie-Mellon University (CMU), and M.I.T., and at eight more universities by 1979-80, growing to more than 80 by 1980-81.

The Mead-Conway approach also stressed fabrication in silicon of researcher designs as a vital aspect of the design learning experience. Mead also pioneered the multi-project chip system for fabrication of research designs for groups of CalTech students by

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[9] Dr. Kahn stated, in an interview on August 7, 1990, that if DARPA had not found an effort in this direction such as that in California, it would have been necessary for DARPA to find a way to develop such a capability.

[10] Carver Mead and Lynn Conway, *Introduction to VLSI Systems*, Addison-Wesley Publishing Co., 1979.

[11] Among the most immediate benefits from Mead-Conway work that was important in the development of MOSIS was the development of CIF 2.0. For the book, it became essential to have a standardized format for specifying design for pattern generation by maskmakers. Mead and Conway sought urgent help from Robert Sproull and Wayne Wilner to provide a robust, accurate refinement of earlier CalTech efforts at a format standardization known as the California Intermediate File. CIF version 2.0, defined in the Mead-Conway book, was a very basic and essential ingredient in providing a standard means of conveying designs for maskmaking.

[12] Scalable design is a key Conway contribution which greatly simplified VLSI design by permitting adjustment of feature sizes to scales different from the initial design without need to change design systems or approaches. This technique permits "bloating" or "shrinking" various layers of designs such that the smallest value can be used as the "feature size" (or "lambda"). Cf. "Quality Control From The Silicon Broker's Perspective," Danny Cohen and Vance Tyree, *VLSI DESIGN*, July/August 1982, p. 24. This approach initially generated much contention in industry where it was widely considered naive and impractical.

arranging to have student designs scheduled into regular test die runs at one of the leading semiconductor firms.[13] As an extension of this experience, Mead conceived the idea of a silicon foundry "as a way to give a large community of chip designers access to fabrication services and as a way to speed up the fabrication process."[14] This concept he developed in response to the obstacles created for researchers by the numerous different proprietary design rules. To implement this concept, Mead encouraged the development of standardized, simplified design rules, and encouraged local or regional communities of principal researchers to negotiate foundry arrangements with fabricators using such rules.

Meanwhile, Lynn Conway at Xerox began to develop, debug, and document simplified methods of integrated design, and a parallel effort to simplify implementation procedures.[15] In 1978, when Conway was making preparations to teach a Fall course in VLSI design at MIT, she met with DARPA's Director of the Information Processing Techniques Office (IPTO), Dr. Robert E. Kahn, to ask his approval to use ARPANET to send MIT designs back to Xerox for coordination of fabrication[16]--the first long-distance multichip project--which he approved subject to establishing a relationship with PARC for that purpose. In December 1978, ARPANET was used to transmit MIT student designs to the Xerox Research Center in Palo Alto, California (PARC), where chip layout was developed. (For this first and the two subsequent multi-project efforts, masks were ordered from Micro-Mask, Inc., and Hewlett-Packard handled all the details of chip fabrication.) Conway then undertook to extend the learning-through-building concept to other institutions by organizing the first remote-entry Multi-project Chip (MPC) fabrication to serve multiple institutions via electronic mail. In the Fall of 1979 and Spring of 1980, Conway orchestrated these first Multi-project Chip efforts: MPC79, in the Fall of 1979, incorporated 82 integrated system design projects from 124 participating designers from 11 universities. The May 1980 project (MPC580) involved over 250 designers, and at least

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[13] Intel.

[14] "MOSIS--THE ARPA SILICON BROKER," by Danny Cohen and George Lewicki, USC Information Sciences Institute, in *CALTECH CONFERENCE ON VLSI*, January 1981, p. 29

[15] Lynn Conway, Alan Bell and Martin E. Newell, "MPC79," Xerox Palo Alto Research Center, in *LAMBDA*, Second Quarter 1980, p. 13. Others who made important contributions to the effort at Xerox were Patricia Castro of the PARC Integrated Circuit Research Processing Laboratory and Merrill Brooksby, Director of CAD Development

[16] For its own research purposes, PARC since the mid-1970s had an in-house VLSI fabrication facility and had *ad hoc* experience in foundry brokering.

171 projects from 15 universities and R&D organizations,[17] chips were fabricated in June and returned by July 1980.

Realizing that in Conway's efforts was potential for the kind of fast-implementation capability he anticipated for the VLSI program, Kahn agreed to collaborate with Conway by assisting both MPC79 and MPC580 by making ARPANET available to transmit designs. Moreover, early DARPA VLSI program funding supported much of the design work which produced early prototypes that were fabricated as early as 1979 in Conway's MPC79.

Conway's approach expanded on the local or regional researcher-foundry concept, envisaging development of a national electronic network of researchers as a way to reduce the cost and facilitate access to a broader community including students. In time for MPC580, Xerox PARC also augmented the power of E-mail transmission by developing a prototype automatic interface and software for project scheduling and allocation of wafer space, so that the capacity of the electronic network was greatly enhanced by the front-end automation of design transmission and administration. This became one of the major initial strengths of the MOSIS automated service capabilities.

Industry skeptics did not believe that the MPC could meet the tight schedules envisaged because delays in getting reticles for masks at that time were believed to make such an approach impractical. A crucial decision made by the MPC sponsors was to use MEBES electron-beam lithography technology to bypass delays in maskmaking. With the success of this gamble, MPC79 "provided a sufficient demonstration of the feasibility and practicality of remote-entry, fast-turnaround VLSI implementation, so as to lead to the funding and operation of a regular, scheduled VLSI implementation service for a substantial government-supported research community."[18] To regularize this service, new coordination arrangements were required to carry on what Conway, Alan Bell, Ted Strollo, Martin Newell and other colleagues had begun at Xerox PARC.[19]

While Conway was organizing the Multi-project Chip efforts, DARPA's Dr. Kahn, had already become attracted to the potential for combining the economies of multi-chip

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[17] Conway et al., op. cit., p. 11. See also "Documentation for Participants in the MPC580 Multiproject Chip-Set: A Collection of Information and Instructions conveyed to the Participating Designers, along with their Packaged Chips," compiled and revised by Ted Strollo, Terri Doughty, Glenn Krasner, Maureen Stone, Wayne Wilner (Xerox PARC), and Danny Cohen (USC/ISI), 7 July 1980.

[18] Conway et al., op. cit., p. 19.

[19] XEROX continued to develop its own fast-turnaround silicon implementation capability for corporate requirements, but decided it could not continue a broader service.

fabrications with the facility of electronic design transmission via ARPANET into a system to provide fast turnaround and inexpensive fabrication for use by DARPA contractors and researchers. In 1979, DARPA undertook to institutionalize the system, since Xerox PARC officials had decided by mid-year that they could not provide that community service beyond the MPC580 effort. They had so informed Kahn and asked if he could figure out a way to continue the service from some other base. Kahn inquired of Keith Uncapher, Director of the Information Sciences Institute at the University of Southern California,[20] and of Danny Cohen, whether ISI would be interested in providing the service; Uncapher and Cohen were definitely interested.

Conway in her account of MPC79 reported that "ISI will operate a VLSI implementation system and coordinate the maskmaking, wafer fabrication, and packaging for the universities in the future, with funding provided by DARPA."[21] DARPA arranged with ISI to carry on the quick-implementation system developed during these MPCs, by developing and operating MOSIS based on the fast turnaround system pioneered by Conway and her colleagues at Xerox PARC.[22] ISI had the computer and communications strengths required. Danny Cohen agreed to head the effort. He took the lead in preparing the proposal to DARPA, and became MOSIS' first Director.[23] He asked that George Lewicki, a semiconductor support specialist from CalTech's Electrical Engineering and Computer Science (EESC) Department be loaned to ISI to provide needed semiconductor expertise and to help with the start-up. Conway reported that by mid-1979, "a transfer of the VLSI implementation system technology [was] underway from Xerox PARC to the Information Sciences Institute (ISI) at the University of Southern California." Cohen and Lewicki worked with Ted Strollo, who managed technical aspects of MPC79 at Xerox PARC, to transfer to ISI the capability to take over the silicon broker service. Preparations moved quickly and by August 1980, the MOSIS name had been coined and ISI had conducted its first pilot multichip fabrication, MO8B, which successfully provided chips

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[20] In 1972 Keith Uncapher, then at RAND in Santa Monica, Cal., asked DARPA if it would provide support for an independent computer group that he proposed to relocate to USC. At RAND the group faced reduced funding, and Uncapher argued that the group could realize its potentials more fully if DARPA would support it as an independent entity. DARPA Director Dr. Stephan Lukasik's approval led to the founding of the Information Sciences Institute in affiliation with USC in that same year. A large part of ISI's work has continued to be funded by DARPA since that time.

[21] Conway et al., op. cit., p. 19.

[22] DARPA contracts MDA903 80 C 0523, under Order No. 2223, and MDA903-81-C-0335, under Order 4012, April 29, 1980, VLSI Fast Turnaround Testbed.

[23] Cohen had taken a sabbatical from USC to work with Carver Mead at CalTech; he had skills and experience in communications, networking, and VLSI, and was familiar with Mead's approaches.

for 65 projects to 8 user organizations.[24] The "MOSIS service" was *formally* instituted in January 1981.

In the period preceding MOSIS' creation, the U.S. computer technology environment was characterized by (1) the tapering off of the rate of improvement in computer performance as the marginal costs rose and marginal gains from extending prevailing technologies declined; (2) extensive insulation of commercial microelectronics firms, concentrating on proprietary developments, from academic communities which were limited in their access to advanced equipment and industry technologies[25]; and (3) exponential growth in the costs of device design implementation. As Conway and her Research Center colleagues realized:

> university engineering and computer science departments were getting shut out of much of the microelectronics revolution because they couldn't afford the equipment necessary to manufacture silicon chips. Even those universities that could afford some equipment could never keep up with the rapidly advancing state of the art.[26]

In this environment, Dr. Kahn proposed the VLSI program in 1977. Through his relations with the academic community going back to the early 1970s, Kahn was aware of both the potentials of work being done at "centers of excellence" at CalTech, Stanford, CMU, MIT, and UC-Berkeley, the cost and proprietary limits on implementing, validating, and demonstrating their work, and the declining research budgets available to the universities from Defense Department sources. The VLSI program was undertaken specifically from a desire to promote the creativity of the academic community, which had played an important role in earlier computer and semiconductor developments but was increasingly thwarted by the mid-1970s. As initially conceived, the VLSI program had four technical objectives to support: (1) development of a design methodology based on use of standard, simplified, scalable design rules; (2) development of computer-aided design (CAD) tools to support designers; (3) simplification of the implementation process to make it easier, quicker, and cheaper, and to free designers from having to deal with numerous different proprietary implementation systems, and (4) demonstration of VLSI

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[24] Phone interview with Danny Cohen May 25, 1990. See also ISI's 1980 Annual Technical Report, Vol. 2, December 1979-September 1980, *A Research Program in Computer Technology.*

[25] Carver Mead at Cal Tech was said to be unusual among academics of the time in having ready familiarity with industry developments, as a result of his long associations with Intel.

[26] "Homebrew Chips," by John Markoff, Phillip Robinson and Donna Osgood, *BYTE*, May 1985, p. 363.

technologies by developing specific computer architectures.[27] MOSIS' role was to achieve the third of these goals, while supporting the other three.

Dr. Kahn managed DARPA's VLSI program in 1977-1978. In 1978 Lt. Col. Duane Adams became program manager. MOSIS was considered central to the goals of the VLSI project, and received strong DARPA support from its origin. In July 1981 when Adams became Deputy Director of IPTO, DARPA brought in Paul Losleben from the National Security Agency (NSA) to assume VLSI program manager responsibilities.[28] Losleben had developed the idea of vendor-independent design rules in his work at NSA, and was attracted to DARPA in part by the opportunity to support implementation of this same basic approach. Kahn, Adams, and Losleben are all highly regarded by the principal investigators contacted for their effective support and encouragement of the VLSI and MOSIS programs during their time at DARPA. The semiannual principal investigator meetings were instrumental in catalyzing broad awareness of new technology developments and in shaping an interactive research community which produced many fruitful lines of investigation. Losleben was also instrumental in encouraging an early transition from the nMOS technology initially used by MOSIS to CMOS implementation, and increased emphasis on testing for quality assurance of fabrication services.[29] MOSIS' first director, Danny Cohen, was succeeded by George Lewicki (1983-90). Cohen and Lewicki made important contributions at DARPA's semiannual meetings of principal VLSI investigators by reporting emerging enhancements in MOSIS service and by learning about the forthcoming fabrication needs of the VLSI community. MOSIS' present director is César Piña.

An early DARPA description of the MOSIS concept (unclassified), circa 1980, states, under the caption "SUBMICRON MICROELECTRONICS":

> This DARPA VLSI technology initiative is focused on developing a capability for effective use of submicron digital fabrication techniques in DoD operational applications. The emphasis of this microelectronic development program is on automated integrated circuit architecture development and detailed "chip" design. Each "chip" may contain as many as one million or more gates. In order to support this level of automated "chip" design, the designer's attention must be focused on the architecture aspects. Detailed layout and fabrication are then accomplished by

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[27] Interview with Duane Adams on May 30, 1990.

[28] Losleben, through his participation at VLSI contractor meetings, knew the VLSI community well and was supported by them for the position.

[29] While at NSA, Losleben had supported early CMOS development and implementation by NSA's vendors, Westinghouse, RCA, Harris, Hughes and others.

> computers which can design, fabricate, and test each chip for delivery by U.S. mail in a 1 to 2 week turnaround time as illustrated in Viewgraph No. 15. It is anticipated that this flexibility will be useful to research engineers, system developers, and possibly even students to provide tailored system functions and new realtime computational functions not possible at lower levels of integration. The capability for fast turnaround implementation of integrated circuits was recently demonstrated in the December 1979 Multi-Project Chip run in which one hundred university designs were merged into a dozen die types on two wafers. The total turnaround time from submission of the design in digital form over the ARPANET to returned bonded chips in the designers' hands was about 6 weeks. By a continued refinement of the process, we believe this capability can be improved to 2 weeks turnaround time or less. The implications of these techniques on design and development of radar, communication, electronic warfare, and a host of other DoD systems are expected to be profound.

This initial DARPA expectation overestimated the potential for further reduction in turnaround times, particularly the speed with which MOSIS could provide submicron feature implementation (which MOSIS was finally developing in 1989 but may first provide only in 1990). Among the main initial objectives of ISI's MOSIS management were: to provide fast turnaround fabrication for the DARPA VLSI community, to expand the VLSI design community, and to encourage more vendors to offer custom VLSI services.

By 1987 issues arose within DARPA about the value and effectiveness of MOSIS. Foremost was whether MOSIS was sufficiently linked to DoD operations to be useful for development of military systems.[30] Also in question were how its costs compared with the commercial market, why it hadn't attracted more commercial users, why its technologies seemed to lag behind the most advanced fabrication technologies available, what its services contributed to the industry and to DoD, and whether and how DARPA should continue supporting it. An internal review resulted in favorable conclusions and a decision to continue DARPA support. Conclusions regarding questions raised about its value are addressed later in this chapter.

2. The MOSIS System

As a process, MOSIS consists of the following basic steps:

1. Users send request, either via E-mail (ARPANET, TELENET) or magnetic tape, in an acceptable design geometry format (CIF 2.0+, CALMA-GDS II); MEBES may also be provided.

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[30] Interview with Dr. Robert E. Kahn, August 7, 1990. Kahn emphasized that this question missed the point of the program, which was to foster technologies aimed at order-of-magnitude improvements in microelectronics and computer functionality which could in turn broadly strengthen defense capabilities.

2. The MOSIS computer processes requests, organizes (groups and places) sets of projects into smaller sets of dies (job decks), translates each die into MEBES format (for maskmaking); MOSIS forwards both to a foundry.[31] (MOSIS has averaged more than five fabrication runs per month in 1989.)

3. A foundry (or a maskmaking house) produces mask sets, then a foundry fabricates the devices, and does initial electrical testing.[32]

4. MOSIS probes each of the chips on a wafer to obtain SPICE parameters, cut them into individual die, package, bond, and retest each device before returning them to designers. This quality control program seeks to (a) refine parameters for wafer acceptance and foundry acceptance criteria, (b) correlate MOSIS and vendor test results, (c) monitor fabrication quality, (d) determine wafer defect density and yield of devices designed with generalized design rules, and (e) extract transistor-model parameters for circuit simulators such as SPICE.[33]

5. MOSIS sends wafers, along with bonding maps,[34] to firms which package and bond the devices.

6. MOSIS acquires and and makes available design cell libraries obtained from previous users and from other sources to facilitate design efforts by current users

This simple schema is now a much more sophisticated and automated process than used by MPC79 and MPC580, but remains essentially the same *in sequence* as those pilot procedures, illustrated in Figure 18-2. Such a simple description, however, neglects many important contributions that ISI made along the way to bring MOSIS beyond the MPC stage to modern-day sophistication, including:

-- Identification of mask houses, and foundries willing to provide increasingly sophisticated, advanced technology services per MOSIS specifications,[35]

-- Development of standards and procedures for specifying and transmitting designs usable by service providers for mask-making and fabrication;

-- Introduction of testing and quality control procedures applied to chips upon their return from fabrication;

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[31] In the early 1980s, ISI worked with as many as eleven foundries. By 1989 the great majority of its MOSIS work was handled by 4 organizations: Hewlett-Packard-NID, ORBIT, IMP, and VLSI Technology.

[32] Initial options were 40 and 64 DIP (dual in-line pins); currently MOSIS can also provide

[33] Cf., Cohen & Tyree, op. cit, p. 29.

[34] To show bonders how to connect the chip to the pins on the package.

[35] Foundry services may be provided either by independent foundries or by system houses willing to provide foundry services for unrelated designers.

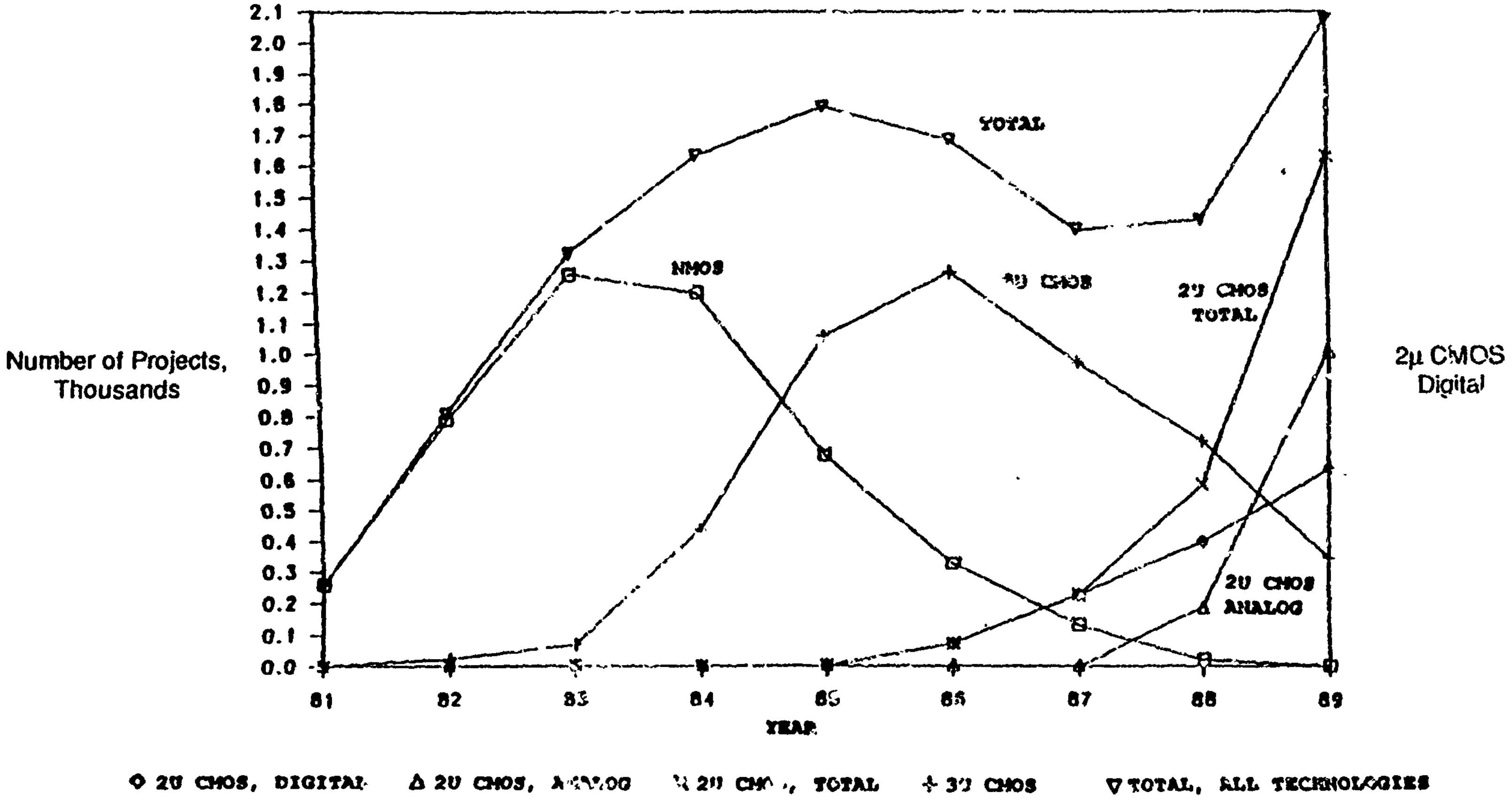

Figure 10-2. MPC79 Flow Chart

These three contributions provide designers with an easy interface for implementing their design, obviating the difficulties of negotiating numerous highly technical and complex interface requirements that vary widely between suppliers and involve a degree of detail which effectively makes implementation for academic and research institute designers prohibitively difficult and expensive.

In addition, constant interaction between MOSIS, DARPA, VLSI and design communities, and implementation-service providers serves to advance the development of MOSIS technologies available in step with user needs and industry fabrication capabilities. As a result of this process, MOSIS has steadily upgraded the quality and technological sophistication of implementation services provided, while keeping turnaround times as tight as possible.[36] In addition to regular production runs, MOSIS provides "technology development runs" as preparation for future use of new technologies in standard runs. Such experimental runs of necessity involve longer turnarounds, currently ranging from 3-6 months, or roughly 50-100 percent longer than regular production runs.

3. Benefits of the MOSIS System.

MOSIS provides fast, low-cost, low-risk fabrication of microelectronic device designs, which are then packaged, tested, and returned to the designer. Among its major benefits are:

-- Ease of Access: Complexities of understanding and adapting to widely differing requirements of available commercial mask houses and fabricators, to say nothing of cost, made access to commercial implementation prohibitive for most universities, colleges, and even small businesses and commercial packaging services were virtually unobtainable until MOSIS started.[37]

-- Economies: Early expectations were that by consolidating many design projects (Multi-project Chips) into each run (Multi-chip Wafers) to achieve economies of scale not possible for individual designers or institutions, the cost per device could be limited to a few hundred dollars. By contrast, to arrange a commercial run at that time would have cost $15-20,000 and taken at least three or four months.[38] By 1984 MOSIS claimed costs per project of a

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[36] Compared with MOSIS initial turnaround target of 6 weeks or less, actual implementation has averaged closer to 7-9 weeks in recent years as the technologies involved have become more complex.

[37] From the beginning of this effort, MOSIS managers faced a plethora of proprietary systems for device fabrication in the commercial sector, and had to work out procedures and standards which would permit use of several fabricators.

[38] Conway, op. cit., p. 12.

tenth to a twentieth of independent fabrication run costs.[39] See Table 18-2 below for illustrative prices for MOSIS fabricators. Costs for DARPA VLSI contractors are funded by DARPA, and for designers eligible under certain NSF programs, by NSF.)

-- Speed: Initial objectives were to provide designers with completed devices within 4-6 weeks of submission. Most designers currently receive completed devices within 7-9 weeks, depending on the technology and vendor used. MOSIS shortens turnaround by grouping design projects and using multiple fabricators, which permits it to schedule frequent runs (almost one per week currently); through its automated interface with users, it provides automated scheduling and wafer space allocation, which avoids delays inherent in dealing with human administrators.

-- Low risk: MOSIS offers reduction of risk in having designs translated into silicon by establishing both the scale and standards for interaction with maskmakers and fabricators to assure production quality in ways that individual researchers and even institutions could not achieve. The National Security Agency (NSA), a major user of MOSIS, reported, for example, that "At least two projects which failed at a contractor were later prototyped with MOSIS quickly and successfully."[40] MOSIS uses a number of procedures to assure protection of proprietary designs. Quality control measures added by MOSIS improved yields and reduced risks of failure due to fabrication deficiencies.

-- Efficiency: time/manpower savings: As a result of MOSIS, "The manpower savings have been substantial by reducing the enormous overhead required to technically and administratively deal with many contractors [e.g., maskmakers, semiconductor fabricators]."[41] The service has also been attractive to foundries which could deal with one source--ISI--rather than dozens or even hundreds of individual designers. NSA reports that "Several...successful prototype runs have led to production follow-on contracts and accelerated award of the production contracts by at least one year."[42]

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[39] A 1987 DARPA sample of costs indicated that commercial runs would cost from $25-50,000 each depending on the complexity of the chip, compared with a range of MOSIS costs of $1-3,000. MOSIS users would in addition save an estimated six work-months of time required to carry out administrative and technical overhead preparations.

[40] "MOSIS SUCCESS STORIES," a 4-page fragment of a larger document described by a cover note, dated March 31, 1987, by Keith W. Uncapher, then Executive Director of the USC Information Sciences Institute as "an ISTO generated list of MOSIS successes," p. J-15.

[41] Ibid., p. J-16.

[42] Ibid., p. J-16.

-- Advanced implementation technology: MOSIS management tries constantly to provide users with access to implementation technologies available from commercial vendors that represent the most advanced available *stable processes* --i.e. those processes that are repeatable with sufficiently high yields to assure users of the credibility of the processes used.

Table 18-2. Illustrative Prices for Highest Project-Volume Technologies

Year	Technology	Smallest Unit	Package Price	Per part cost	Weeks
1984:	4μ nMOS	12	$2,800	$233	9.9
1985	3μ CMOS 2M	12	n/a	n/a	8.4
1986	3μ CMOS 2M	12	n/a	n/a	9.7
1987	3μ CMOS 2M	4 Tiny Chip	$400	$100	n/a
		12	$3,500	$292	n/a
1988	3μCMOS 2M	4 Tiny Chip	$550	$138	n/a
		12	$2,500	$208	n/a
1989	2μ CMOS 2M analog	4 Tiny Chip	$550	$138	
	2μ CMOS 2M analog	12	$3,100	$258	8.1
	"Tiny board" PCB	1	$980	980	

While DARPA's interest and support was the essential catalyst for the creation of MOSIS, its potential for contributing these benefits depended on seven precursor developments: (1) the Mead-Conway simplified scalable design methodology to enable and facilitate design of VLSI devices; (2) proliferation of the knowledge of this design methodology to numerous universities and research institutions; (3) DARPA and other funded research commitments which encourage development of innovative designs; (4) a communications medium for transmitting designs; (5) an intermediary (the "silicon broker") to provide an easy, rapid interface between designer and fabricator; (6) a methodology for accomplishing this intermediation; and (7) standardized formats such as CIF for communicating digitally design details, test parameters, and other implementation methodologies. Mead and Conway efforts provided the design methodology and its propagation to multiple universities; DARPA made possible the primary communications medium through ARPANET, and, with NSF assistance, expanded access to it by authorizing a growing circle of academic and commercial users, as shown in the following:[43]

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[43] DARPA VLSI Program Manager Duane Adams worked out an agreement in 1982 with the NSF's Bernard Chern under which NSF would provide funding for eligible university researchers not working under DARPA-funding programs.

1980	DARPA VLSI community[44]
1981	Approved DoD contractors, NSF-approved institutions
1984	June. MOSIS was approved for use by commercial firms (no government subsidy)
1985	No-cost service extended to approved NSF users[45]
1989	User community reaches 360 institutions

DARPA also enabled the on-going intermediary by contracting with ISI,[46] Xerox PARC developed the initial implementation methodology which was adopted and greatly expanded by MOSIS, as well as some of the initial standards for communicating the design technologies in formats useable by commercial fabricators. Thus DARPA support assured continuation of and access to this fast turn-around brokerage, and catalyzed further development of the component technologies, both independent and DARPA-supported--which came together as much more than the sum of their parts--through the creation of MOSIS.

MOSIS in turn quickly developed its own multiplier impact. As Conway foresaw as early as January 1981, "I believe that in addition to the many business opportunities in VLSI design aids and chip designs, there must also be substantial business opportunities in the area of VLSI implementation systems and services, foundry service brokerage, and foundry services."[47] The cross-stimulation and cross-fertilization of this ARPANET-centered system appeared even as early as the MPC79: a variety of design aids were developed in time for MPC79 and were then refined and shared over the network, which in turn greatly facilitated and stimulated use of MOSIS by DoD contractors and the academic research communities. Also tested in MPC79 was the "Geometry Engine" chip, designed by James Clark at Stanford, a high-performance computer graphics image-generation system developed under funding from DARPA, which was further refined later through MOSIS and evolved into technology later commercialized as the initial stock-in-trade of

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[44] Cohen and Lewicki, op. cit., p. 29. This community consisted mainly of universities supported by DARPA for VLSI research, but included such organizations as Bolt Baranek and Newman, the Jet Propulsion Laboratory, and other government and quasi-government organizations.

[45] For the DARPA, NSF, and DoD communities, the service is free. For other users the MOSIS price schedule is applicable, according to Markoff et al., op. cit., p. 363.

[46] DARPA was instrumental in the founding of ISI at the University of Southern California in 1972. Among ISIs major early activities was extensive involvement in support of ARPANET development, on which ISI became one of the major early nodes.

[47] Conway, op. cit., page 14.

Silicon Graphics, Inc., founded by Clark. Among the most frequent institutional users of MOSIS were the following:

(By numbers of projects implemented on MOSIS)

1984: Jet Propulsion Labs (162), UC-Berkeley (184), USC/ISI (176), MIT (71)

1985: CalTech (549), JPL (216), UC-B (141), MIT (80), MSSU (76)

1986: CalTech (442), JPL (183), UC-B (97), MIT (76), MSSU (92)

While usually recognized mainly for its fast turnaround implementation service, MOSIS in combination with ARPANET had even greater importance in providing a means for researchers not only to implement designs, but to establish proof of concept and then to propagate their research results through ARPANET. This propagation benefit was an dominant objective of the DARPA VLSI program. The spirit of result-sharing was also fostered by Mead-Conway efforts to promulgate the new VLSI design technologies and the Xerox PARC-sponsored MPC trials. It was reinforced by DARPA-convened twice-yearly meetings of institutions under contract to DARPA for VLSI research, at which principal investigators (PIs) would report research progress of the preceding six months. These meetings, conducted by DARPA program manager Duane Adams and continued by his successor, Paul Losleben, were held successively at different participating institutions. Losleben, in particular, focused these meetings of principal VLSI investigators on community-building and problem-solving. They were generally valued by participants contacted by IDA staff as a productive and effective technique for spreading and energizing VLSI accomplishments.[48]

The results in terms of breakthrough technologies that successfully made the transition into commercial application early in MOSIS' existence include development of RISC and MIPS reduced-instruction-set computer architectures (1981). Demands of the design community stimulated by MOSIS intensified efforts to develop and refine early computer-aided design (CAD) tools such as CAESAR and MAGIC, based on Mead-Conway principles.[49] While UC-Berkeley purposely chose not to commercialize its design technologies in order to promote their wide-spread use in the research community, these

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[48] For added background on DARPA techniques in promoting technology transfer, see *Technology Transfer at DARPA: A Diagnostic Analysis*, by Ronald G. Havelock and David S. Bushnell, Technology Transfer Studies Center, George Mason University, Fairfax, Va., December 1985. (DARPA Contract MDA 90364K0331.)

[49] Interviews with Professors John Ousterhout and David Patterson, UC-B Computer Science Division, May 7, 1990.

CAD tools served as prototypes for those subsequently developed in industry,[50] such as Mentor Graphics commercialization of CAESAR.

4. Evolution of MOSIS Technologies and Services

MOSIS has attempted to meet the needs of the VLSI community as a whole, but also to serve specialized needs of DoD contractors without access to fabrication facilities, such as the exhaustive functional testing that defense system devices require. To keep abreast of latest technologies, MOSIS has tried to locate or develop implementation services that are "close to the cutting edge of technology," while avoiding unproven techniques that could complicate or delay implementation. In this way, it gives researchers the opportunity to fabricate in both currently dominant and newly developed but fully proven implementation technologies. Before offering new implementation technologies, MOSIS management needs to assure that it is a stable process that can consistently supply high yields required for custom, semi-custom or gate array devices. It therefore conducts a sufficient number of experimental runs to assure acceptable stability of yields. This approach was largely derived from approaches used at NSA in the 1970s.

Shifting to new technologies often necessitated new vendors. Table 18-3 traces the evolution of basic implementation technologies available through MOSIS from initiation to the present. Table 18-4 illustrates other enhancements added over the years.

New or enhanced technologies may require new design and interface standards, a process which has often taken longer than expected before new technologies could be made available to users. Moreover, with each new technology and new vendor, the effort to keep turnaround times short is rejoined, probably explaining why current turnaround times sometimes run 2-to-3 weeks or more over original ISI aspirations for a 4-6 week turnaround. For example, when MOSIS first provided CMOS implementation, turnaround sometimes exceeded 10 weeks, while nMOS turnaround took only 4. This constant struggle to keep MOSIS-supplied implementation technologies from lagging too far behind those available in industry must always contend with needs of first assuring a stable, reliable process, and of developing necessary design and interface standards.

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[50] Interview with Professor David Patterson, UC-Berkeley, May 7, 1989.

Table 18-3. MOSIS Implementation Technologies Available[a]

Year	Technology	Feature size	Metalization	New Packages	Other
1981	NMOS, digital	5µ, 4µ, 3µ	1 layer	12 DIP 14 users	19 runs
1982	NMOS, digital	5µ, 4µ, 3µ	1 layer	40, 64 DIP	29 runs
new	CMOS, digital	5µ	1 layer		23 users
1983	NMOS, digital	4µ, 3µ	1 layer	24, 84, 128 DIP	40 runs
	CMOS, digital	5µ	1 layer		48 users
new	CMOS, analog	3µ	1 layer		
new	Printed circuit bds				
1984					39 rns, 62 usr
1985	NMOS, digital	4µ, 3µ	1 layer		53 runs
new	CMOS, digital	3µ	2 layers		84 users
	CMOS, analog	3µ	1 layer		
new	CMOS-SOS				
1986	NMOS, digital	4µ, 3µ	1 layer		58 runs
	CMOS, digital	3µ	2 layers		
	CMOS, analog	3µ	1 layer		
	CMOS, digital	2µ	2 layers		
	CMOS-SOS				
1987	NMOS, digital	3µ	1 layer		xx runs
	CMOS, digital	3µ	2 layers		xx users
	CMOS, analog	3µ	1 layer		12 PCBs
new	CMOS, digital	2µ, 1.6µ	2 layers		
	CMOS-SOS[b]				
1988[c]	NMOS, digital	3µ	1 layer	28 ceramic DIP	51 runs
	CMOS, digital	3µ	2 layers		100 users
	CMOS, analog	3µ	1 layer		
new	CMOS, digital	2µ, 1.6µ, 1.2µ	2 layers		
new	CMOS, analog	2µ	2 layers		
1989	CMOS, digital	3µ[d]	2 layers	84, 108 ceramic PGA	51 runs
	CMOS, analog	3µ	1 layer	User DIP, LCC, PGA	360 users[e]
	CMOS, digital	2µ, 1.6µ, 1.2µ	2 layers	Vendor TAB & other	15 PCBs
	CMOS, analog	2µ	2 layers		

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[a] Technologies available for which there was no demand are omitted. Timing of innovation introductions was not consistently reported in MOSIS documents available to IDA; they are listed here based on earliest mention found in available documents, but in some cases may have been introduced earlier than credited in this table.

[b] Silicon-on-sapphire.

[c] NMOS service discontinued by the end of 1988 for lack of demand.

[d] Discontinued after 4-11-90 for lack of demand.

[e] Not including "an increasing number" of DoD contractors and commercial customers.

Table 18-4. Chronology of MOSIS Enchancement Efforts[a]

1980	-- ISI conducts first trial run for 65 nMOS projects by 8 users, with good results.
	-- Creates, offers users VLSI Design Library with some basic circuits for bonding pads, shift registers, etc., acquired from Xerox PARC.
	-- Work toward CMOS implementation capability begins.
1981	-- ISI offered first "official" MOSIS chip fab run, accepting requests by ARPANET and Telenet, accepting CIF 2.0 and MEBES formats, with nMOS 3, 4, & 5μ feature sizes and one layer of metalization.
1982	-- NSF-DARPA cooperative agreement provides cost-free access to MOSIS services by U.S. universities and colleges approved by NSF for projects serving educational purposes, for graduate and undergraduate courses, and principle investigator projects supported by NSF.
1983	-- First CMOS runs; establishes MOSIS design rules
	-- Packaging options expanded from two to five. Plans to offer 1.25μ features in 1983 were frustrated, and ultimately delayed until 1988.
	- CSNet was added to the accepted communication services.
1984	- Adds Printed Circuit Board fabrication to its services
	- Adds NSA design rules for CMOS implementation
	- CALMA GDS2 stream added to CIF as design geometry submission format
	- MILNET added to the accepted communication services.
	- To improve defect screening and yields, MOSIS/Stanford begin to develop functional test language (SIEVE), and began providing functional screening
	- Offers standard pad configurations to facilitate wire bonding of devices
	- Offers on-line access to its library of common circuits, I-O pad circuits, etc.
	- Opens service to commercial users
	- Experimental runs of 1.2μ CMOS.
	- Turnaround 4 to 13 weeks depending on technology involved (nMOS shortest)
1985	-- Accepts fabricators rules for CMOS, in addition to MOSIS & NSA rules
	- Begins to accept MEBES geometry formats in addition to CIF &CALMA.
	- User library expanded to include standard logic and computational functions and memories: USG 3μ p-well CMOS/Bulk standard cell library available
	- MAGIC technology for scalable CMOS design from UC-B on-line
	- Additional quality assurance efforts; further experiments w/ 1.2μ CMOS.
1986	- Experimentation begun on GaAs, wafer-scale integration, and 0.8μ runs.
	- Formal wafer acceptance spec negotiated with all vendors.
	- Two vendors qualified for 1.2μ CMOS/bulk. 1.6μ CMOS available.
	- New parametric test structure (SUPERCHARGER) & report generator in use.
	- MOSIS technology transferred to NSA for classified fast-turnaround facility.
	-- "Tiny chips" program, using standard pad frame to permit automated bonding, offers 4 chips for $400 at 3μ; aimed at needs of university classes;[b]
1987	-- MOSIS begins actively to encourage commercial users of its services
1988	- 2μ Tiny chip added
	- First 1.2μ CMOS/bulk runs commence

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[a] Timing of most service innovation introductions was not reported in MOSIS documents available to IDA; they are listed here based on earliest mention found in available documents; in some cases they may have been introduced earlier than reported here. Detail on technologies available is not exhaustive. For full information, contact The MOSIS Service, 4676 Admiralty Way, Marina del Rey, Cal. 90292.

[b] A Tiny Chip is a means of making custom chips available to designers at a very low cost. By being able to put a large number of different designs on one run, and requiring a predefined pad frame, which permitted packagers to use automated bonding equipment, the cost per device was greatly reduced.

Table 18-4. Continued

	– Vendor-independent DoD CMOSN standard cell library available for 2µ and 1.2µ design; VTI 2 micron library also available – SPICE Level 2 and SPICE BSIM parameter measurements available to upgrade the quality of monitoring
1989	– First experimental prototyping run in GaAs – Ultratech stepper lithography (1.5µ) and 5x stepper lithography (1.0-1.5µ) implemented – First 1.2µ project runs – 2µ CMOS 2M with double poly (low-noise analog) commences – NPN bipolar technology available – Special analog design options made available through commercial vendors – MOSIS library offers DoD standard cell library accepted by all MOSIS vendors, incorporated into five commercial design tool sets – MOSIS begins "netlist-to-parts" service permitting users to specify standard cells from commercial DoD sources for inclusion in design by MOSIS – MOSIS exploring gate array and EEPROM offerings might be feasible
1990	– Last 3µ CMOS run scheduled – GaAs runs to be offered on "demand" basis in 1991 – Design kits available from commercial standard cell library suppliers for both CAE and CAD tools – Experimental runs at 0.8µ 3M planned for Fall, to be available mid-1991 – Acceptability of commercial 1.6µ BiCMOS offerings being assessed – Tape automated bonding for 1µ processes being evaluated

5. Other DARPA Support of Fast Turnaround Implementation

DARPA supported other activities in pursuit of fast turnaround implementation of VLSI design in addition to MOSIS. Directly related to MOSIS, under VLSI contract with DARPA, ISI/USC has carried out a multiyear program of research in support of fast turnaround implementation. Early research was directed at silicon compilation and VLSI-based computer architecture. Work was also begun in the first year of MOSIS to develop ISI's capability to support CMOS technology.

Also, for an early brief period, DARPA was reportedly the primary customer for a commercial silicon broker--Synmos, which handled 1400 chips over a two-and-a-half year period from 1981 to 1983. Synmos received MEBES data, translated it into mask-making instructions, compiled it on a VAX, generated a MEBES control tape, and then arranged masks and fabrication, diced the chips and returned them to the designer. It also supplied design tools. By 1984 it was "on ice," without an order for more than a year.

> In essence, Mr. Matheny [President and CEO] said, "they [Darpa and other potential customers] didn't think what we were doing was worth it." At that time, Mr. Losleben of Darpa confirmed this, explaining that "Synmos was

not adding enough value to the process. He added that there may not yet be sufficient demand for a brokerage service for any one broker to survive."[51]

Within the past two years however, two new commercial silicon brokerage firms have begun operations.

6. Relevance to Defense Technology

MOSIS significance for defense technology can be evaluated in three ways: What did it contribute to: (1) implementation of DARPA/DoD research? (2) cost savings in conduct of this research? and (3) accomplishment of VLSI and Strategic Computing Initiative objectives?

Table 18-5 indicates that at least two-thirds of the microelectronic device projects implemented by MOSIS in 1981-86 were for DARPA contractors or DARPA-affiliated projects carried out by government laboratories. Assuming that from 1981 through 1989 at least 60 percent of the projects implemented were for DARPA-sponsored research, roughly 7,300 chip designs relevant to this research would have been implemented via MOSIS.

One measure of what MOSIS made possible can be gained from considering the contrast between what it costs to implement project chips through MOSIS and what it would have cost to do them commercially. Assuming very conservatively that MOSIS permitted direct implementation costs that were on average $20,000 less per project on 7,300 DARPA-sponsored projects, and also obviated a roughly equivalent per-project expense in administrative and overhead costs,[52] it permitted accomplishment of projects that would have cost $150-300 million or more to do commercially. Since DARPA's total budget for VLSI was far smaller than these amounts, it can be seen how much MOSIS made possible that would otherwise have been prohibitively expensive. Our initial estimate of DARPA expenditures on MOSIS over the period is about $30 million in facility and staff costs plus roughly $24 million in project support costs. If these numbers are roughly correct, the value of MOSIS fabrications accomplished represents a three-to-six-fold leveraging of DARPA's budget in terms of the commercial value of devices produced.

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[51] "In pursuit of the one-month chip: Business outlook," Mark A. Fischetti, *IEEE Spectrum*, September 1984, p. 48.

[52] This is based on several indications that commercial costs per project would be at least $25,000, and MOSIS cost at most $3-5,000. Evidence indicates that average commercial run costs would average much more, and MOSIS costs significantly less on average that these figures. We assume that overhead and administrative costs of six work-months would also run about $20,000.

Table 18-5. Percentage Distribution of MOSIS User Types By End-user, 1981-86[a]

Year	Totals	DARPA			NSF	Com'l
		UNIV	INDUS	GOV		
1981	254	97	3	0	0	0
1982	460	90	8	0.7	1.5	0
1983	699	57	9	0.7	33	0
1984	921	55	15	1.3	28	0.1
1985	1340	58	15	2.3	24	0.8
1986	1850	54	11	3.4	26	1.0

[a] These numbers differ greatly from total project numbers that ISI provided to IDA by type of technology (Table 1). For that reason we have converted the end-user breakdown into percentages. The differences are as follows:

differences are as follows:	1981	1982	1983	1984	1985	1986
By technology	258	809	1332	1634	1790	1683
By user	254	460	699	921	1340	1850
Differences	+4	+349	+643	+713	+450	-167

Less readily measurable, but in all likelihood of much greater significance are the contributions MOSIS has made to DoD/DARPA objectives for enhancement of U.S. defense microelectronic and computing capabilities. By making possible the implementation of VLSI designs for new systems architectures and specialized devices which have become part of VLSI and DARPA's later Strategic Computing Initiative (SCI) programs, MOSIS can be credited with enabling technologies which many believe would not have come into being otherwise, or would have come about much less quickly. See Table 18-6 below. In effect, new computer architectures prototyped on MOSIS brought about the revolution in computing which has put mainframe power into desk-top workstations and supercomputer power into new VLSI parallel processor computers. An internal DARPA assessment states that "MOSIS fabrication services have significantly contributed to major computer architectural developments over the years, which will continue to be important to future DARPA research." In addition to MOSIS-assisted projects that contribute to meeting DARPA system development needs directly, many technologies prototyped or developed in conjunction with MOSIS operations have become successful commercial systems with important potentials for defense applications. A most obvious example are the RISC-architecture based workstations which have been acquired in large numbers by DoD. A few other examples of MOSIS-implemented technologies with direct defense applications identified by DARPA include:[53]

- -- Torus Routing Chip designs for second-generation message passing systems "will have many direct applications within the DoD; for example, SDIO is counting on these systems to support their simulation efforts."
- -- PIXEL Planes graphics engine: "This work has important extensions to three-dimensional modeling for future DARPA efforts in manufacturing technology."
- -- MOSAIC C fine-grain message passing systems: "These compact and very high performance machines will have numerous applications in defense systems."
- -- Monarch: "a very large-scale tightly-coupled parallel processor being developed as part of the DARPA Strategic Computing Program."

While MOSIS can be given only partial credit for development of these and many other defense-relevant microelectronics technologies since 1981, many of which resulted from research projects funded under DARPA's VLSI and SCI programs, clearly MOSIS was an important, and in many cases, necessary condition for their realization.

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[53] "MOSIS SUCCESS STORIES," pages J-14-26.

Table 18-6. Technologies Facilitated by MOSIS[a]

General RISC Architectures

- RISC I & RISC II, UC-B David Patterson (SPARC – SUN Microsystems, A. Bechtolsheim). Independently developed new computer architecture designed to use parallel processors closely linked with memory and communication circuits to increase computer speed and efficiency. UC-B fabricated prototype chips using MOSIS.
- MIPS & MIPS-X, Stanford, John Hennessy, (Microprocessor without Interlock between Pipe Stages) (Mipsco, Inc., John Hennessy). A risc-based architecture which added pipelined data flows to parallel processing. Designed to achieve mainframe-level performance in a VLSI-processor, and supercomputer performance through a VLSI-based parallel processor.

Systolic Array Architectures

- LINK, CMU systolic array chip.
- WARP, CMU, H.T. Kung, (iWARP, INTEL); (SCP, GE). Kung and colleagues fabricated prototype chips using MOSIS to demonstrate capabilities of systolic arrays.

Symbolic Processing Architectures

- SPUR (Symbolic processing using RISC), UC-B. A multiprocessor workstation. The chip sets were fabricated in 1.6µ CMOS using MOSIS.

Neural Networks

- Cochlea, Retina, CalTech, Carver Mead. Neural network analog chips. (Synaptics, Inc.)

Parallel Processing Architectures

- The Connection Machine, MIT, Danny Hillis, (Thinking Machines, Danny Hillis) a massively parallel system representing a fundamentally new architecture
- The Tree Machine, CalTech
- Non-Von, Columbia's Tree Machine architecture
- Cosmic Cube / Hypercube, CalTech, Charles Seitz, (iPSC, INTEL): an approach to message-passing concurrent computer architecture. Hundreds of commercial systems delivered including many to DoD contractors Seitz used MOSIS for prototyping; later cubes were used as a model for setting up MOSIS PCB services.
- Butterfly Parallel Processor, Bolt Baranek & Newman (BBN). First used MOSIS to produce a single-chip switch node; later, chips for 30 production machines ranging from 8 to 128 processors.

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[a] Each listing identifies, where available, in the following sequence: (1) acronym and/or name of the technology; (2) locus of origin; (3) name of principal originator; (3) commercial application name(s) and company name(s) (in bold); (4) name of commercial originator. This is followed by a brief description of the technology and the use made of MOSIS in its development.

Table 18-6. Continued

Parallel Processing Architectures (continued)

- Monarch, (BBN), Medium Scale Prototype of a large-scale tightly coupled parallel processor developed under DARPA Strategic Computing Initiative. Used MOSIS to fabricate several prototype chips for high-speed data transmission, and custom CMOS ICs for a 1024-processor prototype in 1988.
- MOSAIC: CalTech's homogeneous multiprocessor architecture

Routing, Message-Passing Architectures

- Torus Routing Chip (TRC), CalTech. Demonstrates concepts of wormhole routing and virtual channels; implemented in self-timed VLSI design, it reduced message latency by 2-3 orders of magnitude. Advanced versions envisaged for use in SDIO simulation efforts. (Several manufacturers developed commercial routing chips based on TRC.)
- MOSAIC A, CalTech. A fine-grain message-passing system in nMOS. Used MOSIS to fabricate processor chips and PCBs to build first prototype system.
- MOSAIC C, CalTech. A compact, high-performance fine-grain message passing system in CMOS; expected to have numerous defense system applications. (INTEL)
- Digital Orrery, SIMD message-passing system for orbital computations. Used PCBs fabricated through MOSIS.

Specialized Components (Analog-to-Digital Converters)

- Algorithmic monolithic CMOS A/D converters, UC-B, Paul Grey; Medium-speed high-resolution A/D converters. Used MOSIS fabrication throughout the research. Incorporated into several commercial products including a single-chip data acquisition system by Microlinear Corp.
- High-speed pipelined A/D converters, UC-B, Paul Grey, which will allow economic implementation of an AD/D interface directly on video signal processing chips.
- CRRES (Chips for the Combined Release and Radiation Effects Satellite), Jet Propulsion Lab. Used MOSIS to produce key prototype chips, including a MOSFET matrix for transistor parameter extraction and a 64-stage timing sampler for propagation delay measurement.

Fabrication Processes

- WSI - Wafer Scale Integration. Lincoln Laboratory, supported by DARPA as part of its VLSI program. Used MOSIS to fabricate at least eighteen of its WSI projects.

Computer-Aided Design and Graphics Tools

- Geometry Engine, Stanford, Jim Clark (Silicon Graphics, Inc.)
- Pixel Planes, Univ. of No. Carolina (UNC), A general purpose experimental graphics engine, demonstrating affordable solutions to painting fully rendered 3-D scenes; has important applications in 3-D modeling. Used MOSIS for rapid prototyping of component chips.

Computer-Aided Design and Graphics Tools (continued)

MOSIS made important contributions in demonstrating the utility and contributions a variety of CAD and other VLSI design and verification tools could make in facilitating design, fabrication, and quality control in microelectronic device production. In particular, MOSIS encouraged experience and familiarity in use of the following tools:

Table 18-6. Continued

- CAESAR: UC-B, John Ousterhout,
- MAGIC, UC-B, John Ousterhout. A later CAD system, widely available to the research community without restriction. It provided the conceptual origins for a number of commercial CAD systems including those of Valid, Viewlogic, Mentor, Daisy, and Cadence
- SPICE, UC-B. Automation Technology Program, circuit simulator MOSIS played a key role in demonstrating that this design vı. ification tool.
- MOSSIM, UC-B? Automation Technology Program, switch simulator (design verification tool)

C. OBSERVATIONS ON SUCCESS

We find the major results of MOSIS service to have been that it:

1. Facilitated breakthrough technologies: MOSIS "Significantly contributed to major computer architectural developments over the years, which will continue to be important to future DARPA research."[54] It challenged and changed dominant approaches and technologies by enabling the demonstration and validation of RISC architectures. It fostered technologies which directly challenged and are increasingly displacing the prevailing commercial technologies, which were resistant to innovation and change because of existing investments in and commercial commitments to them. Only two years after its initiation, DARPA officials could state: "We believe this service is causing a revolution in system architecture research as dramatic as the introduction of inter-active computation was to programming.... In the words of Chuck Seitz, Cal Tech: 'The past several years have been the first period since the pioneering work of Eckert and Mauchley at the 'University of Pennsylvania in the late 1940's that universities and small companies have had access to state-of-the-art digital technology. The result is a renaissance in both general-purpose and special-purpose computer architectures.'[55]

   DARPA's overall approach in the VLSI program, of which MOSIS was a key component, was to enable and stimulate research in a variety of locations and organizations in ways which permitted and even encouraged competing approaches. DARPA's management philosophy was to do high-risk, high-gain research. MOSIS was a comparatively low-risk, low-cost undertaking, which greatly increased the scope for sponsoring a broad array of high-risk VLSI projects at greatly reduced cost.

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[54] Quoted in "MOSIS SUCCESS STORIES," page J-18.

[55] Quoted in "MOSIS SUCCESS STORIES."

2. Enabled universities to expand education of and contributions by students, faculty, and other independent investigators with limited resources, by providing access, ease (time, effort, high quality, and quick results). From a dozen institutions at the outset to over 360 now, the expansion of its user base is alone a significant measure of its favorable impact. By being able to demonstrate the functionality of chip designs, and speed their integration into working prototype systems, MOSIS has permitted university researchers to achieve both credibility and demonstrable results not feasible before the advent of its services.[56] At a 1986 NSF/DARPA workshop, representatives of 23 universities concluded: "If we had not had it [MOSIS], the [VLSI] community would not exist. We recommend that MOSIS continue to be kept strong, healthy, and tracking the technology."[57]

3. Encouraged successful transitions to commercial applications. Table 18-5 cites examples of significant commercial developments based on technologies either first implemented or refined through MOSIS. Among the most significant developments attributable to MOSIS facilitation, the commercialization of the RISC architectures and of computer workstations and networks have had the most far-reaching impact to date. Stimulated particularly by RISC-based architectures such as the SPARC workstations introduced by Sun Microsystems, and others subsequently developed by Mipsco, RISC-based systems have now been marketed by almost all the lead vendors of computer systems. In addition, the geometry machine, commercialized by Silicon Graphics, brought major advances in computer graphics. Systolic array computer architectures developed through MOSIS are also now emerging in commercial systems bringing new developments in parallel processing. (For more detail see Chapter 17, VLSI Design.) In addition, many other technologies developed through MOSIS were drawn upon by industry but not formally transitioned in their original form.

4. Enabled industry VLSI developments: As early as 1981-1982 trade journals, DoD and DARPA contractors, and semiconductor firms validated the commercial significance of MOSIS by publicizing its projects, to illustrate its value and their services (e.g., "Atari cuts prototyping time 77 percent") [58] "With the [July 1984] opening to the commercial world of ARPAnet..., the basic ingredients to realize the one-month chip are now in place... All the major IC markets, including mainframe computers, consumer products, and military supplies, stand to benefit. Demand for semicustom chips, in

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[56] For an imposing description of the daunting complexities, time, efforts, and costs facing independent designers and researchers wanting to test their chip designs in silicon as 1980 dawned, see "IC Fabrication for the Independent Chip Designer," Robert Hon, *LAMBDA*, First Quarter, 1980.

[57] Report of the Workshop on Rapid Prototyping of Experimental Digital/Analog Systems, Carnegie-Mellon University, December 8-9, 1986, p. 10.

particular, is rising rapidly, and work stations that enable nonexpert chip designers to design them are selling quickly. We are doing this to accelerate the development of the fast-prototyping industry.... ARPAnet is central to 'an essential infrastructure that is not in place yet in the commercial world,' Mr. [Paul] Losleben said, noting that the lack of such an infrastructure has been 'the largest deterrent to fast-turnaround service.'"[59]

5. Expanded the pool of researchers working on high performance microelectronics and their creativity through cross-stimulation. Mead-Conway design methodology contributed to the "intellectual infrastructure." At a time when student researchers were limited to paper drawings of designs which could not be tested or proven to function, Conway demonstrated the feasibility, and MOSIS provided the ongoing capability of doing both within the time constraints of academic terms--generating the excitement that brought forth a tremendous expansion of researchers in VLSI technologies. By extending its service to help researchers develop prototype systems, many of which were quickly commercialized, MOSIS provided yet a further dimension of stimulus.
6. Created a pool of technical talent for industry: MOSIS supplemented general DARPA VLSI support in greatly increasing the number of undergraduates and graduates experienced in VLSI design and implementation. These students in turn stimulated demands within industry for much faster turnaround implementation of intrafirm research designs, accelerating the process of innovation there as well. "Perhaps the biggest transfer to industry occurs through students that are taught VLSI design in a course that uses MOSIS for fabrication. For many of these students, getting a design fabricated and seeing it work changes the way they think about VLSI and digital design. Before their project, they thought of VLSI as something only large companies with millions to spend could do. After designing a working chip themselves, they look at VLSI as a very accessible technology for building high performance electronic systems. Then they carry this attitude into industry."[60]
7. Facilitated access to advanced implementation technologies. By seeking out providers of improved fabrication, packaging, and other process technologies, and by providing a consolidated source of demand for these services on standardized terms, MOSIS has facilitated access to these services by both academic and industry researchers, albeit somewhat behind the most advanced technologies available in industry.

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[58] As reported in the 1982 annual report of ISI, p. 45.

[59] Frischetti, op. cit., p. 47.

[60] From "MOSIS SUCCESS STORIES," quoting Bill Daly of MIT, page J-18.

8. Invigorated commercial research in VLSI Technology: Graduates of MOSIS VLSI joined and shaped corporate research teams in VLSI. These graduates often chaffed under slow chip turnaround in corporate environments, in turn stimulating faster in-house turnarounds for research runs, in some cases even corporate use of MOSIS.

9. Provided major stimulus to development of ASICs (application-specific integrated circuit) technology. When MOSIS began, only large semiconductor firms had the capability to test custom designs in silicon. For small firms and most universities, the difficulties were prohibitive. With the availability of low-cost, fast-turnaround silicon broker service pioneered by MOSIS the development of custom and semi-custom chip design became truly feasible in both communities with sufficient volume to be of growing interest to foundries. (Engineers quoted in a 1984 *IEEE Spectrum* article cited the one-month chip as the biggest development in microelectronics since the advent of the microprocessor in 1971.)

10. Stimulated development of foundry and other commercial process services. The growing demand for limited runs of designer chips, combined with the pioneering of systematic, standardized interfaces between designer and fabricator, both brought about by MOSIS, added to commercial system house requirements, spurred development of foundry services--facilities offering microelectronic device fabrication--which have become an integral part of the U.S. microelectronics industry.

    Also, within the past few years, commercial services have been established to supply silicon brokerage services to commercial users, illustrating the broader value of the concept. MOSIS itself has had its greatest impact on academic and DoD contract users, with relatively minor use by commercial firms. Currently, at least two firms--US-2 of Sunnyvale, Cal. and ORBIT, also of Sunnyvale--offer silicon brokerage services on commercial terms. These firms meet the special needs of commercial customers in part by offering services exceeding those available through MOSIS; e.g., they broker substantial production runs, have special expertise in fabrication technology, and permit and facilitate closer client relationships directly with foundries.

11. Indirect benefits: Sources for this study cited numerous examples of technologies facilitated by MOSIS which did not emerge either as commercial or defense applications, but which nonetheless were instrumental in the development of those that did.

Overall, MOSIS has been a relatively low-cost, low-risk DARPA investment in infrastructure which strongly leveraged its higher-risk investments in VLSI technology. MOSIS was exceptionally fruitful in fostering a wide diversity of successful technologies and their application both in defense and commercial information processing systems, and is expected to continue providing these services well into the future.

MATERIALS

XIX. DIGITAL GALLIUM ARSENIDE

A. BRIEF OVERVIEW

The first experimental work with gallium arsenide (GaAs) and other III-V compounds for use in semiconductors took place in the early 1950s. Several events in the 1950s and 1960--including the discovery of the Gunn Effect and the proposal of the Schottky barrier gate field effect transistor--provided further incentive for the use of GaAs in electronic devices. In addition, the Air Force, and to a lesser extent, the Army and the Navy funded some of the original research in the use of GaAs.[1]

Because the use of GaAs in electronic devices was a relatively new concept, there was no immediate commercial interest in its use in the 1960s. However, the Department of Defense recognized important qualities of GaAs that would increase its military utility as a semiconducting material.[2] These include:

- lower noise potential
- better potential for radiation hardening
- higher frequency of operation
- higher speed signal processing
- higher power
- higher efficiency

Despite the potential benefits inherent in the use of GaAs, there have been significant technological challenges to overcome in using GaAs in semiconductors/integrated circuits. High-yield ion-implantation (the method of fabrication funded under the DARPA program) has been constrained by the complexities associated with a compound semiconductor. Problems such as stoichiometric defects, high impurity content, defective crystalline structure, and a lack of native oxide properties have all limited development of GaAs integrated circuits.[3] In addition to problems of development, questions of producability have also plagued GaAs. While fabrication of GaAs devices has

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[1] The Services were interested in GaAs epitaxy because of the potential for high-speed processing. Original DARPA interest was generated by the potential applications in space systems for ion-implanted GaAs.

[2] *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT 30, Number 7, July 1982, p. 933.

[3] R. Noel Thomas, et al., "Status of Device-Qualified GaAs Substrate Technology for GaAs Integrated Circuits," *Proceedings of the IEEE*, Volume 76, July 1988, p. 778.

some similarities with fabrication of silicon devices, the properties of GaAs have presented unique manufacturing challenges. These challenges continue to affect all aspects of the manufacturing process, from material selection to quality assurance.[4] As Eden and others point out, commercial vendors of GaAs ICs still face serious technical problems in process development, testing, modelling and design of devices.[5]

These problems, in combination with the lack of an immediate commercial market for GaAs devices (particularly in the early years of development) made investment in GaAs a risky venture. Because of the high risk involved in GaAs, no private firms were willing to commit to a large research and development effort. However, the potential military applications of GaAs generated considerable interest within the military services, DARPA, and elsewhere in DoD. To realize these potential benefits, direct DoD support of GaAs technology was required.

B. TECHNICAL HISTORY

1. Origins of Program

The earliest work in producing electronic devices with GaAs took place at several research centers. C.A. Mead at the California Institute of Technology was involved in GaAs research in the early 1960s. Mead constructed the first GaAs FET at Cal Tech in 1965. The first microwave GaAs FET was developed by Fairchild as part of an Air Force contract in 1967. Research by Drangeid at IBM demonstrated the three terminal, high performance potential of GaAs. This work, in addition to results generated by researchers at Fairchild, made it clear that the potential benefits of GaAs justified the high risks involved in funding technology development efforts. Hewlett-Packard, Hughes,

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[4] Further discussion of the manufacturing challenges posed by GaAs can be found in Conilee G. Kirkpatrick, "Making GaAs Integrated Circuits," *Proceedings of the IEEE*, Volume 76, July 1988 pp. 792-815.

[5] Richard C. Eden, "The Development of the First LSI GaAs Integrated Circuits and the Path to the Commercial Market," *Proceedings of the IEEE*, Vol. 76, No. 7, July 1988. Eden also cites several other relevent works, including: Y.D. Shen, et. al., "An ultra high performance manufacturable GaAs E/D process," *Tech Digest 1987 GaAs IC Symposium*, Portland, Ore., Oct. 14, 1987; D. Kiefer and J. Heightley, "Cray-3: A GaAs implemented supercomputer system," Keynote Invited Paper, *Tech Digest 1987 GaAs IC Symposium*, Portland, Ore., Oct. 14, 1987; D.A. Nelson, et. al., "Launching GaAs wafer fab technology into LSI," *Tech Digest 1987 U.S. U.S. Conf. on GaAs Manufacturing Technology*, pp. 77-81. Oct. 12, 1987; T.R. Cheewala, "Packages for ultra-high speed GaAs ICs," *Tech Digest 1984 GaAs IC Symposium*, Boston, Mass., October 23, 1984.

McDonnell Douglas and Texas Instruments were also involved, to varying degrees, in GaAs research in the late 1960s and early 1970s.[6]

In the mid to late 1960s, ARPA established and funded the Center for Materials Research (CMR) at Stanford University.[7] The CMR was established to educate doctoral-level students who, it was hoped, would later be involved with critical, materials-related technology development issues facing government, industry and university labs. In 1967, Dr. A.S. Joseph, from the Rockwell Science Center, spent some time with CMR to gain experience in semiconductor physics. At CMR, Joseph met several Ph.D. candidates (including Richard Eden) who later joined Joseph at Rockwell. Joseph's group was referred to as the Semiconductor Physics group at Rockwell.[8]

The initial research conducted by this semiconductor physics group focused on liquid phase epitaxial growth of GaAs and the fabrication of microwave devices. In 1970, Rockwell cut its internal R&D funding in an effort to reduce research expenditures on projects that management felt had limited potential for payoff. The microwave device research conducted by the semiconductor physics group held much promise for the company, but nevertheless was in jeopardy. Based on concerns generated by this changed environment, Joseph and Eden sought and received GaAs development funding from DARPA in 1973.[9]

Their three year effort included participation of researchers from Stanford and Cal Tech. The program included studies of semi-insulating GaAs substrate materials, interface effects, and ion implantation. They successfully demonstrated the first ion-implanted low-power GaAs MESFET (metal semiconductor field-effect transistor) logic gates, an accomplishment that led to further DARPA funding. Two researchers at Hughes (Huntsberger and Hirsch) also independently made ion-implanted GaAs MESFET's simultaneously.[10]

This success prompted the researchers at Rockwell to seek further DARPA support. In 1976, Richard Eden and others met with then-Director George Heilmeier.

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[6] Paul Greiling, "The Historical Development of GaAs FET Digital IC Technology," *IEEE Transactions on Microwave Theory and Techniques*," Vol. MTT-32, September 1984, pp. 1144-1152.

[7] See the chapter in this report detailing DARPA involvement in the CMR.

[8] Eden, 1988.

[9] ARPA Order Number 2489, "High Frequency GaAs Technology," managed by Richard Reynolds, February 26, 1973.

[10] Eden, 1988. See also Greiling, 1984.

> A presentation was made to...Heilmeier, and it was favorably received, except that he commented that our depletion-mode MESFET GaAs IC approach would not be usable because at least 1000-gate LSI complexity level integrated circuits would be required for such a processor, and it was well known that LSI complexity levels could not be achieved in depletion-mode MESFET GaAs (rather, only in enhancement mode MESFET GaAs ICs). George was repeating a point of view promulgated by Charles Liechti of Hewlett-Packard who, with Rory Van Tuyl had made the first D-MESFET GaAs ICs under an Air force program starting in 1972.[11]...Perhaps as a politic justification for the simultaneous Air Force support for both of these GaAs IC programs, or out of failure to consider the possibility of much lower power D-MESFET logic circuit approaches, Leichti made his often-quoted statement that D-MESFET's were useful for extremely high speed MSI, but that enhancement-mode FET's would be required to achieve LSI levels of circuit complexity. (The statement would probably have been true of 10,000 gate VLSI, but not 1000-gate LSI). In our 1976 meeting, I argued with George Heilmeier that there was in fact no fundamental reason why D-MESFET GaAs ICs could not be made with low power levels, and that we intended to do just that. His response was that when we had done so, he would be very interested in funding our program to develop a planar localized ion implantation GaAs D-MESFET LSI integrated circuit fabrication technology. Our demonstration in December of these first little milliwat-level D-MESFET LSI integrated circuits fulfilled our end of the bargain, and George Heilmeier fulfilled his by approving the program.[12]

In April 1977, DARPA funded the first effort (at Rockwell) specifically aimed at developing a high speed, low power digital integrated circuit (IC) technology using Schottky barrier FETs and selective ion implantation into a semi-insulating substrate.[13] The program goal was greater than 1000-gate LSI complexity level in GaAs ICs, to be developed in three years. Initial costs for this project were $5.47 million. DoD interest was generated by the potential advantages of GaAs, particularly its inherent resistance to radiation damage[14], and the improved speed and power of GaAs.

During the course of the effort at Rockwell, DARPA management insisted that the "reality" of the technology be demonstrated by proving the repeatability or manufacturability of the process. As a result, DARPA insisted that Rockwell build an

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[11] R. Van Tuyl and C.A. Liechti, "High Speed integrated logic with GaAs MESFETs," *Digest of Technical Papers, ISSCC*, pp. 112-115, February 1974, as cited in Eden, 1988.

[12] Eden, 1988, p.760.

[13] *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT 30, Number 7, July 1982, p. 933. This effort was covered under ARPA Order 3384, "Ion implant GaAs IC processing," February 25, 1977. Sven Roosild was the DARPA program manager.

[14] The surface of a GaAs device is stabilized by surface defect states, rather than passivated by a native oxide. See Sherman Karp and Sven Roosild, "DARPA, SDI and GaAs," *Computer*, October 1986, pp. 17-19.

extensive data base on the device characteristics obtained with their manufacturing process. Eden states that this proved to be an important contributing factor to the success of the program.[15]

Rockwell successfully fabricated a GaAs IC with LSI capability and over 1000 gates in September 1980, three years and five months after the start of this phase of the DARPA GaAs program. Currently, Rockwell is still developing GaAs technology, moving toward completion of a 64K memory and eventually a 256K device.

An interesting by-product of the Rockwell effort is the establishment of at least two commercial producers of GaAs devices. The Vitesse company was founded in 1984 by Dr. A.S. Joseph, the former head of the Rockwell Semiconductor Physics Group, who left Rockwell before the completion of the DARPA contract in 1980. In 1981, Richard Eden and Fred Blum, the Vice-President of Microelectronics Research at Rockwell (Blum had replaced Joseph in the DARPA program), founded GigaBit Logic. Eden and Blum left Rockwell primarily because Rockwell was not going to "commercialize" the product of their research. The contributions of these companies are discussed more fully in the discussion of the insertion program later in this paper.

In the early 1980s, the Defense Science Office of DARPA decided to expand efforts to develop digital GaAs ICs.[16] DSO was interested in developing a digital chip with a large (6000 gates) configurable gate array. Given that the most complex digital GaAs chip developed at that time contained 1008 gates (fabricated by Rockwell), the path toward producing a 16K or 64K bit SRAM with 6000 gates appeared risky.[17]

Concurrent with this effort, DARPA's Strategic Technology Office, under the advanced on-board signal processor (AOSP) program, was investigating space-borne signal processing. GaAs was judged to be the best technology for application in the AOSP. In 1982 the two DARPA offices combined efforts to develop an all--GaAs prototype of the AOSP.[18] The problems facing both DARPA offices are best described by Karp and Roosild:

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[15] Eden, 1988.

[16] At the same time, DoD was also involved funding monolithic microwave integrated circuits (MMIC), also using GaAs, but because microwave and digital devices are so different, the programs were separate.

[17] Sherman Karp and Sven Roosild, "DARPA, SDI and GaAs," *Computer*, October, 1986, pp. 17-19.

[18] Karp and Roosild, 1986, pp. 17-19.

> Both complexity and yield of GaAs ICs had to increase by orders of magnitude simultaneously. Only by phenomenally increasing yield could a sufficient number of memory and gate array chips of the desired complexity be produced to realize the GaAs AOSP prototype. Clearly it was necessary to emulate the same learning curve improvement in yield and complexity that had propelled silicon technology into the VLSI era--and in a shorter time.[19]

The initial pilot line developing memory and gate array signal processing chips for the AOSP was begun in 1983; a second line was added in 1985. The lines were contracted to Rockwell and McDonnell Douglas, respectively.[20]

In 1984, in addition to developing chips for the AOSP, DARPA began development efforts aimed at an all-GaAs microprocessor to drive the AOSP. The only single-chip design that would meet the program requirements was a reduced instruction set computer (RISC) design called a microprocessor without interlocked pipeline stages (MIPS). The original MIPS concept was developed (with DARPA support) at Stanford University.[21] Initial Phase I contracts were awarded to Texas Instruments, RCA and McDonnell-Douglas,[22] and in 1985 TI and McDonnell were selected to fully develop the microprocessor. These DARPA funded efforts are acknowledged to have led the research community in its understanding of GaAs microprocessor design and architecture.[23]

In the course of funding development of different GaAs devices, DARPA established multiple pilot lines for production of GaAs components. Hence there was a need to find some way to make the chip designs transferable from one line to another. A DARPA objective was to avoid the problem that confronts some manufacturers of silicon chips—refabricating the same chip design in different chip technology requires repeating the entire design process. In order to "minimize this problem across the several GaAs pilot lines," DARPA sponsored the development of a comprehensive computer aided design package at the Mayo Foundation.[24]

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[19] Karp and Roosild, 1986, p. 18.

[20] "Low-power radiation hard GaAs LSI pilot line," DARPA contract F290601-84-C-0010, Rockwell International Microelectronics Research and Development Center, Newbury Park, Cal. "Pilot line for space based memories," DARPA contract F290601-85-C-0023, McDonnell Douglas Microelectronic Center, Huntington Beach, Cal.

[21] See also the chapter in this volume on VLSI in the MIPS.

[22] Funded under authorization of ARPA orders 4494. 4495, 4496, 4497 and 4498, January, 1984, all managed by Sven Roosild.

[23] Veljko Milutinovic, "GaAs Microprocessor Technology," *Computer*, October 1986, pp. 12-13.

[24] Karp and Roosild, 1986, p. 18. This effort was funded under ARPA order 4450, December 14, 1981. Program manager was Sven Roosild.

After the Phase I contracts were awarded, DARPA's GaAs pilot program was transferred to the Strategic Defense Initiative Organization (SDIO). The transfer was made primarily because SDIO was focusing on radiation-resistant space signal processing DARPA has continued to manage the program for SDIO.[25]

2. Insertion Program

The results of DARPA efforts in the development of GaAs technology are documented in an extensive literature. As a follow-on to the technology development efforts, in 1989 DARPA began a GaAs insertion program. This program was designed to begin the process of incorporating digital GaAs circuits in fielded defense systems. and win general acceptance of the new technology by relevant system program offices. Under this program, six manufacturers of defense systems (listed in Figure 19-1) will upgrade weapons, communications, intelligence, and electronic warfare systems they currently manufacture with devices produced by three firms: Vitesse Semiconductor; TriQuint Semiconductor; GigaBit Logic.[26] The insertion program was undertaken because of the potential advantages of using GaAs in military systems that were displayed in early DARPA-funded research:

> Digital gallium arsenide devices are particularly well suited for military systems because they consume a fraction of the power, operate at much higher speeds, function over wider temperature range and are much more resistant to radiation than silicon components.... Although GaAs chips typically cost more than the silicon components they replace, their greater performance can lead to cost savings because fewer components are necessary to implement a particular function.[27]

DARPA commitment to GaAs was integral to firms such as GigaBit receiving backing from venture capitalists. (See discussion on page 19-5). Without strong confidence that DARPA would continue to support the development of GaAs technology, it is unlikely that venture capital would have been available to GigaBit, which was the first firm to be funded to produce GaAs ICs for commercial markets.[28] As a result of the funding for GigaBit, several other small start-ups were also able to secure venture capital.

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[25] Karp and Roosild, 1986, pp. 17-19.

[26] *Defense Electronics*, August 1989, p. 10.

[27] Department of Defense press release, as reprinted in *Defense Electronics*, August 1989, p. 10.

[28] Eden, 1988.

Main System Contractor	GaAs InsertionSystem	Target Date
McDonnell Douglas Electronics	System Processorfor OH-58D	Requirements and TradeOff Study--April 1990
Honeywell	Digital Map Computer	Design Study--Oct 1990
Martin Marietta Electronics	Signal Processor inLongbow Missile	HITL Demo--Sept 1990
Kor Electronis	Digital RF memory	Pre-production model- Oct 19[illegible]
ITT Avionics	Digital RF memory	Lab Demo--Feb 1991
Sanders	IF Processor	Lab Demo--Aug 1992
E-Systems ECI Div	A/D Converters forPRC-126 Radio	Lab Demo--Mar 1992
E-Systems Greenville Div	Digital Processor for RC-135	Demo--Sept 1991
Martin Marietta Space Systems	On-board Processor	Demo--Sept 1992
Texas Instruments	Signal Processor for P-3C	FlightTest--Sept 1991
Grumman Aircraft Systems	Signal Processor forE-2C Radar	Feasibility Study--April 1990

Figure 19-1. Gallium Arsenide Insertion Projects.

C. OBSERVATIONS ON SUCCESS

It is clear from the accomplishments of the organizations funded to develop GaAs technology that the DARPA digital GaAs has yielded viable results. Practical applications are being developed under the insertion program. It is the opinion of several of the primary researchers involved with GaAs that without DARPA involvement, the technology would not have been developed.[29] From the early DARPA funding of the Center for Materials Research at Stanford to the development of GaAs ICs at Rockwell and other organizations, DARPA funding of GaAs has been essential to the development of the technology.

Since the digital insertion effort began just over a year ago, it is too early to assess its impact. However it is clear that the program has advanced the state of the art in GaAs devices. Sven Roosild, the DARPA program manager, indicates that DARPA's involvement in GaAs should draw to a close in the near future. DARPA funding has been instrumental in furthering research that may have potentially valuable defense applications. DARPA contractors have become the first to fabricate complex digital integrated circuits, and the spin-off companies such as Vitesse and GigaBit Logic are the first commercial firms to profit from the fabrication of digital GaAs devices. If there are pervasive applications of digital GaAs technology in U.S. systems in the future, it will most likely be as a result of DARPA's substantial efforts in this field.

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[29] Eden, 1988, and Greiling, 1984.

XX. THE INTERDISCIPLINARY MATERIALS LABORATORIES

A. BRIEF OVERVIEW

In response to a DoD assignment in late 1959 ARPA undertook support of the major part of a new national effort to improve education in the materials sciences and increase the number of graduates in this important area, through the establishment of the "interdisciplinary (materials) laboratories" (IDLs). Setting up the IDLs led to new materials science departments at more than 100 major universities. Responsibility for the IDLs was transferred to the National Science Foundation in 1972, which has continued their support [renamed Materials Research Laboratories (MRLs)] to date. About 3,000 PhD graduates in the materials science area have been produced by the IDLs and MRLs to 1989.

B. BACKGROUND

DoD directive 5129.33 of December 30, 1959, assigned ARPA responsibility for project PONTUS, "to obtain, at the earliest practicable date, a major improvement in structural and power conversion materials to satisfy the military requirements of the several U.S. surface. air or missile programs...," adding that the detailed work program undertaken will be consistent with the national materials research program. This directive led to the first major phase of ARPA's activity in the materials area, in the period 1958-72.

There was considerable background to this assignment to ARPA, which at the time seems to have had on its staff only the related expertise of Dr. John Kincaid, a chemist of ARPA/IDA. Kincaid also had responsibility for PRINCIPIA, which was another large assignment given to ARPA a little earlier, aiming also at a step improvement in propellant performance capabilities. There were other early ARPA occupations with materials problems (under project DEFENDER) relating to ballistic missile nose cones, hypervelocity impact phenomena, and, under the ARPA space program, construction of space vehicles and components.

The PONTUS assignment came directly from Dr. H. York, the first DDR&E, who had agreed at an earlier meeting of the Federal Council for Science & Technology (FCST) that DoD would take responsibility for funding several materials laboratories as recommended by the Council's coordinating committee on materials R&D. The Federal Council's decision to start what was essentially a national materials program was influenced by, in addition to York's DoD commitment, statements from NASA representatives that they each would support two such laboratories, although AEC and NSF expressed reluctance.[1] It was clear, however, that DoD would provide the major share of the laboratories' support in the national program and could act more quickly and with more contract flexibility than the other agencies. One major reason for DoD's "lead" in this respect was its capability to make multiyear contracts, which were essential to get universities to put up new buildings for the new laboratories. Eventually AEC did participate, apparently after a suggestion by G. Kistiaskowsky, then the President's Science Advisor, that AEC retain title to the buildings.[2]

In turn, there was considerable background to the FCST meeting. In the mid-1950s there was a growing appreciation of a need for a national effort in materials R&D. This view came from earlier experience with major materials projects in WW II and from current frustrations in missile and nuclear weapons-related work due to a lack of capability in the materials areas. One of the earliest recommendations in this regard came from an AEC materials advisory group to the General Advisory Committee (GAC) of that agency, that some new materials institutes be funded. Despite the strong positive convictions about the importance of more research on materials held by two very influential GAC members, J. Von Neumann and W. Libby, no action was taken. Navy and Air Force study groups made similar recommendations (the latter specifically suggesting national materials laboratories) with similar lack of response. Soon after, however, SPUTNIK put new forces to work: the PSAC (President's Science Advisory Committee) and ARPA. PSAC discussed materials needs of various important projects, and noted, as mentioned above, that most defense-related U.S. materials work in the past had been done under various "systems" projects. Each of these materials efforts could be described as a saga of its own with little or no transfer of knowledge between projects.

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[1] NSF declined to participate in the new materials program, citing as its reason a policy to support only individual investigators (discussion with D. Stevens, 6/90). There had been exceptions, however, to this NSF policy, perhaps most notably the IGY international geophysical year. For a discussion of AEC's reactions, see *A Scientist in the White House*, by G. Kistiakowsky, Harvard [illegible]5, pp. 14, 16, 22.

[2] Ibid., p. 148.

Also, the same inefficient pattern of materials work was going on under the large military projects of the time, illustrated by the then current ARPA work related to space vehicles, ballistic missile nose cones and hypervelocity impact. PSAC believed that a large national effort should be launched that would begin by fostering a new type of graduate education in science and engineering stressing the interdisciplinary nature of most materials development as well as sharply increasing the support for university facilities and related needed instrumentation. The new national level of support in the materials area would be aimed primarily at producing more graduates trained in such an interdisciplinary academic environment. These views were codified in a paper on "Coordinating Materials Research in the U.S." by W.O. Baker of PSAC, one of the leaders in its related discussions.[3] Specifically, Baker's paper suggested that the FCST, which included heads of federal agencies with substantial S&T budgets, should consider and act on this recommendation. In what was apparently its first official action the FCST in turn formed a multiagency "Coordinating Committee on Materials R&D" (CCMRD) and called on it to respond. D. Stevens of the AEC, CCMRD chairman, promptly drew up what was a modification of the earlier AEC advisory committee's recommendation, which was presented and approved.

In late 1958, before the actual FCST meeting to discuss the CCMRD's draft response, Stevens and Libby from the AEC met with York, whom they knew from his past association with that agency, to go over the situation and persuade the DDR&E of the important role DoD could play.[4] York asked Kincaid to look into the matter, and soon afterwards, Stevens and Kincaid visited a number of universities.[5] Kincaid's resulting "program justification" memo, dated 6 April 1959, reaffirmed the PSAC and CCMRD conclusions, pointing out also that the DoD would have to be responsible for 50 percent or more of the national programs, and that the university contracts required 3-year forward funding.[6] This was an important issue because forward funding was possible for DoD but not for AEC and NASA in their usual contracting mode.

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[3] Much of the PSAC discussions occurred in the broader context of how to strengthen American science, a question which had been given to them by Pres. Eisenhower in 1957. One of the first PSAC recommendations in this regard was to establish a FCST. See J.R. Killian, p. 191, in *Lost at the Frontier*, by D. Shapley and R. Roy, ISI Press, 1985.

[4] "Materials Research Laboratories, the Early Years," by R. Sproull, in *Advancing Materials Research*, National Academy Press, 1987, p. 27.

[5] Ibid.

[6] IDA TE 69, 6 April 1959, by J.F. Kincaid, Materials Program: PONTUS. Actually, a substantial amount of "Forward Funding" of university research had been done earlier in ONR.

C. ESTABLISHMENT AND HISTORY OF THE IDLs

The formal assignment of PONTUS to ARPA was made in December 1959. Actually, the first related ARPA actions were to provide for assistance from the National Academy's Materials Advisory Board (MAB), in late 1959 and in early 1960, to make provision for equipment at universities other than those first selected.[7] Cornell, Northwestern, and Pennsylvania Universities were selected for ARPA funding in 1960, and eight more in 1961.[8] A strong competition took place for the selection, in which ARPA was assisted by an advisory group from the National Academy's MAB. Only three of 45 proposals were funded in the first round.[9] This competition was the first of its kind, and has been described as having a broadly healthy impact on both the materials fields and on the universities.[10]

The impact on the Universities involved has been described by R. Sproull, who had the unique experience both of running an IDL laboratory and being an ARPA director:

> The important features at each university were the following. First, that an umbrella contract provided for continuity of support and for the ability to buy large quanta of equipment and facilities. Second, a local director committed a substantial fraction of his career to making the program succeed. He could use the longevity of support to extract concessions from the university and departmental administrations. Third, the contract provided, in most cases, reimbursement over 10 years for the new construction required to do modern experimentation on materials. Fourth, the longevity of the contract induced the university to allocate to the project scarce and prime space in the middle of the campus, thereby establishing the maximum informal connections among disciplines. Fifth, central experimental facilities (such as those for electron microscopy or crystal growth) could have state-of-the-art equipment, even if it was very expensive, and they served as a mixing ground for students and faculty from several disciplines. Sixth, an executive committee composed of people with power and influence in the individual disciplines but oriented toward the success of the program helped the director over the rough spots with department chairmen, people who often were overly protective of their bishoprics and palatinates. Seventh, a contract was not given to an institution unless it had a strong disciplinary base on which to build.

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[7] ARPA Order AO 108 of 10/59, "MAB Support," and AOs 142, 143, and 144 of 5/60 for instrumentation. Actually other DoD research funding agencies also had substantial extra funding from DDR&E for equipment at this time. The source for this, as for the IDLs, was the DDR&E's "emergency funds."

[8] "Materials Research Laboratories: Reviewing the First Twenty-Five Years " by L.H. Schwartz, in *Advancing Materials Research*, ibid., p. 33.

[9] Schwartz, ibid., p. 36. Table 1, and AO 157 of 6/60, "IDLs."

[10] Donald K. Stevens, ibid.

> Interdisciplinary programs perched on weak disciplines are dangerous; interdisciplinary work already had a bad name on many campuses because of programs alleged to be interdisciplinary but without disciplines (on many campuses home economics was the example cited). Eighth, individual grants and contracts with federal agencies continued; most well-established principal investigators received the majority of their support from some other agency and might enjoy help from the program only in the central facilities or the building space. Thus, when the executive committee and director found that they had to say "no" to a local high priest, it was not really, "no" but only "no" with the umbrella contract's money, and that made life easier.

Despite the fact that DoD could only contract for 5 years, the initial contracts were large and ARPA could otherwise give the Universities enough assurance of a virtual, if not actual, 10-year program duration for them to be able to borrow funds for the new IDL buildings.[11] ARPA had thus made, in a sense, a 10-year commitment, along with the other agencies, which was carried out despite pressures which grew in the mid-1960s against "forward funding," in the DoD, and against military research in the Universities in the same period. Another important feature of the IDL program was the "block funding" characteristic: allocation of the "block" funds was left to local university management, with a very broad work statement:

> The contractor shall establish an interdisciplinary materials research program and shall furnish the necessary personnel and facilities for the conduct of research in the science of materials with the objective of furthering the understanding of the factors which influence the properties of materials and the fundamental relationships which exist between composition and structure and the behavior of materials.[12]

There was a considerable impact on the universities. "Materials science" now became a recognized discipline at many major research universities, in contrast to the previous situation in which departments of physics, chemistry, metallurgy, mining and engineering all had had separate courses in materials and different research projects in the area. By 1989 there were about 100 materials departments in the universities.[13] Teaching and research also became possible in new areas.[14] Graduate students increased in number

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[11] Apparently Dr. York wanted to get around the problem by a big enough "grant" to permit amortization. Cf., Kistiakowsky, ibid., p. 22, and Sproull, ibid, p. 31.

[12] Lyle Schwartz, op. cit. p. 37.

[13] *Materials Science and Engineering for the 1990's*, National Academy Press, 1989, p. 148.

[14] Harry C. Gatos, in *Lost at the Frontier*, p. 178. The IDL's were not, however, the first example of interdisciplinary laboratories at universities: the Joint Services Electronics Program, was established in 1946, and had set up such groups as MIT's Research Laboratory of Electronics. See J.R. Killian, ibid., p. 190, and "Fortieth Anniversary Symposium of the JSEP," U.S. Army Research Office, 1987.

and began to satisfy growing demands of the generally growing universities, industry and government laboratories. While some of the early specific motifs for the IDL program, as noted above, were mainly associated with structural and power conversion materials, one of the fastest growing demands in this time period was that associated with the near-exponential growth of integrated circuit density, which depended on continuing improvements in the processing of, and controlled deposition on, semiconductors.

During the early 1960s, in addition to the IDLs, ARPA also funded efforts in specific materials areas, including: thermoelectrics, semiconductors, ceramic windows for high power microwave devices; lightweight armor; crystal growing and characterization; fatigue; and on properties of materials needed particularly for space application, such as beryllium.

In 1963 R. Sproull became ARPA's director and soon afterwards initiated a "pull" of the IDLs toward industrial and defense applications. Partly, this action was in response to a lessening of the national earlier feeling of crisis. Sproull's "pull" mechanism was to form "coupling" groups of university-industry-government laboratories.[15] After a few years' trial, however, the "coupling" programs were discontinued as a separately identified theme.[16] Sproull also initiated discussions with NSF about transfer of the IDLs, but without success.[17]

In the late 1960s, there were several new pressures on ARPA in regard to the IDLs. Apparently Dr. Foster the new DDR&E did not look favorably on the "forward funding" concept in general, and also did not like the rather academic character of the program.[18] Demands of the growing Vietnam war also caused a reduction of DoD R&D funding generally, affecting IDLs in the late 1960s. The DoD "THEMIS" program, aimed at raising the level of research and teaching capabilities of a wider geographic distribution of universities in science and engineering, also had some "materials" content, but was another drain on funds that might have gone to the IDLs.[19] In 1966, an internal review of the IDLs

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[15] E.G. AO's 876 and 878. This type of approach has been advocated more recently in many quarters, cf., Gatos loc. cit.

[16] One of the reasons for discontinuance of the coupling programs was a recognition of ARPA's lack of adequate management at the time. Communication from R. Sproull, August 1990.

[17] R. Sproull, ibid.

[18] "The Advanced Research Projects Agency," 1958-1974, Richard J. Barbar Associates, 1975, pp. VI-49 and VIII-57.

[19] Ibid., p. VIII-59.

was conducted by ARPA, concluding that many of its goals had been met.[20] In late 1968, Congress' Mansfield amendment, requiring a direct link of research projects funded by DoD to its mission, made it even more difficult for ARPA to justify the IDLs. Further, the attitude toward the Vietnam War at many universities made it a delicate matter for ARPA to press for more explicitly defense-related efforts at the IDLs.

Discussions were therefore held with the NSF and the White House's OSTP (successor to PSAC), pointing out the national nature of the DoD responsibility, and the 10-year "virtual commitment" involved, which still had a few years to run. In 1971 NSF conducted a review of the IDL program, and in 1972 assumed full responsibility for it. The NSF review brought out that the specifically interdisciplinary character of the IDLs needed more emphasis. NSF, which had avoided the responsibility for the IDLs at the beginning because of a preference (or policy) for individual, or disciplinary, support, now stated that block support, locally administered, would continue, but that scientific excellence was considered a necessary, but no longer sufficient, condition to qualify.[21] The IDLs, now named by NSF, Materials Research Laboratories would be judged by their ability to do "coherent" multi-interdisciplinary and multi-investigator projects in major thrust areas requiring the expertise of two or more materials-related disciplines."[22] The clear implication was that ARPA management had not pushed the IDLs toward being truly interdisciplinary and also that the universities hadn't accomplished this on their own. However, given the political climate of the times, NSF probably could get away with such a push without a strong backlash, but DoD could not.[23]

Another extensive review of the IDLs-MRLs (including also the AEC and NASA laboratories) was made a few years later by the National Academy's Committee on the Survey of Materials Science and Engineering (COSMAT).[24] This evaluation concluded that the IDLs had been successful in:

- Drawing "attention to the emergence of coupled materials science and engineering as a new interdisciplinary focus of activity in a way which could not have been achieved otherwise."

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[20] Ibid., p. VII-28.

[21] Several AOs transferring the IDL programs began with AO 2044 of December 1971.

[22] Schwartz, op. cit., p. 40-41.

[23] In fact NSF accepted the transfer somewhat reluctantly and because of a White House edict. The transfer also caused organizational changes at NSF. Stevens, op. cit.

[24] COSMAT, Vol. III, National Academy of Science, 1975.

- Demonstration "that block funding is perfectly feasible on a campus."
- Development of "excellent research groupings of faculty members, the building-up of a reputation and attraction for good students, and the training of first-rate materials scientists, physicists, chemists, and other professionals."
- Administrative efficiency achieved "through faculty saving their time in writing proposals and seeking support, and the agency officials likewise saving a great deal of administrative time."
- "A large number of students were trained in an excellent environment for advanced degrees."

On the negative side, the Academy report found a limited number of joint publications, taken as evidence of a lack of truly interdisciplinary effort at the IDLs and pointed out that the number of graduates in materials sciences had seemed to rise over the years since establishment of the IDLs at about the same rate as did those in other engineering areas. One objective of the ARPA program had been to increase the number of materials graduates more rapidly than in other fields. COSMAT added, however, that the characteristics of education in the materials fields had changed, and that its quality had improved.

However, about the same time as the COSMAT report, NSF also commissioned a study by MITRE to examine the publications for IDLs with respect to those of directly-funded investigators. The conclusion seems to have been that publications from the IDLs-MRLs had a generally high quality with a larger number of major accomplishments at MRLs than at non-MRLs.[25]

A deficiency of these reviews due to the widespread impact of IDLs on the universities has been pointed out by R. Sproull:

> In the Mitre and NSF reviews of the IDLs, some attention, but not enough, was paid to the movement of the rest of the academic world. Many institutions which were unsuccessful competitors for the ARPA program established interdisciplinary materials laboratories of their own. When comparisons of the IDLs were made with the non-IDL schools, it was impossible to account for the changes at those latter schools which were brought about in order to compete with ARPA schools and because "materials" as a discipline was given credibility by the ARPA program.[26]

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[25] Schwartz, op. cit., p. 44.

[26] R. Sproull, op. cit.

Between 1972, when the transfer took place, and 1975, the time of the MITRE study, the number of faculty involved in IDLs-MRLs had shrunk, along with their funding, from 600 to 532, and by 1985 there were only 400 active.[27] NSF has also added five new MRLs at different universities and closed seven of the old ones. The stronger institutions, however, have persisted in this competition.[28]

In 1968, a separate ARPA materials program began to expand in specific areas, including non-destructive evaluation, optical materials for lasers, rare earth magnetic materials, superconductors, fracture mechanics, rapid-solidification technology and semiconductors. Some of these are described in other chapters in this volume. During and after the transfer of the IDLs to NSF, and in line with its new orientation to support specific materials areas, ARPA supported sizable efforts in some of these areas at the IDLs for a few years.[29]

In 1987 a 25-year MRL symposium was held at the National Academy, with a published volume of the proceedings.[30] In addition to historical articles about the IDLs-MRLs, the volume presents a valuable review of the materials area as of that date. However, in one of the articles providing perspective on the relations of materials research and the corporate sector, Dr. H.W. Paxton, then of U.S. Steel, recounts that his query to colleagues in industry about the impact of the MRLs brought the answer that they could not think of anything that affected their current concerns.[31]

While NSF support for the MRLs continues, more recently there have been new types of related "interdisciplinary" programs funded, such as the University-Industry Centers, Engineering Research Centers, and the Materials Research Groups, a kind of intermediate "thrust" oriented activity between the MRLs and individual investigation support.[32]

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[27] Ibid., p. 41.

[28] D. Stevens, op. cit.

[29] Examples are AOs 2442, 2470 of 1/73 and 2488 of 3/73. Details of some of these specific efforts are given in other chapters in this volume.

[30] *Advancing Materials Research,* op. cit.

[31] Ibid. p. 362.

[32] Schwartz, op. cit., p. 48.

D. OBSERVATIONS ON SUCCESS

The IDLs were established in response to a DoD assignment, making ARPA responsible for the major part of a national program to strengthen academic capabilities in the materials area. The assignment came from an appreciation of the key importance of materials to many important military projects, and of the need to have more people educated in this area in an "interdisciplinary" way, as a fundamental step toward obtaining the desired level of national capability. The rapidity of ARPA actions in setting up the IDLs resulted from close relations, at the time, of many of the key players in upper levels, and in good use of expert advice. There was an immediate and strong impact on the universities in the material fields. While the IDLs did not constitute the sole materials-related effort at ARPA, in 1960-68 they were its largest part. The early statement of the program objective, to directly obtain advanced key materials and characteristics, was quickly replaced by one expressing the broader perspective of establishing the national capability to move toward these and other needed advances in the future.

While NASA and AEC eventually also participated, the major role in this national program was played by ARPA. To get the Universities' cooperation ARPA had to make a virtual commitment to a 10-year program while having legally only a 5-year contract span, which was partly circumvented by the size of the initial contracts and their 5-year contracts each year.[33]

Later, there were difficulties when some of the original "national crisis" atmosphere had faded, and there were pressures on the one hand from the DoD to push toward DoD-related applications during the Vietnam era, and from academia on the other to appear "free" of such applications.[34] Conscious of its commitment and of the value of the national program, ARPA appears to have "kept the course" until NSF took over. NSF, which initially chose not to be involved required some White House-level pressure to take over responsibility. However, the transfer to NSF took about 3 years, about the same time as required for other DoD programs to be taken over by that agency.[35]

The NSF pre-acceptance review appears to have been critical of ARPA management (and of the universities') in that the specifically interdisciplinary aspect of the IDLs hadn't developed as rapidly as it should. However, given the climate of the times it is difficult to

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[33] Sproull, op. cit., p. 32.

[34] In 1972, when NSF finally took over the IDLs, ARPA also became DARPA, the Defense Advanced Research Projects Agency.

[35] Other examples included ARPA's ARECIBO Observatory and ONR's STRATOSCOPE.

see how ARPA could have pushed the Universities much during these years. NSF, with a non-military flavor, could do so and have it accepted. NSF had to do some reorganization to deal with the MRLs. In the same period NSF also had to reorganize to carry out their own efforts toward applications programs with broad social impact: IRRPOs, and later RANN. NSF has since become much more occupied with related questions of applied research at the Universities. The IDLs/MRLs were one of the early pushes toward academic and educational transformations, which are still widely discussed and tried out in various forms.

The objective of increasing the number of materials science graduates having at least something of an interdisciplinary background was achieved during the ARPA program, and these graduates were quickly involved in many areas where they were needed. About 3,000 PhDs have been produced by the IDLs and MRLs.

It is difficult to trace any very specific impact of the research at the IDLs on industrial or military materials work. However, it must be recognized that the very existence of a mature and operating interdisciplinary materials philosophy at universities (trickling down to industrial and government laboratories) forms a much more efficient and receptive framework for accomplishing DoD contract research. While the effectiveness of this framework is hard to quantify, it is instructive to note a recent survey of DARPA and NSF staff members.[36] This survey identified examples of materials research advances which were believed to have been difficult or infeasible to achieve under the traditional disciplinary project support. Some of the early examples listed were organic metals, splat cooling, ultra-low temperature technology, phase transitions, on polymers, lithium riobate for laser harmonic generation and fiber-organic composites.

The current NSF outlay for MRLs is about $25 million per year. ARPA's outlay for IDLs between 1960 and 1972 was about $158 million. To 1989 NSF has spent approximately $350 million on the IDLs.

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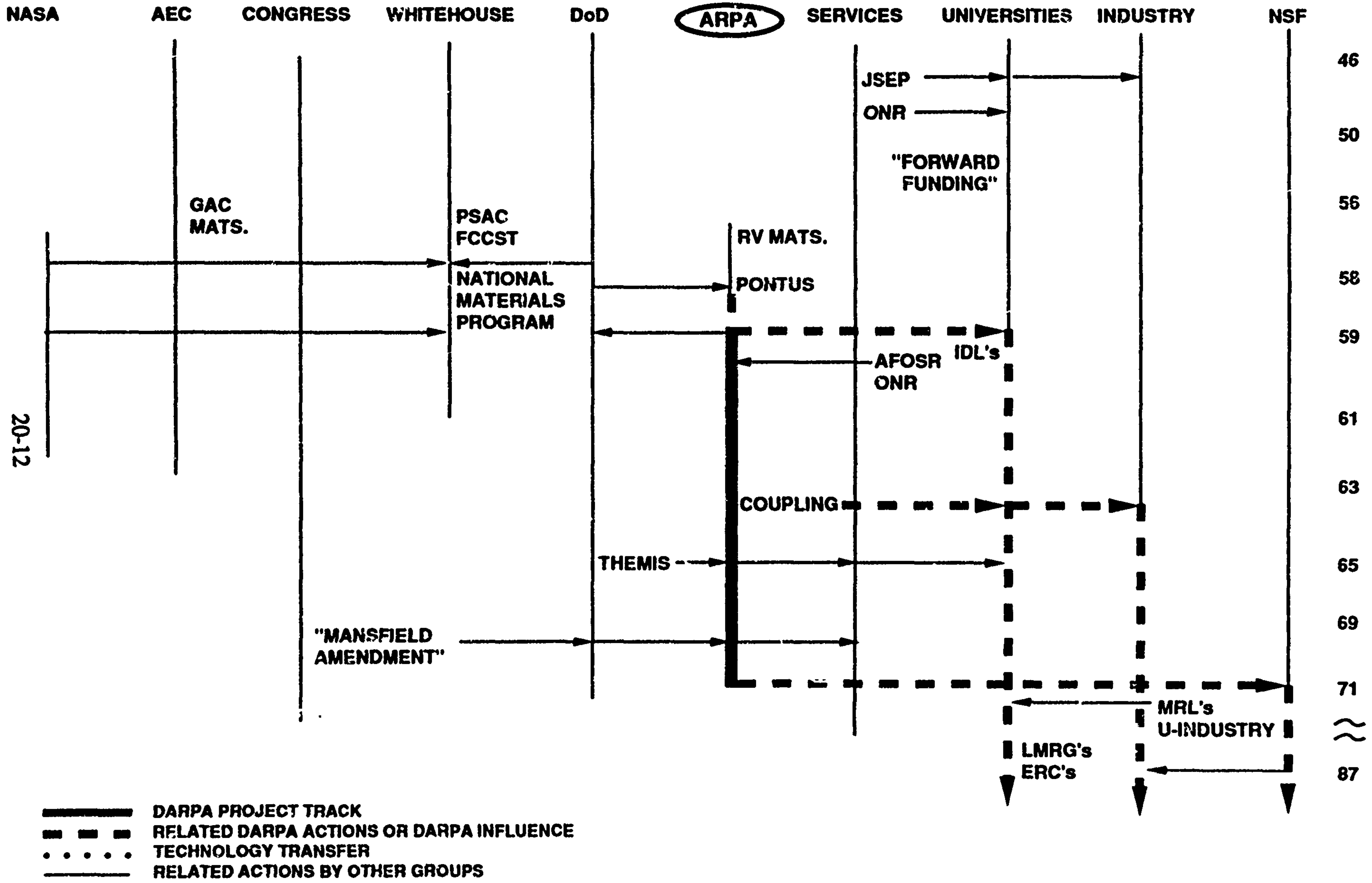
[36] Unpublished. Performed by Dr. Martin Stickley, former director of the DARPA Materials Sciences Office, under the auspices of Dr. Ben Wilcox, presently heading the DARPA materials Sciences Division.

IDL's



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XXI. F-100 ENGINE RETIREMENT FOR CAUSE

A. BRIEF OVERVIEW

In the mid-1970s, DARPA and the Air Force Materials Laboratory (AFML) started a joint project to develop quantitative non-destructive materials testing and/or evaluation (NDE) techniques. In the late 1970s DARPA provided major funding for a study to develop a new methodology termed "Retirement for Cause" (RFC), which involved a novel integration of the new NDE developments with probabilistic fracture mechanics, logistics, and economics, as part of a joint program with the Air Force to establish the basis for a major change in maintenance procedures for the Pratt & Whitney F-100 aircraft engine. The Air Force is now using the RFC methodology for its maintenance and logistics related to the F-100 engine, and has also incorporated RFC into its standards for all Air Force aircraft engine design and maintenance.

B. BACKGROUND

In the early 1970s DARPA began to support several efforts in the technology area of materials failure by fracture, and in related techniques for non-destructive test and evaluation (NDE).[1] The objective was to make NDE a quantitative, rather than a mainly qualitative technique as it had been up to that time. Part of the basis for quantitative NDE was available since previous research had developed an understanding of the deterministic mechanics of crack propagation as related to cycles of applied stress in metals and alloys. The main uncertainty in predicting materials failure seemed to be in the ability of NDE to reliably detect and measure small crack-initiating flaws. A depiction of the sequence of events in a typical crack-induced failure is given in Figure 21-1.[2]

A strong motif for a broad intensification of DoD efforts in this area was provided by the crash of an F-111 aircraft in the early 1970s due to crack-induced failure of a wing

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[1] E.g., AO 1576 of 1/70 for surface crack propagation, AO 2083 of 3/72 for low-cycle fatigue investigations, AO 2481 of 2/73 for metal fatigue and fracture, and AO 2485 of 3/73 for stress-corrosion cracking. Some related work was also supported on low-temperature armor embrittlement.

[2] Taken from "Engine Component Retirement-for-Cause," John A. Harris, Jr., AFWAL-TR-87-4069 August 1982, p. 4.

pivot. This led to a build-up of related work at the AFML at Wright Patterson Air Force Base. A proposal made by AFML[3] was supported by DARPA for a broad joint effort on "flaw acceptance criteria," emphasizing NDE investigations.[4] An important feature of this joint AFML-DARPA effort was a series of yearly workshops on quantitative NDE, which provided a scientific forum in related areas as well as a means to monitor progress. Participants in these workshop/reviews included contractors in the NDE program from academic institutions, government laboratories, and others from U.S. and foreign research institutes. The workshops also attracted others engaged in related efforts including some from institutions supported by the Atomic Energy Commission (AEC) who were engaged in a large effort to develop methods to estimate the probability of accidents at nuclear power plants.[5] The Air Force-DARPA workshops helped focus NDE-related research, which initially emphasized ultrasonic methods and their theoretical interpretation but included also electromagnetic and other methods for quantitative measurements of small cracks.[6]

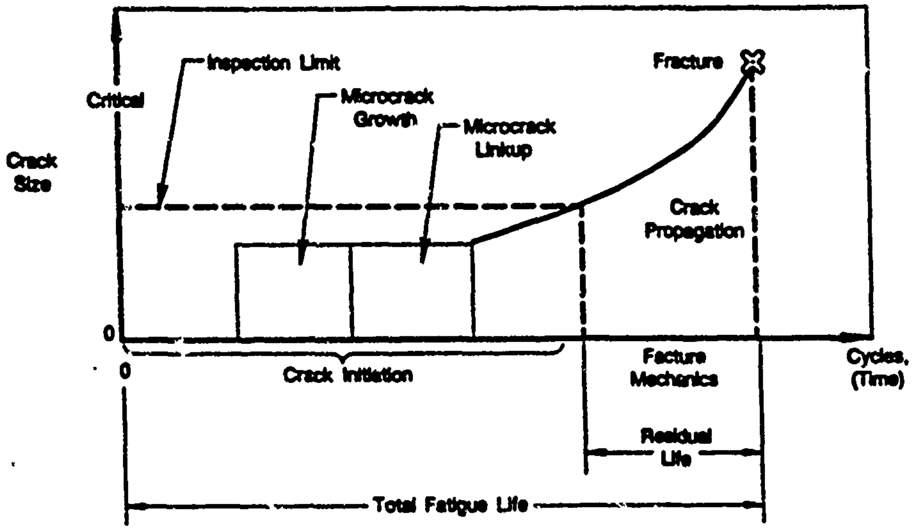

Figure 21-1. Total Fatigue Life Segmented Into Stages of Crack Development, Subcritical Growth and Final Fracture (from Harris op cit.)

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[3] AFML became the Materials Laboratory of the Air Force Wright Aeronautical Laboratories (AFWAL) in 1980.

[4] AO 2828 of AFMD, of 7/74, "Flaw Acceptance Criteria."

[5] WASH-1400, USAEC 1974, the "Rasmussen Report," A. Bement, who became head of DARPA's materials effort in the mid-70s, had previously worked in this area.

[6] E.g., Comments by M. J. Buckley, DARPA, and J. Moyzis, AFWAL, in "Proceedings of the DARPA/AFWAL Review of Progress in Quantitative Nondestructive Evaluation," Technical Report AFWAL-TR-81-4080, 1981, p. 5.

In the late 1970s, besides the continuing joint efforts with AFML, DARPA supported several additional related topics, including NDE standards, component life prediction technology, and a prototype NDE testbed.[7] However, after 5 years, in 1979, a number of techniques from the DARPA NDE effort were apparently considered "transferred," and DARPA faced a decision about reduction of its NDE budget and turnover of more of the program to the Services.[8]

C. RETIREMENT FOR CAUSE

The concept of applying the combined technologies of fracture mechanics, stress analysis, materials characterization and test, non-destructive evaluation, probabilistic risk assessment, and, eventually, logistics and economics analysis, to the problem of maintenance of aircraft engine components grew out of AFML and Air Force Aeropropulsion Laboratory (AFAPL) in-house research and development, in the early 1970s.[9] Pratt and Whitney (P&W), the makers of the F-100 engine which came into operational use in the F-15 in the early 1970s, initiated a similar internal effort at about the same time as AFML[10] under corporate, IR&D, and Air Force sponsorship. In 1975 a joint AFML, AFAPL, and Aeronautical Systems Division (ASD) study of the third stage turbine disk of the TF-33 engine showed that such an integration of technologies could provide for a major change in existing maintenance philosophy and procedures, now called "Retirement for Cause" (RFC).[11] In this and the P&W internal efforts, attention centered on rotating components that were made of special alloys and were costly and "fracture critical" (i.e., failure of one such component could result in a power failure in a single engine aircraft).

A good statement of the problem addressed by RFC, and of the expected benefit of implementing it, was made by the P&W group:[12]

> Historically, methods used for predicting the life of gas turbine engine rotor components have resulted in conservative estimation of useful life. Most rotor components are limited by low cycle fatigue [LCF], generally

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[7] AOs 3374 of 2/77, 3400 of 4/77, and 3556 of 1/78.

[8] M. Buckley and P. Moyzis, op. cit.

[9] Harris, op. cit., p. 6.

[10] Ibid.

[11] "A Retirement for Cause Study of an Engine Turbine Disk," by R. Hill, et al., AFWAL-TR-81-2094, Nov. 1981.

[12] "Engine Component Retirement-for-Cause," by C. G. Annis et al., in the DARPA/AFWAL Review, Ref. 5, p. 12.

> expressed in terms of mission equivalency cycles. When some predetermined cyclic life limit is reached, components are retired from service.
>
> Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase [see Figure 21-1 above]. Engine rotor component initiation life limits are analytically determined using lower bound LCF characteristics. This is established by a statistical analysis of data indicating the cyclic life at which 1 in 1000 components, such as disks, will have a fatigue induced crack of approximately 0.03 inch length. By definition then 99.9% of the disks are being retired prematurely. It has been documented that many of the 999 remaining retired disks have considerable useful residual life. Retirement for Cause (RFC) would allow each component to be used to the full extent of its safe total fatigue life, retirement occurring when a quantifiable defect necessitates removal of the component from service. The defect size at which the component is no longer considered safe is determined through non-destructive evaluation (NDE) and fracture mechanics analyses of the disk material and the disk fracture critical locations, the service cycle and the overhaul/inspection period. Realization and implementation of a Retirement for Cause Maintenance Methodology will result in system cost savings of two types: parts which would be retired and consequently require replacement by new parts; and indirect cost savings resulting from reduction of use of strategic materials, reduction in energy requirements to process new parts, and mitigation of future inflationary pressure on cost of new parts.

The RFC objective was to utilize safely the full "life capacity" of a component, not to extend that life.

However, to achieve RFC required substantial investment and effort toward integration of NDE with fracture mechanics, economics, and logistics. The agreement that the payoff from RFC might be very high seemed persuasive, and in 1979 the Air Force and DARPA joined to start a technical program at AFML, to demonstrate RFC on the P&W F-100 engines. The F-100 engine was chosen because there were many of them in the field (in excess of 3,200 by 1987), some of the components were scheduled for retirement under existing maintenance procedures, and logistical support of this high performance augmented turbofan engine was a significant cost to the Air Force. As a first step in this program DARPA funded a P&W study entitled "Concept Definition: Retirement for Cause of F-100 Rotor Components."[13] This study estimated return-on-investment (ROI), evaluated risks, and established the need for a probabilistic approach to the analysis of component useful lifetimes.

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[13] Harris et al. TR-87-4069.

The results of this P&W study and of a parallel internal AFML study was briefed to a high level Air Force-DARPA review committee. This committee agreed that if DARPA would provide major support for a more complete RFC methodology study, and if the results would confirm those of the preliminary ROI study, the Air Force would undertake the effort required for the logistics implementation for the F-100 engine.

Accordingly, along with the mainly DARPA funded methodology studies, the AFML established a major thrust towards reduction of RFC for the F-100 engine to operational Air Force logistics practice by 1986.[14] An integrated development plan for RFC was set up, with participation from several Air Force commands and including the major engine contractor P&W and several other organizations, together with provision for independent review. Included in this thrust was a Manufacturing Technology effort for an NDE system for RFC of gas turbine engine components (RFC/NDE), and eventual participation by the ASD and the Air Force Logistic Command (AFLC) in the implementation of RFC at San Antonio Air Logistics Center (SAALC).

DARPA support and development of RFC methodology included the following: a systematic approach to probabilistic life analysis; review and expansion of the related fatigue and fracture mechanics technology base; validation of the methodology by laboratory testing of specimens, subcomponents and components; correlation with engine testing and F-100 operating fleet experience; selection of F-100 components; economic analysis of the benefits and risks, and evaluation of RFC for other engines.[15] This P&W accomplished in several phases, under a contract managed by Dr. Reimann at the AFML.[16]

In the first phase of the P&W RFC effort a probabilistic life analysis technique (PLAT) was developed which embodied a computer program model integrating NDE and materials test statistics, fracture mechanics, stress and fatigue information, and engine component maintenance management.

A simplified depiction of the type of result from a typical PLAT analysis is given in Figure 21-2, which shows generic life cycle cost versus crack "propagation margin": the ratio between crack propagation life to the "return to service interval" (RTS) adopted in

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[14] Harris, ibid., p.7.

[15] AO 3993 to AFML, F-100 Retirement for Cause Methodology of 4/80. Cf., AFWAL, TR-87-4069, p. 23.

[16] "Engine Component Retirement for Cause," AFML Contract No. F33615-80-C-5049.

maintenance procedures.[17] Since the F-100 engine has modular construction, the RTS will differ for the components from different modules. Since there are now 5 different versions of the F-100 and 5 modules for each, the PLAT analysis is quite complex. PLAT results defined levels of risk that could then be used in life cycle cost/risk analyses for different maintenance strategies.

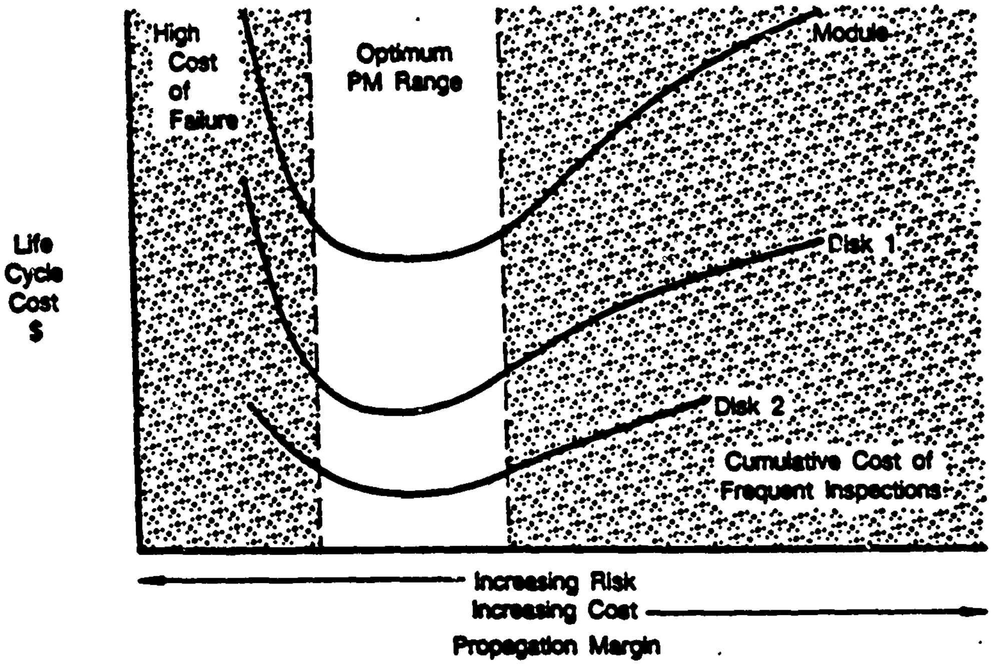

Figure 21-2. Propagation Margin Is Determined from an Economic Balance Between High Cost of Failure and Cumulative Cost of Frequent Inspection/Overhaul[18]

In the second phase of the RFC effort, extensive laboratory testing of materials, specimens, components, and subcomponents was performed to further verify the analysis done in Phase 1. Much of this testing was done in cooperation with other Air Force programs concerned with the F-100 engine. Among the main cooperative efforts was the F-100 Components Improvement Program (CIP) in which accelerated mission test data were obtained using a full F-100 engine to validate both the fracture mechanics analysis used in RFC and the use of smaller specimens to obtain statistical failure data. These were the only F-100 engine test data obtained by RFC, but the results were considered to

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[17] AO 2828 of AFMD, of 7/74, "Flaw Acceptance Criteria."

[18] Ibid.

validate the use of specimens and individual component laboratory tests for the remainder of Phase II efforts.[19] In general, the statistical data from the subcomponent and specimen tests indicated that the fracture mechanics applied in PLAT was conservative. Other F-100 programs such as the "F-100 engine structural diversity and damage tolerance assessment program" which began in 1978, also contributed data useful for RFC component analysis.[20]

The Phase II efforts of this P&W RFC contract included a large effort to validate and, where necessary, further investigate the technology in PLAT. The investigation included: obtaining statistics on crack propagation variability; the investigation of large crack initiation by linkup of multiple smaller cracks: thermal effects on crack growth, since the assumptions for PLAT were based on isothermal fracture mechanics; the validity of extrapolation of large crack growth rates to small cracks; the effects of high cycle fatigue, caused by vibratory response, superimposed on low-cycle fatigue; effects of materials quality and characteristics on crack initiation; and stress histories as related to mission profiles, which were notably different for the F-15 and F-16, both of which used the F-100 engine.

In addition, work towards defining the NDE hardware to be used in F-100 RFC was undertaken by the Air Force's manufacturing technology (Man Tech) program. This involved two stages, the first defining the NDE module and techniques for analysis of its results, and the second in actual fabrication and evaluation of the NDE modules. Currently, the NDE applied in RFC is predominantly electromagnetic rather than ultrasonic.[21]

RFC is now implemented by the Air Force logistic command for the F-100 engine and its modifications now in, or beginning, service.

Estimates have been made of F-100 life cycle cost savings due to RFC by several groups attempting to make the most objective judgment possible. The consensus has been that the life-cycle savings due to parts reduction, and in the time involved in maintenance, totals more than $1.2 billion.[22] In addition, due to RFC there are substantial savings of

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[19] Harris, op. cit., p. 10.

[20] Ibid., p. 19.

[21] Discussion with Don Thompson, 9/90.

[22] Harris, op. cit., p. 46.

thousands of tons of critical materials such as cobalt, used in some rotating component alloys.

In addition to the life cycle cost savings in the F-100 engine program, the RFC demonstration has provided enabling technology for the Engine Structural Integrity Program (ENSIP), defined by Military Standard 1783 (USAF). ENSIP "provides the basis for establishing requirements, criteria, and methods for the design"[23] of all future Air Force engines. Included in ENSIP is the requirement to determine crack propagation life in design, and to establish NDE inspection criteria. ENSIP is applied in the initial design and development phase of an engine program. Retirement for cause is applied during the in-service operational use phase of an engine system.[24] The net result of using RFC technology in ENSIP can result in cost savings many times the cost saving calculated for the F-100 engine.

DARPA expenditures for RFC were about $7 million. Earlier related outlays for NDE and related work were about $6 million. The Air Force outlays for later phases, including those from Man Tech, appear to have been about $100 million. As mentioned above, the estimated F-100 life cycle savings were about $1.2 billion. The dollar value of the critical materials savings associated with RFC has not been estimated.

D. OBSERVATIONS ON SUCCESS

"Retirement for cause" seems to have been an Air Force initiative. It was based, however, on the development of quantitative NDE techniques, which was greatly assisted by a predominantly DARPA-funded joint NDE program. This DARPA effort made NDE a quantitative, rather than qualitative technique, and put it on a much firmer scientific basis. However, after some 5 years of this program, DARPA was considering dropping the area, and it seems to have been an AFML initiative to propose RFC as a major application of NDE to aircraft engine maintenance. The AFML group felt it was important to get DARPA involvement in order to make progress--the RFC idea was apparently regarded by many as quite risky, and involved a considerable up-front expense to develop a usable methodology. If implemented, it involved a major change of maintenance philosophy and procedure. DARPA's first action was cautious and prudent: to fund a preliminary study at P&W of expected return on investment of RFC applied to the F-100 engine.

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[23] Harris, TR-87-4089, p. 18.

[24] Ibid.

The results of this P&W ROI work and of a parallel AFML study were briefed to a high-level Air Force-DARPA review committee, who agreed that DARPA would provide major support for a more complete RFC methodology study, and the Air Force would take responsibility for the follow-on efforts required for implementation.[25] The Air Force was able to make this commitment because it had control of the F-100 from acquisition through maintenance and operations use. The cost savings estimated from RFC were very attractive to the Air Force at the time, and have apparently been borne out in practice.[26]

The methodology developed with DARPA support remains the basis for the RFC program that has been put into effect by the Air Force. It is considered very unlikely by key Air Force participants that the Air Force would have undertaken RFC without DARPA's involvement. Other experts in applications of NDE consider that the RFC development was a major innovation at the time, which has encouraged further developments such as the recent national thrust under the Deptartment of Commerce's National Insitute for Science and Technology toward integrating a wide range of materials design, test, and manufacturing.[27]

RFC did not involve materials development. It included an effort to make more quantitative statistical characterization of fracture of well known alloys. RFC depended on a demonstrated ability to make reliable quantitative measurement of small cracks, which was the basis for the application of fracture mechanism in a probabilistic sense. About the same time as RFC, other probabilistic fracture mechanics was beginning to be applied to several other important systems (e.g., the BIA) and to estimation of failure of reactor pressure vessels by the AEC.

While RFC at first was integrated into ENSIP, for example, by using the ENSIP-determined RTS intervals rather then using those determined by RFC, as time went on ENSIP in turn adapted to and used the RFC data to change these intervals. The success of RFC for the F-100 has led the Air Force to write the procedure into its ENSIP standards for all Air Force engine design and maintenance management.

While RFC has encouraged further applications of NDE, it does not seem to have been as yet adopted by the Navy or commercial airlines. In the latter case, stress cycles are

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[25] Discussion with J. Henderson, 7/90.

[26] Discussion with J. Harris, 8/90.

[27] Discussion with H. Yolken, 8/90.

much more limited than in military engine usage, and commercial aircraft engines are apparently not regularly inspected as the Air Force does for its engines.[28]

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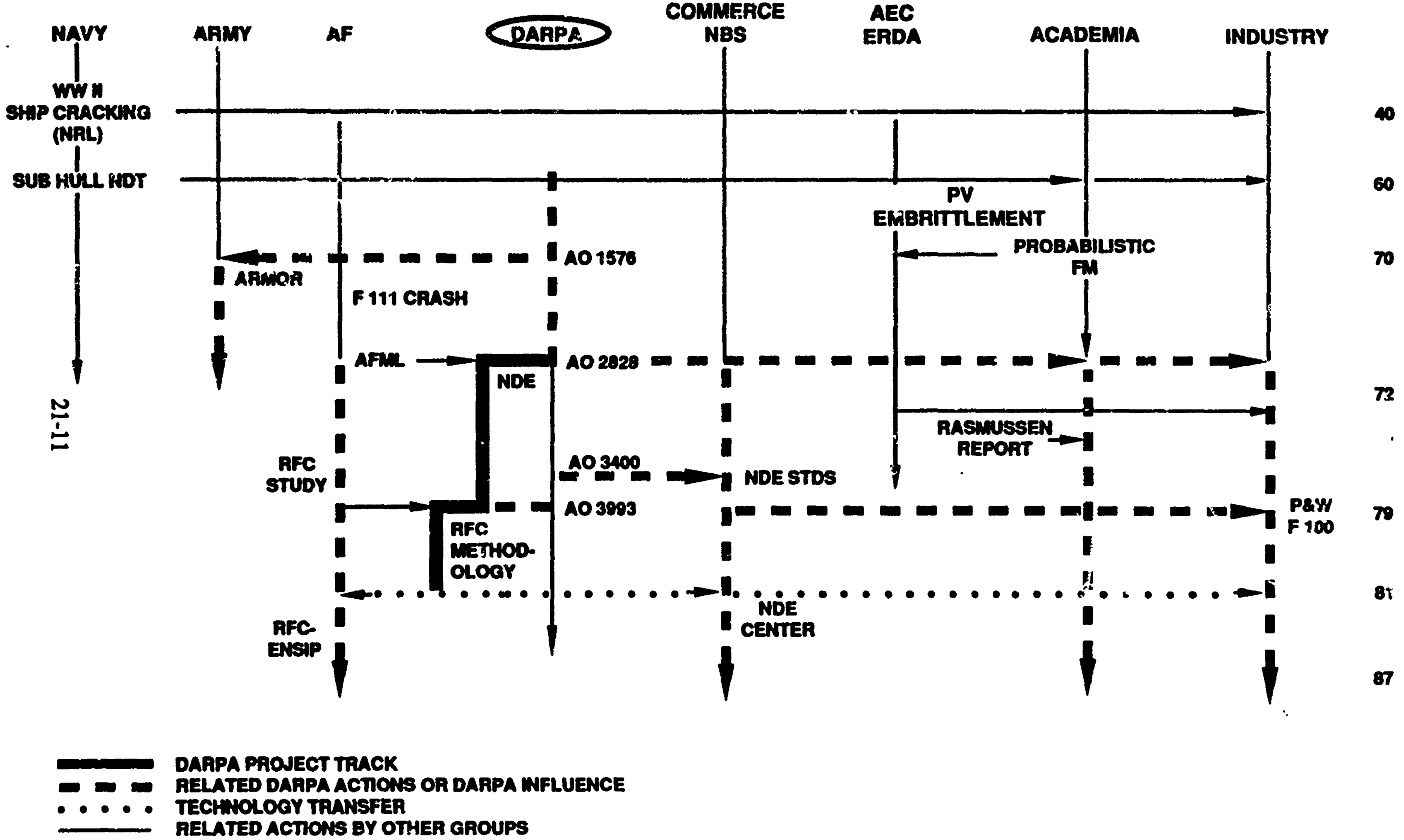
[28] Discussion with J. Henderson, 7/90.

F-100 ENGINE RFC



9-25-90-1M

GLOSSARY

ABM	anti-ballistic missile
ABRES	Advanced Ballistic Reentry Systems
ACCAT	Advanced Command and Control Architecture Testbed
ACVC	Ada Compiler Validation Capability
ADAR	Advanced Array Radar
ADST	Advanced Distributed Simulation Technology
AEC	Atomic Energy Council
AFAPL	Air Force Aeropropulsion Laboratory
AFHRL	Air Force Human Resources Laboratory
AFLC	Air Force Logistics Command
AFML	Air Force Materials Laboratory
AFWAL	Air Forced Wright Aeronautical Laboratory
AI	artificial intelligence
AIE	Ada Integrated Environment
ALCOR	ARPA Lincoln C-band Observable Radar
ALS	Ada Language System
ALTAIR	ARPA Long Range Tracking and Instrumentation Radar
ALV	Autonomous Land Vehicle
AMR	Atlantic Missile Range
AMRAC	Anti-Missile Research Advisory Committee
ANSI	American National Standard Institute
AOA	Airborne Optical Adjunct
AOSP	advanced on-board signal processor
ARAP	Aeronautical Research Associates of Princeton
ARC	Acoustic Research Center
ARPA	Advanced Research Projects Agency
ASAS	All Source Analysis System
ASD	Aeronautical Systems Division
ASMS	Advanced Strategic Systems (Program)
ASP	Advanced Signal Processor

ASUPT	Advanced Simulator for Undergraduate Pilot Training
ASW	Anti-submarine Warfare
ATAC	Advanced Technology Assessment Center
ATACMS	Army Tactical Missile System
ATGM	anti-tank guided missile
AWACS	Airborne Warning and Control System
BETA	Battlefield Exploitation and Target Acquisition
BICES	Battlefield Information Collection and Exploitation System
BIM	BETA Interface Module
BMD	ballistic missile defense
BMEWS	Ballistic Missile Early Warning System
BRL	Ballistic Research Laboratory
BSRO	Behavioral Science Research Office
CAD	Computer Aided Design
CAE	computer aided engineering
CCMRD	Coordinating Committee on Materials R&D
CECOM	(Army) Communications and Electronics Command
CELT	Coherent Emitter Location System
CFV	Cavalry Fighting Vehicle
CHAALS	Communications High Accuracy Airborne Location System
CIG	computer image generation
CIP	Components Improvement Program
CM	Connection Machine
CMR	Center for Materials Research (Stanford)
CORCEN	correlation center
COSMAT	Committee on the Survey of Materials Science and Engineering
CPU	central processing unit
CRT	Cathode Ray Tube
CTO	Cybernetics Technology Office
DAMP	Down Range Anti-Ballistic Measurement Program
DARPA	Defense Advanced Research Projects Agency
DCA	Defense Communications Agency

DD	Differential Doppler
DDR&E	Director of Defense Research and Engineering
DMA	Defense Mapping Agency
DME	Distance Measurement Equipment
DSB	Defense Science Board
ECCM	electronic counter-countermeasure
ELINT	electronic intelligence
ELS	Emitter Location System
ENIAC	Electronic Numerical Integration and Calculator
ENSCE	Enemy Situation Correlation Element
ENSIP	Engine Structural Integrity Program
ERDA	Energy Research and Development Agency
ESD	(Air Force) Electronic System Division
FCST	Federal Council for Science & Technology
FEBA	forward edge of battle area
FIPS	Federal Information Processing Standard
FME	Fixed Mobile Experiment
FOFA	Follow-on Forces Attack
GAC	General Advisory Committee
HALE	high-altitude long-endurance
HAPDAR	Hard Point Demonstration Array Radar
HAPDEC	hard point decoy
HASP	Heuristic Adaptive Signal Processing
HIBEX	High Booster Experiment
HIMAG	High Maneuverability Gun
HOLWG	Higher Order Language Working Group
HRRO	Human Resources Research Office
HSTV/L	High Survivability Vehicle Technology (Light)
ICBM	intercontinental ballistic missile
IDA	Institute for Defense Analyses

IDL	interdisciplinary materials laboratory
INU	Inertial Navigation Unit
IOC	initial operational capability
IOS	instructor operator stations
IPTO	Information Processing Techniques Office
IR	infrared
IR&D	industrial research and development
IRBM	Intermediate Range Ballistic Missile
IUA	Image Understanding Architecture
IUS	Image Understanding System
JDR	Journal of Defense Research
JPO	Joint Program Office
JSTARS	Joint Surveillance and Target Acquisition Radar System
JTACMS	Joint Tactical Missile System
JTF	Joint Tactical Fusion (Program)
JTF	Joint Task Force
KMR	Kwajalien Missile Range
KREMS	Kiernan Reentry Measurements Systems
KTS	Kwajalien Test Site
LAN	local area network
LCF	low cycle fatigue
LHN	long haul network
LLNL	Lawrence Livermore National Laboratory
LOCE	Limited Operational Capability Europe
LRM	language reference manual
MAB	Materials Advisory Board
MAC	Machine Aided Cognition
MARCAS	Maneuvering Reentry Control and Ablation Studies
MARV	Maneuvering Reentry Vehicles
MESFET	metal semi-conductor field-effect transistor
MICOM	(Army) Missile Command

MIRV	Multiple Independently Targeted Reentry Vehicle
MLRS	Multiple Launch Rocket System
MRL	Materials Research Laboratory
MRV	multiple reentry vehicle
MTI	Moving Target Indicator

NSA	National Security Agency
NASA	National Aeronautics and Space Administration
NAVALEX	Navy Electronics Systems Command
NATO	North Atlantic Treaty Organization
NDE	non-destructive evaluation
NMRO	Nuclear Monitoring Research Office
NRAO	National Radio Astronomy Observatory
NRL	National Research Laboratory
NSF	National Science Foundation
NTEC	Naval Training Equipment Center
NTSC	Naval Training Systems Center
NUC	Navy Undersea Center

ONR	Office of Naval Research

P&W	Pratt and Whitney
PARC	Palo Alto Research Center
PIPS	Pattern Information Processing System
PLAT	probabilistic life analysis techniques
PLSS	Precision Location Strike System
PRESS	Pacific Range Electromagnetic Systems Studies
PSAC	President's Science Advisory Committee

R&D	research and development
RBIG	Reentry Body Identification Group
RFC	Retirement for Cause
RHOGI	Radar Homing On-Board Guided Intercept
RISC	reduced instruction set computing
RMP	Range Measurements Program

ROI	return on investment
RPV	Remotely Piloted Vehicle
RTS	return to service interval
RV	reentry vehicle
S&T	science and technology
SAALC	San Antonio Air Logistics Center
SAC	Strategic Air Command
SALT	Strategic Arms Limitation Treaty
SCP	Strategic Computing Program
SAR	Synthetic Aperture Radar
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SFF	Self-Forging Fragment
SIMNET	Simulator Networking
SOI	Space Objects Identification
SOTAS	Standoff Target Acquisition System
SPARC	salable processor architecture
SRAW	Short Range Antitank Weapon
SRI	Stanford Research Institute
STARS	Software Technology for Adaptable Reliable Systems
STO	Strategic Technology Office
TAWDS	Tactical Air Warfare Direction System
TDOA	time difference of arrival
TGSM	Terminally Guided Submunitions
TOA	time of arrival
TOAD	TRADEX Optical Adjunct (telescope)
TO&E	table of organization and equipment
TRADEX	tracking and detection experiment radar
TRADOC	(Army) Training and Doctrine Command
TTGT	Tank Team Gunnery Trainer
TTO	Tactical Technology Office
TTR	Target Tracking Radar

UCOFT	Unit Conduct of Fire Trainer
USAREUR	U.S. Army Europe
VLA	very large array
VTRS	Visual Technology Research Simulator
WAAM	Wide Area Anti-Armor Munitions
WARF	Wide Aperture Radar Facility
WP	Warsaw Pact
WSEG	Weapons System Evaluation Group
WSMR	White Sands Missile Range