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A PROTOTYPE STRATEGY FOR AIRCRAFT DEVELOPMENT

Robert Perry

RAND Corporation

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PREFACE TO REVISED VERSION

This Memorandum was specifically prompted by discussions of the possibility of using a prototype strategy in developing a new tactical fighter for the United States Air Force. The discussions are of 1968 vintage, and the data used here were derived from experiences of earlier years. Some of the practices and policies noted herein were changed in 1969 and after, but even in 1972 the question of when or whether prototypes should be built and what sort of management structure is appropriate to prototype programs continues to trouble the Congress, the Department of Defense, and the aircraft industry.

As originally issued in April 1968, this report contained elements of information then classified and data drawn from sources then considered proprietary. In the intervening years, most of the defense information has been declassified, and the data once held to be proprietary are no longer sensitive. Very minor changes in wording have been made in the course of revision to eliminate a few residuals of each and to ensure stylistic consistency. But in form and substance, this version is almost identical with its predecessor.

As part of RAND's continuing work on research and development policy for the Air Force, this Memorandum should be of particular interest to that part of the research and development community concerned with the management of systems development, with reconciling requirements and the status of technology, and with the selection of weapon systems for eventual procurement.

SUMMARY

This Memorandum examines the conditions that warrant the use of a prototype strategy in the development of military aircraft and evaluates some recent experience, here and abroad, that bears on the issue. A related theme, one more cleanly separable from the theory of prototype use than from its application, concerns the management approach that is most appropriate to a prototype strategy.

The central thesis of the Memorandum is that in certain circumstances it is sensible to build and fly a prototype of an aircraft before finally deciding to produce it in quantity. Such circumstances can occur if the technological risks inherent in the design are substantial and cannot be reduced to manageable proportions by analysis and wind tunnel or ground tests alone, if there is significant uncertainty about the advisability of producing an aircraft or about the requirement for it, or if there is appreciable uncertainty about which is the more desirable of two or more proposed aircraft that have roughly the same mission potential.

The difficulty of deciding when to adopt a prototype strategy arises from the necessity of deciding a priori how substantial are the technological, mission assignment, or source-selection risks. A recent instance of prototype experience in the United States clearly demonstrates that the technological risk can be far greater than anticipated. Experience abroad, particularly in France, supports the proposition that building and flying a prototype can create a useful set of alternatives that encourage the developers to apply a basically good design concept to several rather different operational applications.

In the conduct of prototype programs, there are abundant indications that a policy of austerity in the assignment of resources pays substantial dividends, not only in program costs, but also in focusing attention on crucial uncertainties that should be resolved before production commitments can sensibly be made. Consideration of the available evidence suggests that a prototype strategy can be applied to

many different techniques of aircraft acquisition and that including a prototype phase does not necessarily make the cost or duration of a development program significantly greater than the cost or duration of more conventional development-production programs.

ACKNOWLEDGMENTS

Collection of the illustrative information that forms the central part of this Memorandum was in many respects a joint enterprise in which Robert E. Johnson of The RAND Corporation was an equal partner. The primary thesis, that a prototype strategy is uniquely attractive in some development environments, also owes much to continuing discussions with many colleagues, particularly George R. Hall, Giles K. Smith, Burton H. Klein, and Thomas K. Glennan, Jr. Earlier work by L. L. Johnson laid a foundation on which Burton Klein, T. K. Glennan, G. H. Shubert, and the present author have since built. Helpful and critical comments on an early draft of the manuscript were provided by Arthur E. Raymond, Almarin Phillips, Deane N. Morris, and Richard Schamberg; their suggestions added greatly to whatever merit the Memorandum may have. Faults of fact or interpretation that have eluded such careful scrutiny are entirely the responsibility of the author.

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I. INTRODUCTION

Conventional wisdom has it that a prototype is a redundant and often costly adjunct to the design and development process. This Memorandum considers the proposition that under given circumstances the most effective way of resolving some of the uncertainties of aircraft development is by building and testing a prototype aircraft. It begins by examining the circumstances in which a prototype aircraft program is appropriate or inappropriate; by suggesting, at least in the broad, what uncertainties can be effectively resolved through prototype aircraft development, and what cannot; and by describing the characteristics of an expeditious, efficient, and economical prototype program. Underlying the discussion is the premise that no single specified pattern of behavior can adequately provide for all of the contingencies that will arise in the course of aircraft development.

To many people, the word "prototype" evokes images of the 1930s and 1940s, suggesting the angularity of a biplane, the quaintness of goggles, the texture of varnished linen. But what is being discussed here is something quite different: a tool for lessening technological uncertainty. It might be more appropriate to call that tool _a definition-phase test aircraft_ or perhaps a _demonstrator aircraft_, if only to deter prejudgment. But prudence suggests merely defining the term as it is to be used here and leaving language reform for another occasion.

This Memorandum consists of six sections, one concerned with conceptual matters, another dealing briefly with background, two taking up recent prototype experience, a fifth treating some of the cost and scheduling implications of using prototypes, and a final section summarizing the choices open to development policy-makers and the rationale of various alternatives.

There are at least two dominant themes in any consideration of the use of prototypes in development. One concerns the rationale for using prototypes either as an adjunct to or a substitute for other means of resolving various uncertainties. A second has to do with the proper conduct of development programs; it stems from the proposition that the advantages of using a prototype strategy may be more fully realized if austerity in the expenditure of resources is a guiding principle. Because the more obviously successful prototype programs of the immediate and near past have uniformly been founded on the austerity principle, it has sometimes been difficult to discover whether it is austerity in development or the adoption of a prototype strategy that caused certain aircraft development programs to seem particularly attractive, and whether austerity or a prototype strategy should be recommended, or both, and in what proportions. The adoption of a prototype strategy need not be dependent on the simultaneous adoption of an austere development policy and austerity in development could have advantages in many settings where prototypes would be quite inappropriate. But there are indications that the effective application of a prototype strategy to solving problems of aircraft development is enhanced by adherence to tactics involving developmental austerity. An effort has been made to distinguish between these elements and to avoid entangling a consideration of strategies with an evaluation of tactics; yet to the extent that the supporting evidence bears on the central issue the two themes tend to blend into one another. Like many another characteristic of the real as opposed to the ideal, it is neither easy nor always desirable to separate one characteristic of the development process from others that influence it or are influenced by it.

II. CONCEPTS

The hypothesis from which this Memorandum reasons is that: (1) establishing the detailed configuration of a new aircraft requires many decisions, each difficult, and each dependent on the resolution -- or avoidance -- of uncertainty; (2) the elemental substance of R&D is error and uncertainty, and delay in the detection and correction of error or oversight is a principal cause of inefficiency or ineffectiveness of development; (3) the early resolution of uncertainties in technology, objectives, schedules, and costs is vital, there are various ways of resolving such uncertainties, and a technique of resolution most appropriate to the problem at hand should be chosen; and (4) in some circumstances, which can be defined, the most desirable way of resolving technological uncertainty in military aircraft programs may be to build and test a prototype aircraft.

There are many definitions of "prototype" and little profit in laying them end to end for scrutiny. Basically this Memorandum will consider a prototype aircraft to be an engine-airframe combination approximating, in full scale, the main features of a prospective operational aircraft. Flight tests must yield information that will permit the timely identification and resolution of technological uncertainties and ultimately support a sound decision about the procurement of production aircraft. Owing to the nature of a prototype, it is not very likely that all prospective subsystems will be available as early as the airframe and engine, and it is patently undesirable to hinge total configuration decisions on the behavior of a subsystem that may be supplanted once production has begun.*

*Without belaboring an issue about which many system planners are particularly sensitive, it is useful to recall some data summarized by B. H. Klein in Policy Issues Involved in the Conduct of Military Development Programs, The RAND Corporation, P-2648, October 1962. Klein pointed out that four of six fighter aircraft of the 1950s studied at RAND ended up with engines other than those originally programmed, five of the airframes had to be extensively modified, three incorporated electronic systems different from those scheduled, and three emerged from development with operational roles substantially different

Seen thus, a prototype is a device to moderate some of the uncertainty that characterizes the decision process. Because a prototype is a full scale, flyable representation of what is intended to be in time an operational aircraft, decisions buttressed by experience with prototypes tend to be founded on less tenuous technological grounds than those based on abstract analysis and derived assumptions. Reliance on prototypes appears to be advantageous for four general classes of development decisions. (1) When there is uncertainty about the advisability of producing a given aircraft, testing a prototype will provide reliable information about the attributes of the aircraft and will reduce the quantity and importance of misgivings. (2) When there is uncertainty about which of two similar aircraft to produce, testing prototypes built by two contractors will ease the decision. (3) When there is uncertainty about which aircraft to build of two or more that have been proposed in clearly different configurations, testing prototypes will provide hard information on which a choice can be based. (4) When there is uncertainty about the technological feasibility of a configuration, prototype testing can assist in resolving the main issues.

The matter of whether a prototype program is inherently more or less costly than a program that bypasses the prototype option can be treated, for the moment, as incidental. It is apparent, however, that cost and schedule estimates derived in part from experience with prototype aircraft will tend to be somewhat less uncertain than estimates based solely on analytical predictions of development progress. From the fact that specific uncertainties of technology, configuration, and

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from those initially planned. The only airplane that entered operation with roughly the same technical ingredients and operational assignment specified for it from the start was the F-106 -- which was delivered five years later than scheduled and which was procured in smaller numbers than planned because the F-101, designed for quite another role, was deemed an even better air defense interceptor. In time even that judgment was reversed.

probable mission responsiveness will be moderated by the very existence of a prototype, it may be adduced that a prototype strategy can be used as a means of preserving a production option -- putting off a final decision until requirements or technology are better understood while concurrently working toward that understanding.

It should be clear from the foregoing that prototypes could be used in virtually any development strategy ever conceived except one involving the immediate production of something defined in a design proposal. There is no inherent reason why "total package procurement," for example, should not include a prototype phase if the "total package" decision specified quantities and schedules but made configuration definition a function of an evaluation process following prototype testing. Or, for that matter, "total package" could be interpreted to mean all development and production activity following a definition phase that provided for building and testing prototypes.

It is often assumed, and with considerable justification, that "production prototypes" built on hard tooling capable of supporting at least a moderate rate of quantity production are not prototypes at all, but merely early production aircraft (which may lack some of the non-vital subsystems of operational aircraft) intended for early flight testing. The primary consideration is not so much that the results of flight testing may force expensive changes in tooling, or even that relatively large numbers of aircraft may be built before essential changes can be identified and incorporated at the production-line level, but rather that there are obvious disadvantages to devoutly ministering to production rates during a period when engineering refinement should be the primary concern. Although the costs of retooling or of extensively modifying (or even scrapping) early production articles are extremely important considerations both to budget controllers and to operational forces, they are inherently less important to the quality of the final product than the effectiveness of the development process. Prototypes built on "soft" or "semi-hard" tooling are acknowledged from the beginning to be subject to change. Change is expected, and if not sought for, at least accepted as one of the probable consequences of development. The assumption may not always be stated plainly, but resort to "hard" tooling at the onset of the fabrication phase of a development-production program at least implies that neither the customer nor the producer anticipates making any substantial change to the approved design as a consequence of early flight testing. The producer, who is quite sensibly preoccupied with meeting production schedules he has agreed to, will instinctively resist pressures to change the production article. The customer, who is concerned with satisfying a time-factored requirement, must be equally resistant. Changes, then, tend to be approved only when they are unavoidable; both producer and consumer will go to great lengths to find ways of avoiding them. Such preconditioning affects the reception of changes arising in altered operational requirements as well as those imposed by the need to correct technological defects.

The issue of "soft" versus "hard" tooling was somewhat less confused a decade ago when airplane structures were pretty much of a common breed. It has become a distracting side issue with increasing reliance on sandwich skins, chemically milled panels, and main structures made of materials so peculiar in their properties that they cannot be fashioned on "shop tools." Thus there may be compelling reasons for not using wholly "soft" tooling for some high-performance prototypes. However, so long as the purpose of building a prototype is kept clear in the minds of all those concerned, that factor has no special importance.*

It may also be that some aircraft -- for example, a B-70 or a C-5 -- are so large that reliance on "soft" tooling would be entirely impractical. But in such cases the crucial issues of what to build or whether to build something are unlikely to be put to the test of a prototype program because the investment is so enormous that almost

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*It should not, to consider a special case, be permitted to influence evaluations of analyses of past prototype experience in which the distinction between "soft" and "hard" tool prototypes acquires importance. The evidence strongly suggests that "soft" or "hard" really means "change amenable" or "change resistant."

any alternative way of resolving various uncertainties is likely to prove preferable.

In the end, then, a prototype is built in the expectation of change, and the expectation of change is its only substantial justification. The objective of building a prototype is to discover what changes are necessary -- what decisions must be made -- before a design is committed to production, or to discover if any number of changes will end in a desirable production airplane. Such a characterization does not invalidate the use of prototypes to aid in resolving mission uncertainty or to aid in contractor selection or to contribute to a decision on whether (rather than what) to produce, but it emphasizes the contribution of a prototype to the diminution of uncertainty, whatever the nature of that uncertainty.

From such assumptions arise two principles for the conduct of programs based on the use of prototypes: (1) controlled investment -- that is, obtaining an informational return at an expenditure commensurate with the worth of the information, and (2) defining and limiting uncertainty, which is to say, having the principal features of an aircraft reasonably well defined before undertaking construction. Although planners may squirm at the thought, there is no obvious reason for specifying the detailed operational assignment of an aircraft while a prototype is being built and tested; the question of whether it should have swept or straight wings cannot be put off in the same way.

A prototype aircraft should not be expected to resolve uncertainties that are peripheral to the main purpose of building it, nor should peripheral uncertainties be permitted to dominate a prototype program.* Technical problems that can readily be identified and solved by analysis

*In 1951 the Navy built a prototype variable-sweep fighter, the XF10F, that did precisely what was required of it as regards the variable-sweep feature. But it flew abominably because it also included, gratuitously, a novel and badly designed control system. The program failed thereby. That is a fine example of deferring to peripheral uncertainties.

and subscale testing should not be left to a prototype flight inquiry. Nor should very great technical uncertainties be left for resolution by means of a prototype aircraft. Basic technological feasibility is not an issue that can be satisfactorily resolved at the prototype level; feasibility demonstrations cannot be put off until operational requirements begin to hinge on their success. The problem of identifying "great technical uncertainties" and of distinguishing between problems that can be solved by analysis and those that cannot is a very knotty one. Perhaps it must be approached by way of another general principle: a fully useful prototype is basically a proof-test article suitable for reducing recognized uncertainties.

When the time or urgency of a requirement is in doubt and it is possible to select between two courses, one of study and proposal and the other of build and test, the relative advantages of the two should be very carefully evaluated. If a prototype can be built for not much more than the cost of conducting an extended analysis, a prototype seems preferable because it can be expected to produce more reliable information than a study. And because such information becomes available in advance of a production decision, the lead time between production decision and availability of operational aircraft will presumably be lessened by the amount of "learning time" that would otherwise follow a decision to produce a defined-on-paper airplane. Indeed, the performance of the prototype in flight trials may not only enhance the validity of acquisition decisions, it may also clarify them, as a decision based on an existing prototype will generally contain less residual uncertainty than one based solely on analysis of engineering expectations.

The shortened lead time factor previously mentioned has considerable importance for occasions when the nature or gravity of a threat cannot be adequately predicted. If, for example, planners cannot foresee whether an air superiority fighter or a fighter bomber will be the next TAC inventory requirement, a prototype of each (or even competing prototypes of each) could be justified if (a) one type or the other was reasonably certain to be needed and (b) delaying a start on hardware and test phases might subsequently oblige the USAF to invest in a high-risk "crash" development-production program.* The prototypes would represent first-rate options to be taken up when and if needed. The disadvantage of such an option (as compared with continuing paper studies) is that once in existence it may lose currency as time passes. Such technological aging will be less important if either the technology and performance of the prototype satisfy requirements into a measurable future, or airframe performance itself is subordinate to subsystem performance that may be continually improved. The latter case is of particular importance in an era when airframe performance is improving neither rapidly nor dramatically. Finally, it is also possible that airframe and engine performance can be improved during the period of option retention.

In essence, then, the construction of prototype aircraft can provide a hedge against requirements (strategic) uncertainty. It does so by permitting a more certain resolution of technological uncertainties than can design studies, no matter how elegant they are. The central fact is that under almost any conceivable circumstances the transition from design proposal to first lot of production articles brings on change, and change introduces new uncertainties. Some are uncertainties that can be resolved with no particular difficulty while production continues. <u>The function of a prototype is to permit the early identification of previously unrecognized problems and the resolution of recognized uncertainties that might, if they went undetected, precipitate major changes in the performance, cost, or availability of specific weapon systems</u>.

Adhering to the principles described above would be difficult in any circumstance. It is very difficult today. The pressures for early commitment to production are enormous. The customer (in this instance the Air Force) is conditioned by the ordinary military environment to be less interested in the comprehensive resolution of uncertainty than

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*The premise that prototypes <u>delay</u> development is widely and uncritically accepted. An implicit assumption of the foregoing proposition is that they do not. The question is taken up in greater detail in Sections III and VI.

in the early delivery of operational aircraft. There is a natural tendency to assume that all problems will be little ones. Then, the producer has very little motivation for investing time and money in a prototype. Profits come from production; firms are not paid very well for military development in this country.* Contractors would rather build what are incorrectly called "production prototypes" than "development prototypes," because a "production prototype" implies a strong commitment to production while a "development prototype" represents a proposal of which the faults, if any, are all too evident. Here again, when a "production prototype" is built the producer will be optimistic about the possibility of solving all problems early and, as has been observed, the customer is anxious to believe such reassurances.

These factors encourage a strategy of design competition -- on paper -- followed by formal commitment to build substantial numbers of elaborately defined aircraft. The theory that supports such a strategy is that a comprehensive design effort is unavoidable in any case and that pausing at any point to construct a prototype merely lengthens the program and increases its cost without securing any equivalent benefits. The argument is that engineering problems will be encountered in both cases, but that careful study and design analysis will identify them earlier than will prototype construction. Furthermore, it is widely held that the construction of a prototype leads designers to overlook compatibility problems, to create something that is less than a system and that must be substantially re-engineered before it is ready for production. Although problems of that sort did occur in the 1940s, they have been inconsequential since the widespread adoption of systems analysis techniques in the early 1950s. Moreover, such an argument stems ultimately from the proposition that aircraft should not be constructed until all configuration uncertainties have been resolved and that, as has previously been suggested, is not a very convincing argument against using prototypes.

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*There are exceptions, of course, but it is common for aircraft firms to take on development assignments under relatively unfavorable terms in the expectation of recouping any losses once large-scale production begins.

Neither supporters nor opponents of prototyping have been able to make much of a case from statistical or empirical evidence. Programs that have begun with prototypes differ dramatically from one another and from programs that have begun with the construction of what is intended to be a production aircraft. In this country there were no prototype programs of any consequence for a decade and more before 1965, and evidence taken from experiences of the 1940s and 1950s may have little obvious relevance to the conditions of later decades. Yet recent events have made it apparent that design analysis, subscale testing, and development planning, however thorough, will not of themselves insure that crucial technological uncertainties have been resolved in advance of the flight test of new aircraft.* Specifically, the weight of the F-111, its drag characteristics, and the performance of the engine-airframe combination have not come up to expectations even though extreme precautions were taken in the design and definition phases to insure that all contingencies had been foreseen. The drag characteristics of the C-5A, a subsonic transport certainly well within the bounds of modern design knowledge, failed to conform to expectations. The OV-10A, an aircraft no more than modestly novel, has had to be very substantially redesigned in the wake of disappointing flight tests. The point is that unforeseen and potentially serious design deficiencies have appeared in three contemporary aircraft programs started on the basis of elaborate pre-construction design analysis. And the lesson is that techniques of 1965 were no more perfect than those they replaced.

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*Means of resolving uncertainty are plentiful and several means are often applied, more or less at once, to a single problem. T. K. Glennan, Jr., in Issues in the Choice of Development Policies, The RAND Corporation, P-3153, October 1965, suggests that for military aircraft there are six main techniques of uncertainty resolution: analysis, review of design by specialists, focused applied research, model testing, prototype testing, and production-item testing. He points out that "development policy is concerned with the distribution of effort among these methods of uncertainty resolution, not the choice of one method or another. Prototypes cannot profitably be built without being preceded by analysis and model testing. But if a prototype is built, less analysis and model testing will be required than if the first full scale testing is done on production articles."

III. BACKGROUND

One of the difficulties of dealing with development strategies is that, in the United States at least, whatever is the current doctrine tends to be treated as exclusive. Perhaps that is but a reflection of the peculiar American notion that there is only one right way to do anything, but its application to research and development has had some painful consequences. Until the middle part of the 1930s the ordinary way of introducing a new aircraft model was to build and fly a prototype and, on the strength of test results, decide whether to produce it. Test results were generally interpreted by a prospective customer, an airline or one of the military services. Not uncommonly, the military insisted on competitive "fly-offs." Prototypes were built rather quickly and for little more than the cost of a production aircraft of the same sort -- mostly because they were built by the same people with the same skills and tools and in very much the same way.

When rearmament began in the years before World War II, the practice of using prototypes as the normal entry to development was given up.* Large-scale production, it was assumed, could not accommodate the prototype approach although there was no real evidence that using prototypes delayed operational deployment. The Air Force and airplane companies accepted the premise that given a large enough group of engineers, almost any conventional design could be quickly transformed into a production aircraft. With minor exceptions, the aircraft that fought the war had been designed before it began. Performance improved through piecemeal technology. Urgency of delivery justified any waste incurred by building numbers of imperfect aircraft.

Some unique aircraft incorporating radically new technology were built by most of the major warring nations, but none had any important influence on the course of the war. Moreover, prototypes were

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*Even when prototypes were built production decisions frequently were made before the results of prototype tests became available.

ordinarily authorized and paid for by sponsoring air forces rather than by private firms. Perhaps partly because there was more money to be spent and less concern about spending it, they cost a great deal more than prewar prototypes, both absolutely and in comparison to the price paid for initial production aircraft. But higher costs also reflected the fact that most of them edged farther ahead of the state of the art than prewar prototypes. Disregard of the risk factor caused some to be pushed into production even though it was known that all the technical problems had not been solved.

High development costs and relatively long intervals between concept and operational readiness became characteristic of aircraft programs undertaken immediately after the war. That trend, coupled with cost increases arising from complexity and radically improved performance, encouraged the notion that prototyping itself was in some way responsible for the greater duration and cost of aircraft development projects.

With the start of the Korean War the problem of quickly acquiring very advanced combat-capable aircraft again became dominant. Combining development with production, both conceptually and contractually, seemed one way of compressing the cycle and insuring that what was developed could be rapidly produced. One proposed remedy was "fly-before-you-buy" -- which meant building a small lot of aircraft on production tooling and in what was assumed to be an operational configuration. But early "production" aircraft almost always had to be substantially modified before they could satisfy operational needs. Therein arose the conviction that the injudicious incorporation of high-risk technology in weapon system programs was the prime cause of delayed progress and high costs. To correct such faults, a new strategy was adopted. It was based on the premise that exhaustive preliminary systems analysis, reliance on pre-developed subsystems, and very comprehensive pre-contract system definition efforts would suppress the uncertainties of system development. That philosophy was embodied in the development-production policies of the 1960s.

There is reason to suspect that the summary rejection of the use of prototypes may have been an unwise response to a set of transitory conditions. Still, conviction prevailed over evidence, or its lack, and prototyping alternatives were disregarded. It was widely believed that a fly-before-you-buy approach took at least a year longer than the contract definition, integrated program approach and a competitive prototype approach even longer, perhaps by as much as an additional year. Data to support these assumptions were scant. Most "authorities" held, nevertheless, that programs based on prototypes or fly-before-you-buy were substantially more costly than those involving an intricate technique of define and produce. The additional expense was assumed to arise in the cost of prototyping new subsystems and in the time lapses that occurred between the discrete phases of prototyping and fly-before-you-buy

Some of these premises may be valid, or partly valid, but there is little evidence of it. There is at least as much evidence that the integrated program approach is <u>not</u> inherently less costly than the prototype approach and that there is little to choose between them in the matter of program duration.*

The chief argument against the prototype thesis as it was advanced by Klein, Glennan, and Shubert is that their examples were taken from a period when the present development environment did not exist. The examples they cited seem to be too diverse and too unlike more recent programs. And because there were almost no modern examples of prototypes to examine, and virtually no instances in which direct comparisons of similar aircraft developed by different techniques were attempted, it was difficult to make a case for prototypes.**

Only once between 1945 and 1965 did two different firms use radically different procedures in building two aircraft that were very

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*B. H. Klein, T. K. Glennan, Jr., and G. H. Shubert, <u>The Role of Prototypes in Development</u> (U), The RAND Corporation, RM-3467-1-PR, April 1971.

**That it was therefore equally difficult to make a convincing case for present policies was an inconvenient fact commonly ignored.

nearly indistinguishable to the uninformed eye, designed to the same specifications, and done in the same period. The case of the OV-10A/Charger development is interesting for many reasons. It deserves particular attention because more than almost any other similar event of the 1960s it casts light on the features of prototype development programs.

IV. THE OV-10A AND THE CHARGER

On December 5, 1963, the Department of the Navy issued a Request for Proposal (RFP) covering a light armed reconnaissance aircraft (LARA). The action stemmed indirectly from a Marine Corps requirement of 1961 by way of several contractor-originated proposals and a December 1962 decision that an aircraft particularly suited to Military Aid Program needs should be designed and built. The aircraft was to satisfy requirements for visual reconnaissance, target marking, battlefield illumination, escort and protection of helicopters, destruction of enemy helicopters, limited close air support, and logistics support. The Marines wanted "a light, simple STOL aircraft to support operations ... during and following amphibious landings." Performance requirements included a cruise-speed range extending from 80 to 300 knots and a maximum speed of 350 knots, high maneuverability, 3.5 hours loiter (carrying no external stores), and ability to operate from 500-foot sod fields with 1200 pounds of external stores. Two engines were specified, and there was a considerable emphasis on one-engine operating capability.

Seven contractors responded to the RFP by submitting the customary lot of detailed design proposals. One, Convair Division (San Diego) of General Dynamics, also elected to build a prototype with its own money on the premise that having an actual aircraft to back up its paper proposal might improve its chances of getting the contract. If Convair won the contract and had an aircraft in being, there was an excellent prospect of passing development milestones much earlier than would be the case in a "normal" development program. Under the terms of a fixed-price/incentive contract, the rewards for early satisfaction of program goals were very attractive. Finally, of course, there was the possibility that a contract for three "development aircraft" with options for four more would lead to a profitable production contract, and Convair-San Diego needed such work.

With all its hopes, Convair was not prepared to gamble large sums of money on the prototype. The airplane approved for construction was to be an accurate representation, in scale and flight performance, of what the company hoped the Navy would buy. But it would not incorporate some of the more expensive subsystems essential to an operational aircraft (wheel, brake, and ejection seat development that promised to cost nearly one million dollars was put aside for the moment as no great uncertainties were involved), and the prospective suppliers of other subsystems were invited to share in the risk (engines, instruments, and avionics). It was generally known that the Navy Department had authorization to commit something less than twenty million dollars to the purchase of the first seven aircraft. Engines and major subsystems were included in the total, of course. Convair expected to spend very much less on its prototype.

Convair's management approved the gamble in mid-March 1964, aiming at a first flight in late September of that year. The completed aircraft -- the Model 48, or "Charger" -- was rolled out some six weeks later than scheduled and made its first two flights on November 25. The delay was mostly due to late delivery of engine gear boxes. At the time of roll-out the company's actual cash investment was $1.722 million. During the next eleven months the prototype accumulated 193 hours of flying time, although laid up for modifications during some 25 of the 48 weeks of its flight test program. Pilot error caused its destruction in an October 1965 accident. Funds Convair had invested to that time totalled $3.30 million, the increase reflecting the costs of flight testing and modification.

Shortly before the "Charger" was rolled out of its assembly shop the Navy announced that North American (Columbus Division) rather than Convair had been awarded the formal development contract for what was to be called the OV-10A. The final fixed price agreement, signed on October 15, 1964, called for a total of seven "demonstrator" aircraft. It was apparent that "system prototypes" nearly indistinguishable from production aircraft were wanted. Confidence in that outcome was indicated by the fact that the seven "early" OV-10As were built on "semi-hard" tooling capable of sustaining a four-aircraft-per-month production rate. Convair had built the "Charger" on "soft" tooling -- literally wooden jigs plus a few "L" beam and tube sections.

The first OV-10A flew in mid-July 1965 and the seventh in early October 1966. During the first two years after award of the contract, the OV-10As accumulated about 650 hours of flight time. Initially, government funds amounting to $16.4 million were allocated to research, development, test, and engineering affecting the basic airframe, and an additional $1.7 million to engines and lesser subsystems. How much more was invested by North American cannot be stated with any great assurance, but there are indications that the company had spent about $20 million of its own (expenditures not covered by contract) by the time the seventh "prototype" was completed.*

The difference between costs for the two programs is not as startling as raw figures suggest. True, the Charger was built and flown for what seems to be roughly ten percent the cost of the officially sponsored program. But the sponsored program, the OV-10A development, obviously included quite a lot of important activity that Convair did not undertake on its own, and some subsystems that Convair temporarily ignored, and it covered seven aircraft, not one. It is not unreasonable to assume that the information obtained from OV-10A tests may have been worth a great deal more than that obtained from tests of the "Charger."**

But was it?

The flights of the "Charger," even before its destruction in October 1965, highlighted several performance defects. Drag forces

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*Attempts to obtain from open sources a summary of actual RDT&E costs for the first two years of the program were fruitless. The $20 million used here as an "over-and-above-contract-cost" figure is, however, based on reliable data.

**Available information will not support a determination of how much of North American's investment went into tools and jigs usable in a production program, but more than 90 percent of the sum originally allocated to the seven-airplane program was to support basic airframe work. The cost of the "information" the aircraft were intended to produce is the key question here, in any case.

considerably greater than predicted made speed, range, and climb performance inadequate, the lateral control system was marginally effecttive, propeller-induced noise in the front seat was dangerously high, the aircraft had a serious yaw problem, directional stability was unsatisfactory at low speed with flaps down, and forward visibility was not of the best. Some of these defects were partially corrected on the prototype as a result of early flight tests: chamfered wing tips substantially improved handling, for example. But other problems could be fixed only by major redesign. By the time the "Charger" crashed, Convair had completed a list of proposed design changes that in the opinion of both company and independent aerodynamicists would have made a "Charger II" a considerably improved airplane. Principally, Convair proposed: (1) increasing the span of the wing by about 15 percent to reduce induced drag and improve flight performance; (2) adding small dorsal and ventral fins to improve directional stability characteristics and single-engine handling; (3) increasing fuselage length and depth (and changing exterior contours) to reduce drag; (4) more completely fairing intersections between horizontal and vertical surfaces, also to improve drag characteristics; (5) increasing engine output from 650 to 750 shaft horsepower; (6) adding a revised lateral control system (including some power boost features); (7) improving over-the-nose visibility; and (8) reducing cockpit noise by relocating the pilot seat and changing the propeller diameter. The entire program (not completely detailed here) would increase the empty weight of the aircraft by 430 pounds. When rolled out, the "Charger" weighed seven pounds less than specified in the Convair brochure of the previous March.

What changes came out of the first year of OV-10A tests? Flight tests disclosed the existence of stability and control problems, higher-than-predicted aerodynamic drag, an incompatibility between the engine and the airframe, a weight and balance problem, and trouble with the pilot ejection system. A Pratt and Whitney engine (T74) of the type used in the "Charger" was installed in the seventh aircraft as insurance against inability to make the Garrett (T76) engine operate properly, fairings were added to junctions of horizontal and vertical surfaces to reduce drag, a substitute ejection seat was installed for test purposes, the control system was modified, the tail assembly was altered, and the span of the wing was increased by 30 percent to improve lift. A more powerful engine for the production version was selected early in 1967. Various difficulties in early testing and a requirement for modification of the final few test aircraft caused a five-month delay in the delivery of the seventh OV-10A "prototype" and somewhat smaller slippages in delivery of earlier aircraft. Moreover, the Air Force (prospectively the principal user) was much more interested in a completely redesigned OV-10 with much larger engines, fuselage, and wing than in an improved version of the original. Nonetheless, what was procured was a much altered edition of the original OV-10A. The first six production aircraft were used to validate the design of the modified OV-10A, so substantially different from the first lot of "prototypes" as to require retesting.

In many respects the defects of the OV-10A and the "Charger" were markedly similar and were equally unexpected, very much the same sorts of corrective measures were applied to each, and at the end very much the same sort of aircraft was again proposed by both contractors, although they had worked quite independently. Production cost differences promised to be insignificant. Pilots who flew both aircraft tended to think that there was not much to choose between them in handling and performance. At the end the two project groups came to essentially the same conclusion: a substantially different aircraft, cleaner in airflow, with more powerful engines, with improved lift and various detailed design changes, was needed to satisfy the basic requirement.

Disregarding for the moment differences of cost between the "Charger" and the OV-10A approaches, it seems evident that building and flight testing what were inherently, in both cases, prototype aircraft, paid substantial dividends. Industry and the services assumed that designing and producing an aircraft of the LARA type was a task well within the capability of industry, a task invoking no extreme advances in the existent state of the art. Yet it was necessary to make substantial changes to both aircraft in order to satisfy design objectives, and even then the original program goals were not attainable. Quite a lot of study and design analysis preceded the start of construction in each instance, yet in both cases unanticipated performance defects appeared. Convair and North American agreed on one vital point: the principal defects of the aircraft could not have been identified in advance of flight test, however comprehensive the study and analysis process. Had the aircraft been committed to production on the strength of design proposals alone, it seems almost certain that (1) production would have been halted while major changes were made to the basic airframe, the engine-airframe interface, and the airframe-integral subsystems. Alternatively, (2) early production aircraft could have been delivered with performance defects or (3) early aircraft could have been run through a modification line once the essential changes had been identified. Such, at least, had been the principal remedies of the past. And they all were costly. Another option, of course, was (4) to cancel the entire program, but staunch support for the basic requirement made that an unlikely alternative. Almost any other course seemed preferable to both producer and customer.

Tentatively, then, it seems safe to conclude that building prototypes was a sensible course. But there is a second issue. On the evidence it appears that Convair's prototype provided the information needed to resolve unknowns of design and performance at a lesser cost, and sooner, than did the sponsored prototypes.

In some respects that may be an unfair assessment. First, the case being considered may not have been typical. Second, North American had no real options: the Navy had specified the terms of the agreement and North American merely tried to carry them out. Third, part of the cost difference must be attributed to the numbers of OV-10As (a hedge against the early loss of one or two prototypes during test), while the greater investment in "hard" tooling represents, in some part, a hedge against the probability of a "good" outcome -- an aircraft that would require few changes to move from prototype to production phase.

Neverthless, the constraints under which North American operated as well as the procedures both North American and the Navy preferred seem to have penalized OV-10A development. Given the known attributes of the two approaches, if the cost of getting information by way of the OV-10A was but twice as great as by way of the "Charger" it would be tempting to conclude that one lot of information was worth twice as much as the other and that the books were more or less balanced. But the two kinds of test aircraft began life looking and acting very much alike, neither performed as well as hoped, rather substantial changes were recommended for each, they were nearly the same changes, and the second generation designs again were very much alike. In one instance the information on which change recommendations were based apparently cost more than $30 million to obtain and took two years to get; in the second instance the information cost was less than $5.0 million and the time investment was about 18 months. Such differences seem significant.* It is reasonable to ask what caused them.

How was Convair able to do design, engineering, fabrication, and preliminary test so much more cheaply than North American? The first factor of importance was manpower. The Convair group never included more than 55 "engineers" at any time, and some of these were more properly classified draftsmen than design engineers. The North American project, at Columbus, apparently was staffed by some 450 engineers and draftsmen -- about nine times as many as Convair used. Whatever the merits of exhaustive engineering, Convair obviously managed to get along reasonably well on a substantially smaller staff of professional designers.

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*The $5.0 million represents Convair's $3.2 million actual plus a 60 percent allowance for "contributed" subsystems. The Convair figures are actuals and the OV-10A figures approximations, though based on what seem to be good data, if "informal." The Convair totals do not include much but airframe, as engines, propellers, avionics, and instruments were provided by companies that shared the risk. Convair estimated that less than $1.0 million was involved in these "contributions," but the figure seems low. Therefore it has been inflated by 80 percent for the purposes of this comparison.

Second, procedures. The Navy was ordinarily more austere in its assignment of personnel to a program office than the Air Force, and traditionally allowed an airplane contractor greater freedom of action than did the Air Force. Nevertheless, the OV-10A contractor was obliged to provide extensive program documentation under the Navy's PROMPT (Program Reporting, Organization and Management Planning Technique) procedures, under terms of the Technical Development Plan (which incorporated requirements, for example, for nine recurring periodic reports on reliability engineering and numbers of others dealing with maintainability and logistics support), plus a number of other scheduled and "hotline" reports on progress and problems. Deviations from standard specifications required approval (though the process was less cumbersome than the comparable Air Force deviation approval procedure), and in general a great deal of paperwork was demanded.

Finally, mostly because the Convair effort had carefully limited objectives and comparatively fewer resources, the "Charger" program had to rely on some techniques of austere development not much favored in other military programs of the 1960s. In one sense Convair's emphasis on development austerity was incidental to the main issue of relying on prototypes, but the rather remarkable differences between the "normal" procedures imposed on North American and the irregular procedures used by Convair certainly do much to explain why the Convair prototype produced information at a lower cost than its North American counterpart.

In the "Charger" program the project group used the preliminary design specifications as a standard reference. Only three approvals were required before a drawing went to the shop floor: one for aerodynamics, one for structures, and one for fabrication. The approving supervisors were physically present in the design shop and could approve or disapprove changes on the spot. Indeed, the entire prototype project group was confined within one moderately small building that also housed the assembly floor. From start to finish only 78 engineers and draftsmen were involved in the project (60 in the design section and 18 in the technical section), and the number engaged at any one time did not exceed 55. There were only three supervisors; everybody else worked on a drawing board. Only two production engineers participated and their chief function was to review final drawings for production implications.

Perhaps most important, no outside interference with the design group was permitted. A special electronic key card was needed to gain entry to Building 69, which housed the "Charger" project, and only two people who were not directly and regularly engaged in the work ever acquired keys. No visitors were permitted. Between the time of the decision to build a prototype and the day of its rollout there were no formal presentations, charts, reports, or studies. Neither an inspection section nor a tool design unit was authorized; supervisors and foremen performed inspections as appropriate to the pace of work, and one man designed all the tools and fixtures needed for the prototype. Only engineering decisions affecting the basic configuration of the aircraft or its ability to satisfy the stated requirements had to be approved at a level above the project office, and until the aircraft went into flight test there were none. In so many words, nothing was done that did not directly, immediately, and specifically enhance the real objectives of the project group.

Both resources and expenditures were tightly controlled. At the start of prototype work the project engineer estimated that he would need 50,000 engineering man-hours to do his job. Management initially authorized 40,000, and the time actually required was 53,200 (including about 6,900 hours of unpaid overtime). Notwithstanding the pressure of the schedule, the fact that the work area was by turns cold and drafty and hot and stuffy, that quarters were crowded and noisy (the drawing room and the assembly shop were separated only by an eight-foot partition), morale and enthusiasm for the project were exceptionally high.

Contained within that random lot of observations on how the "Charger" project was conducted are the elements of a "good" prototype program.* The most obvious characteristic of the project was the concentration of authority and responsibility and the counterpart absence of reviews, reports, and higher level approvals. Second in importance was agreement that nothing should be attempted that was not absolutely essential to the central purpose of the project -- in this case, to the design and construction of a prototype aircraft that would provide information needed for the final satisfaction of general requirements laid down by the Navy Department. (Yet reasonable precautions against design error were taken, as evidenced by the construction of an alternate horizontal stabilizer that did not incorporate the advanced aerodynamic features of the stabilizer actually used.) A third factor was that very capable people, in quite small numbers, were assigned specific tasks and given the responsibility for them. (Some of the original group who were unable to adjust to such a different development environment had to be taken off the project.) Fourth, it was assumed that major changes would result from flight experience and that unreasonable attention to such functions as maintenance, logistics, tool design, and production planning would be wasted effort until most of the configuration uncertainties had been reduced. (Because the "Charger" was not put into production there is no way of deciding whether too little attention had been paid to such factors and whether putting it into production would have been unusually costly, but there were no obvious indications of that oversight.) Finally, and inherent in all of the others, it was apparent that extreme austerity in expenditures and resources had all sorts of unpredicted benefits over the long run. (Had greater resources been available to the project group they might have been invested in more intensive tool design, for example, and that would have required more careful coordination of fabrication activities with production planning, more supervision, more drawings, more specialized people, and so on.)

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*Had not the Convair prototype been built so economically, and had not the two programs been so similar in their technical outcomes, the OV-10A might justifiably be called a "good" program. As compared with possible alternatives the OV-10A seems "good." But in comparison the "Charger" clearly is "better."

Procedures of the sort employed in the "Charger" project ran counter to nearly all of the rules of the road adopted since the appearance of the weapon system concept in the early 1950s. And, of course, they were incompatible with the management manuals on which the Air Force relied in the 1960s. Still, they had been used, rather successfully, in a surprisingly large number of specialized programs. The Lockheed design group under "Kelly" Johnson, the Hawker-Siddeley group formerly under Sir Sidney Camm, and the Dassault development division at St. Cloud had done some spectacularly effective work along similar lines in the recent past. The argument that each represented "an exception," that such things could not be done by ordinary people in an ordinary way, was specious on its face. What was wanting was an understanding of how exceptional results were obtained. Perhaps it was only incidental that austerity paid large dividends in prototype programs, but it seems plain enough that in this instance reliance on prototypes was thoroughly justified and that a combination of the prototype approach with unorthodox development practices substantially reduced the cost of the total program without significantly devaluing the information content of its outcome.

V. OTHER RELEVANT PROGRAMS

In the pre-1968 western world only five nations designed and built their own supersonic fighter aircraft. Canada did so once, although the aircraft was not put into production. Only one supersonic British aircraft, the Lightning, went into production, although several others reached prototype stage before being cancelled. The Swedes had progressed to their second major supersonic fighter project, the Viggen. The United States had put 14 supersonic fighters into production since 1952 and carried three or four others to the pre-production stage before cancellation. The French, starting in 1955, carried one basic airframe design through at least seven variations and produced relatively large numbers of fighters and a light bomber scaled up from the original fighter design.

With the Viggen, the Swedish Air Force adopted a systems approach and decided to build a systems prototype on "semi-hard" tooling, a significant departure from the practices Sweden had honored since the start of its first domestic fighter program in 1941. The concept used in 1968 in Sweden was derived mostly from U.S. experience.

The only relevant British experience of 1955-1965, the TSR-2 program, proceeded from a systems development concept but actually included several "stripped" prototype aircraft, though scheduling problems rather than intent probably explained the availability of such prototypes.

The French consistently built prototypes and had had some rather striking successes with them. The prime exponent of the prototype approach in France was Avions Marcel Dassault; its prime product was the Mirage series of aircraft.*

Perhaps the most widely used production fighter in service in 1968 was the Mirage III, a descendant of a privately funded design project

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*Dassault was in 1968 the only supplier of supersonic aircraft in France; but Sud Aviation used essentially similar techniques for earlier fighters, and both Nord and Breguet favored prototype strategies. Since 1968 Dassault and Breguet have merged.

that began in 1954. It was the standard fighter of the French, Israeli, South African, and Australian air forces, was on order for the Swiss (to be built under license), had been ordered by Lebanon and Pakistan, and, as indicated in Table 1, was being considered by several other nations. It was a relatively lightweight aircraft (the heaviest variant to that time had a gross weight of 26,500 pounds) with several operational configurations ranging from close support to long-range intercept. The ordinary export model then delivered for roughly $1.1 million, complete with a basic fire control system and provisions for gun or air-to-air-missile armament.

The original prototype, the Mirage I, was a 12,000-pound interceptor with an accessory rocket engine, built in 1954 largely to test the characteristics of a high-performance delta-planform aircraft in flight. A Mirage II project was abandoned before completion when Dassault concluded that a larger aircraft with full armament provisions would be a better production prospect. The Mirage III prototype was also laid out with an eye to possible adoption as a standard NATO fighter. Unlike its predecessor, the Mirage III had but one engine. It was the first French aircraft to incorporate area rule technology and the first to exceed Mach 1.5 in flight. Nevertheless, Dassault employed only 14 engineers and draftsmen in its design and only 70 shop fabricators in its assembly.* So impressive was its performance that the French government cancelled development of the Durandel fighter earlier ordered from Sud-Toulouse and ordered Mirages.

The pre-production Mirage III A, which first flew in May 1958, reached a speed of Mach 2.2 and an altitude of 82,000 feet one month later. It differed from the earlier prototype chiefly in having an improved flight control system and somewhat more powerful Atar engine (13,200 pounds of thrust as against 9,900 pounds). The III B was a two-place trainer version (October 1959 first flight) and the III C a scaled-up model of the B (21,000 pounds gross weight) with more comprehensive all-weather equipment and greater range. It first flew in

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*The number may be misleading; wing and landing gear were built by Sud, but to Dassault designs.

Table 1

MIRAGE III AND MIRAGE 5 ORDERS AND DELIVERIES THROUGH 1967, EXCLUDING PROTOTYPES AND PRE-SERIES AIRCRAFT (MIRAGE III-A)

Model	No. Delivered and On Order	Remarks
III-B	42	40 to Armée de l'Air, 2 to Swiss
III-C	100	1 to Swiss, balance to Armée de l'Air
III-E	180	France
III-R	70	France
III-S	7	France
III-S	(33)	Swiss-built
III-R	(17)	Swiss-built
III-O	(81)	Australian-built
III-CJ	72	To Israel
III-BJ	3	To Israel
5-J	50	For Israel, not delivered
III-CZ	16	To South Africa
III-BZ	3	To South Africa
III-DZ	3	To South Africa
III-EZ	16	To South Africa
III-RZ	4	To South Africa
III-O	19	To Australia; 2 assembled in France, balance in Australia
III-EL	10	To Lebanon
III-BL	2	To Lebanon
III-EP	18	To Pakistan
III-DP	3	To Pakistan
III-RP	3	To Pakistan
Total	774	

Pending orders: Brazil (15-30 III or 5 models plus 35 Mirage 5s); Iraq (20 Mirage III-E, R, D models); Peru (12 Mirage 5 and 5 DP models).

Source: Flying Review International, March 1968; Interavia, December 1965.

October 1960. The III E and III R followed in 1961, grossing from 19,800 pounds to 26,400 pounds depending on armament provisions and internal electronics. The Mirage III E / III R version had a larger fuselage than its predecessors (to accommodate additional radar and computer installations) and was equipped with more powerful engines (Atar 9C models with 14,000 pounds of thrust, plus an optional SEPR 844 rocket for boost performance).

The procedures adopted for development of the Mirage III F variant (later known as the Mirage F2) were perhaps more pertinent to considerations of prototype policy than were the details of almost any other fighter development of these years. Although basically a further development of earlier Mirage fighters, the F was heavier than most, had a considerably higher wing loading (93 pounds per square foot against a range of 53 to 80 for the III E), and incorporated high-lift flaps to offset the effects of weight increases on airfield performance. Earlier Mirage models had been of classic delta-wing layout; the F incorporated a modified (short chord) delta that approached more usual wing plans in layout. The F also incorporated conventional tail surfaces while retaining the main fuselage arrangements of the III E. The F was designed to strike-fighter requirements and against the premise that it would be used to fill the gap between the III E and a variable geometry fighter (the III G) expected to be available after 1973. Like the other members of the Mirage III family, the F had a maximum speed on the order of Mach 2.2, but it was specifically intended to operate effectively at low-altitude speeds ranging between Mach 0.8 and 1.2. It represented, in all respects, a thoroughly modern fighter aircraft development.

The initial F2 development program cost about $3.8 million, of which prototype construction accounted for roughly $2.3 million. Design work began in March 1964 and construction in July; the F2 prototype flew in July 1966. Engineering manpower committed to the program ranged from a starting level of 8 engineers to a peak of 50-53 in the period September 1964-February 1965. During the detail design phase, about 40 percent of the engineering force consisted of graduate engineers and the balance of draftsmen. The total cost of engineering manpower through the first flight was less than $1,000,000. Included in the development costs were the expenses of constructing an engine test bed (the Mirage III T2, a modified Mirage III-E), prototype tooling, flight test instrumentation, the installation of a reconnaissance radar, spares, ground handling and test equipment, and a mockup that was built in parallel with the prototype.*

The various Mirage prototypes were different in many respects from prototypes that would ordinarily be built in the United States. In essence, each prototype tended to emphasize one or a few significant design innovations (the wing and tail for the F2 for example, or the delta planform for the Mirage I). Structural parts were deliberately made over-strength for the prototypes, and there were no detailed stress analyses until the prototype had flown. That habit reflected the practice of basing relatively important structural changes on the findings of flight testing. Equally strange to American habits was the Dassault practice of deferring the compilation of detailed design specifications until the completion of flight testing. The development work was habitually conducted under some very basic performance specification requirements. Many of the major problems that might otherwise occur were offset by reliance on developed and fully tested components and subsystems, some of which were used without change in a succession of aircraft within a general family. At least one observer of the Dassault techniques suggested that the time advantages apparent in the Dassault prototype process arose as much in having avoided extensive development subcontracting (dealing with parts suppliers rather than parts designers and fabricators) as in other manpower economies.

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*Dassault procedures called for concurrent assembly of the prototype and the mockup, contour detail for the flight aircraft being derived from the mockup -- which served as a sort of cut and try assembly "prototype" for the flight prototype.

The reporting procedures applied to Dassault developments, and for that matter to virtually all government sponsored weapons programs in France, were simple and the requirements few. For practical purposes, no periodic reports and no accomplishments reports were required by the sponsoring project office. The relatively small military project staff (consisting of 5 to 20 people, at most) was expected to keep cognizant of events in an informal way, but problem identification and problem solving were treated as contractor responsibilities. Contracts were written for short terms and to cover specific portions of the development task: for flight testing, for example, short and simple individual contracts were prepared sequentially as the program progressed from one test phase to another. Dassault preferred fixed price contracts with incentive clauses for development, although the Air Ministry had no deep seated objections to the use of cost-plus contracts. Incentives were hinged on performance specifications; penalties could be levied for either schedule or flight performance faults, but premiums were awarded only for performance. Notwithstanding the nomenclature used in describing contracting practices, the contracts were actually a form of cost reimbursement with a price ceiling. Their short term gave an impression of fixed-price contracting.

The effect of such practices (and others that might be inferred from this brief summary) were apparent in many ways. One that may be significant was time from start of design to first flight. Typical were these:

Aircraft	Design to first flight (months)
Mirage I	17
Mirage III (prototype)	9
Mirage III A	16
Mirage III F2	27
Mirage IV-01	17 (bomber prototype)
Balzac V	20 (vertical-rise Mirage III V prototype)

Other effects appeared in costs. On the strength of some basic comparisons without any compensation for differences in requirement, the development of a production ready aircraft in the Dassault organization appeard to cost from one-sixth to one-third as much as comparable work in America. A difference of 30 or even 50 percent might be explained in terms of wage differentials and the fact that the French seemed to take smaller and more deliberate development steps, but the appreciably greater differences that gave every evidence of being real could not be ascribed to any factors so obvious.

The advantages of the Dassault approach seemed to arise mostly in a management approach that took maximum advantage of deliberately limited resources. The entire Dassault aircraft enterprise employed fewer than 8,000 people, yet in 1967 an F2 prototype was in flight test, a variable-sweep (III G) prototype in construction, a vertical-rise prototype (Balzac) in test, and the production of Mirage III C and E, Mirage IV A, and Mystere-20 aircraft was proceeding at a rate in excess of 20 per month. Even though 40 to 70 percent of the parts, by weight, of a Dassault aircraft were built by associate or subcontractors, assembly was solely a Dassault responsibility. Output was high by almost any standard of comparison.

One additional thought may be introduced. The various Mirage aircraft were very highly regarded by professional airmen, by experienced designers, and by all their users. Although somewhat inferior to contemporary American fighters of the F-4 type in payload, range, and elegance of equipment, the Mirage III aircraft had an excellent performance, high reliability, and very low price to speak for them. On balance, it would be difficult to convince an unbiased observer that the Dassault practice of building prototypes had adversely affected either the availability or the excellence of the product. It was evident, moreover, that having a basic airframe available in prototype permitted the French to make delayed decisions on operational configurations and enabled them to exploit several rather different applications of the Mirage III in a relatively brief period and at costs that were surprisingly slight.

Apart from the examples previously discussed, there were in the 1955-1965 period few instances of prototype construction and test prior to a decision on production, and still fewer on which reliable cost figures were available. One prospectively interesting case may be noted: both the North American T-39 (Sabreliner) and the Dassault Mystere 20 (Fan-Jet Falcon) appeared as prototypes, were carefully tested, and were subsequently ordered into production. Both production versions differed from the respective prototypes in several respects. North American invested roughly $12 million in the T-39 prototype, which flew in September 1958; and Dassault invested about $23 million in the Mystere 20, which made its maiden flight in May 1963. The Dassault total included the cost of changes made as a result of flight testing; adding equivalent charges made the North American total about $20 million.*

The two aircraft were markedly similar in many respects, although the Mystere incorporated somewhat more advanced technology than the Sabreliner -- as would be expected in an aircraft that appeared five years later. In 1968 market prices, the Sabreliner was about ten percent cheaper. Their performance was not greatly below that of high performance fighter aircraft of the early 1950s; indeed, both owed more than a little to fighter designs produced by their parent firms, the F-86 and the Mystere B. Each prototype was privately funded, which suggested that the cited cost totals represent real costs not susceptible of much reduction.

Although the United States Air Force had not deliberately used a prototype development strategy in any system development program of the early 1960s and though its published development doctrine made no allowance for any such variation, other services, private constructors, and other nations had resorted to prototypes when the development

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*The Dassault total was provided by Dassault management in discussions about the costs of new aircraft projects; the North American total is a rough approximation of prototype costs plus related engineering costs and was obtained from Air Force files on the T-39 contract. Both figures are given in 1963 dollars.

environment permitted or encouraged that course. The available evidence indicates, on balance, that such an approach did not unduly compromise the excellence, availability, or cost of the final article. The advantages arising from extensive flight testing in advance of a production decision seem substantial and the costs relatively slight. That in particular instances various organizations had successfully conducted austere development programs involving prototypes is almost incidental, although it is not reasonable to dismiss the possibility that reliance on prototypes encouraged development austerity and afforded secondary but appreciable advantages in terms of program cost. Yet austerity is a separate issue; the several advantages of a prototype approach seem to be apparent from a review of experience, however limited it has been. Theory, then, has a foundation on empirical evidence.

VI. SOME IMPORTANT CONSIDERATIONS: COST AND TIME

The assumption that building prototypes adds substantially to program costs or appreciably delays the operational availability of an aircraft system has been mentioned previously. An examination of that assumption was inherent in a Klein, Shubert, Glennan study originally written in 1963.* The analysis could identify no significant differences. The predictability of costs and schedules has been repeatedly analyzed, most notably by Marshall and Meckling. They concluded that unpredictability was a dominant characteristic of development. If all problems can be identified in advance of development, the cost of solving them and the time needed for their solution can probably be predicted. But because the probability of anticipating precisely what difficulties will be encountered in development is very slight, so is the accuracy of schedule estimating. Schedule variables caused by all sorts of program perturbations are normally so large that they absorb the relatively smaller effects of building prototypes. That phenomenon becomes particularly apparent when an attempt is made to distinguish prototype programs from development-production programs solely in terms of time from program approval to operational availability.

The rationale for ascribing quite high costs to prototype development is not supportable by experience. Table 2 summarizes the costs (and some other relevant data) for two different sorts of fighter-aircraft prototypes. Part A includes aircraft prototypes built and tested before a production decision was taken. Such aircraft were mostly built on "soft" tools. Part B considers "prototypes" that were built after production commitments had been made and that generally were built on "hard" tools intended for production line use. The data are summarized here merely to indicate the general magnitude of investment in a prototype approach.

In each of the programs listed in Table 2(A) extensive changes in configuration, and consequently in tooling and production planning,

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*It has been reissued, with classified and proprietary data deleted, as RM-3467-1-PR, April 1971.

Table 2

COMPARISON COSTS OF U.S. PROTOTYPE FIGHTER AIRCRAFT

(A) Before Production Commitment

Model	(1) Number of Prototypes	(2) Year of First Flight	(3) Prototype Cost ($ Million)[a]	(4) 200-Aircraft Program Cost (Including Prototypes)	(5) (3) ÷ (4) (%)
F-80	3	1944	6.4	n.a.	n.a.
F-84	3	1946	10.2	73.4	13.9
F-86	3	1947	13.0	77.1	16.9
F-89	2	1948	15.3	n.a.	n.a.
F-104	2	1954	18.7	214.8	8.7
(B) After Production Commitment					
F-100	2	1953	32.2	196.0	16.4
F-102	2	1953	29.3	411.8	7.1
F-105	3	1955	50.0	617.3	8.1
F-106	2	1956	48.9	546.0	9.0
F-107	3	1956	69.8	n.a.	n.a.

<u>Source</u>: Data assembled by T. K. Glennan, Jr., The Rand Corporation, in 1962.

<u>Notes</u>: [a]All figures are 1962 dollars.
n.a. indicates not applicable.

occurred in the wake of early flight tests. (The F-107 was never ordered into production, but many preparations had been made before the program was cut back to the three prototypes.) The XF-104 was the only prototype in the "Century Series" to be built on "soft" tools.

(The others were really intended to be "fly-before-you-buy" programs in which the verbs somehow got transposed, which may explain why the F-104 cost only about two-thirds as much as other "prototypes" of its generation.)

The accuracy of R&D program cost forecasts has not been very high in recent decades. Errors ranging from 100 to 300 percent are common. In the case of the F-102, for example, the cost of retooling and re-engineering to reflect differences between the first and the eventual production aircraft exceeded $30 million, and the cost of making engineering changes was even higher.* Retooling for the production of the F-104 after a much altered configuration had been selected was costless; the two prototypes had been hand-built around interim engines, so what was needed was a translation of reasonably reliable engineering data into designs for production items. And in that instance the time required to design, build, and test prototypes plus the time needed to redesign, construct tooling, and deliver operational aircraft bettered the concept-to-delivery pace of four contemporary fighters (F-101, F-102, F-105, F-106) developed by the conventional technique of moving quickly from design study to production. It was only marginally slower than a fifth (F-100).**

Considered as a percentage of the cost of 200 production aircraft, the cost differences between the "before and after" prototype aircraft in Table 2 are not pronounced. But actual prototype cost was less for the former, mostly it seems because the latter were built on "hard" or "semi-hard" tooling and prototype costs also covered some production commitments.

The case of aircraft built only in prototype during the late 1940s and the mid-1950s is somewhat difficult to evaluate. The last

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*Engine, avionics, and armament changes were major contributors.

**See A. W. Marshall and W. H. Meckling, "Predictability of Costs, Time, and Success of Development," in The Rate and Direction of Inventive Activity (Princeton University Press, 1962); other data were collected by L. L. Johnson.

fly-off competition, in June and July 1950, involved three "programs" and a total of six flight articles (although only one aircraft in each of three different models -- XF-88, XF-90, and XF-93 -- was actually in the competition). The government paid the three concerned contractors a total of $40.4 million for six airframes.* The cost per prototype is reasonably close to the average cost of those aircraft prototypes in Table 2(A) that were built before 1950. (The total includes nearly $15 million invested in XF-93 tooling before the aircraft was downgraded from a production to a prototype program.)

The XF-104 prototype cost $18.7 million; the contemporary F-105 "prototype" (actually built on early production tooling), cost about $50 million. Both aircraft were in service in 1967, and in many respects were technically comparable to more modern designs. The last of the "prototypes," the F-107, cost about $70 million -- or about 10 percent of the cost of the first 200 F-105s it would have replaced if built in quantity. The total cost of six "prototype" airframes in the F-105 and F-107 configuration came to rather less than $120 million, and all were built on relatively "hard" tooling.

The experience of the Air Force in buying "soft tooling" prototypes, including the two XF-104s, suggests that under appropriate conditions an airframe very useful for flight testing of both basic designs and readily available subsystems might be obtained for about 60 percent of the cost of a "hard tooled" prototype.** And of course it becomes available much sooner. The evidence also says that much is learned, and quickly, from "soft tooling" prototypes. The OV-10A versus "Charger" episode does much to reinforce that conclusion, as does knowledge of Dassault experience.

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*1962 dollars. The total does not include government furnished aeronautical equipment, which was relatively substantial.

**If there is a "scale effect" in prototype costs, it may work to reduce the relative costs of larger aircraft. The B-52 and B-47 prototypes cost more nearly six than ten percent of the costs of the first 200 production airframes.

One further observation seems relevant to the prototype question. The native inaccuracy of the cost estimating process for aircraft approximates 20 percent, and the uncertainty of cost outcomes is characteristically somewhat greater. In that situation, an additional investment of about ten percent of predicted program costs in a 200-aircraft program would be virtually undetectable. Such a prototype phase would not be "costless" of course, but as an element of probable program costs it would be inconsequential. A prototype phase is likely to be beneficial to program outcomes in several respects; in particular, it has the potential of reducing subsequent cost growth that occurs because of the late discovery of technical problems. If the time needed to progress from start of development to first operational article is actually no greater when a prototype phase is included than when it is not, and if the cost-benefit balance is generally favorable, all the purported advantages of bypassing a prototype phase become questionable.

VII. ISSUES AND CHOICES

In some circumstances the construction and test of a prototype aircraft affords a developer the opportunity of obtaining information sooner or more cheaply than by other means, although design analysis, wind tunnel testing, and other methods of resolving technological uncertainty must be used in concert with prototype fabrication if the effort is to be successful. A developer is liable to get better and more reliable information from a prototype than he can elsewhere. The construction of a prototype may constitute a valuable development option in that it reduces to some extent the time required to go from production decision to production item. All of these attractive attributes of prototypes arise because a prototype is a useful tool for reducing certain important technical uncertainties, and reducing technical uncertainty markedly decreases program risks in the broad.

As a substitute for prototypes the past decade has produced a technique of design analysis that permits developers to focus more quickly and more surely on important conceptual uncertainties and uncertainties of cost and schedule. That ability lies at the heart of "program definition" phases of the early 1960s. But it is also apparent that design analysis leaves untouched other uncertainties predominantly technological in origin, and that the resolution of these can be just as costly, risky, and time consuming as was true a decade ago. What seems to be needed is a way of limiting investment in those phases of aircraft development that produce relatively low confidence information at a relatively high cost. Prototype aircraft can be built relatively quickly, at a cost that is a relatively small portion of total program costs, and with massive advantage to total program goals _if_ those prototypes are built in accordance with procedures specifically tailored to real program objectives. In essence, that means buying hardware _rather than paper_ during a particular phase of development; merely adding the cost of a prototype to the cost of an elaborate design study serves a lesser purpose at a greater cost.

One vital qualification of a prototype program that has not been much emphasized hitherto is the importance of what T. K. Glennan, Jr., calls "interrelatedness." In bald terms, there is neither point nor profit to building a prototype aircraft unless it is capable of demonstrating the primary performance attributes of the desired end article in a realistic environment. It must include vital subsystems -- subsystems that, if materially changed later in the program, will substantially alter the performance of the total system. The qualifier here -- an extremely important one -- is that "interrelatedness" appears to be less crucial to total system performance than is often assumed. An airframe designed for subsystem flexibility and for growth potential permits the later accommodation of subsystems for which it was not designed. The costs to which most planners object most strenuously arise in the late substitution of subsystems and consequent changes to production tooling. A prototype permits those planners to make "interrelatedness" decisions before a production configuration is determined, and at relatively low cost.

Development austerity is a striking characteristic of successful prototype programs. The principal features of austere programs are careful selection of and adherence to primary program goals; concentration on engineering problems, rather than peripheral issues; remarkable economy of manpower permitted by compact management structures with real authority and by responsibility concentrated immediately above the working level; and simple, direct, and deformalized program management procedures (report and review functions). None of these characteristics is found in isolation -- they are dependent on one another. Thus a ritualized reporting process requires the addition of engineers who record progress without contributing to it; reports prompt "advice" and "program guidance" from reviewers who have no association with actual program progress and who have only a tenuous hierarchic responsibility for meeting program goals; and once the policy of doing only the essential has been abandoned, costs begin an irreversible climb.

Uncluttered program management procedures seem essential to an economical, efficient prototype program. It is plain that they cannot be provided under present methods of program management because, among many other considerations, they require either a very passive program office or one that is both small and essentially integrated with the development group itself. Such procedures represent a means of controlling and frequently of reducing program costs in that phase of development where costs tend to be most unpredictable at present. Perhaps the greatest advantage of a prototype approach over an "integrated program" approach is in its simplification of procedures; and because of institutional commitments to present ways, simplification also represents to established development agencies one of the least attractive alternatives.

Another difficulty that has sociological rather than technological antecedents is the reluctance of development agencies to acknowledge that inadequate engineering can be just as much at fault as procedural defects when development programs turn out badly. The normal response to technical difficulty is to invest in <u>more</u> engineering and to impose more stringent controls over the activities of the developer. These seem, on their faces, to be self-defeating measures, but they have the apparent advantage of substituting predictable costs (always high) for the unpredictabilities that reside in the riskier -- and much cheaper -- course of buying high quality engineering that can function with full effectiveness only when ritualized program controls are relaxed or abolished.

To recapitulate:

(1) The circumstances under which the construction of a prototype aircraft becomes a desirable element of a total development program include:

a. A program sufficiently well defined to permit developers to undertake the resolution of specific technological uncertainties that cannot realistically be expected to succumb to alternative techniques of uncertainty resolution (such as subscale wind tunnel testing) or that can be alternatively resolved only at greater cost than by the prototype route.

b. When the developers have accepted the premise that successful prototype programs require management techniques very unlike those common to programs based on multiple redistillation of design studies.

c. When the developers understand that the real purpose of a prototype aircraft is to identify necessary design changes quickly and accurately, and that one outcome of a prototype program can be a decision not to proceed to production. The object of a prototype is to permit a prompt and economical decision in such matters.

d. When scheduling and availability considerations permit the comparative evaluation, in flight trials, of competing aircraft that reflect substantially different design concepts.

(2) A prototype can resolve technological uncertainties of a specific kind, and the resolution of such uncertainties can ease the task of making decisions concerning application, general requirements, program scope, force structure, and the like. But a successful prototype cannot, of itself, justify a production or deployment decision.

a. The use of competitive prototypes clearly can aid in choosing between two proposals <u>if</u> the choice is to be made on technological grounds. Insofar as production practices, prospective costs, and schedules are influenced by the technology a prototype demonstrates, they may also become factors in a competition.

b. The successful fabrication and test of a prototype during a period of requirements uncertainty can create a useful strategic option by lessening the time needed to go from production decision to operational availability. A decision on taking up that option can be delayed, if appropriate, until force structure needs become clearer. But the option becomes less valuable with the technological aging of the prototype. Obsolescence of an option can be delayed or offset by continued development of the aircraft itself, but at a cost that should be separately calculated and weighed against the cost of starting again with something newer or better.

(3) A prototype approach is compatible with virtually any development strategy ever conceived except those based on the immediate production of an aircraft detailed only in a design proposal. There is no evidence that the introduction of a prototype either delays the availability of the production article or increases the cost of development. There _is_ evidence, however, that a prototype program exempted from the ordinary controls and constraints of program management as it existed in 1965 _could_ cost substantially less than would a prototype program not so exempted, and that important technological uncertainties could thus be resolved both sooner and at lower cost than would otherwise be the case.

The inhibitors of a prototype approach are quite important. It is evident, for example, that successful low-cost prototype programs must include provisions for organizational simplicity, limited intervention by sponsoring project people, and abbreviated reporting and documentation procedures. At the same time, regard for the public interest requires the erection of reasonable controls and safeguards, and it seems equally important to provide continuing competition so that the customer can preserve his selection options as long as possible. In some respects these are contradictory requirements because protection of the public interest suggests close and continuing scrutiny of progress, whereas it is apparent that the "best" prototype programs operate relatively free of the interference that "continuing scrutiny" implies. In the end, it is the quality of program participants that determines whether reconciliation of apparent contradictions is possible.