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Washington, DC 20375-5320

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National Security and the U.S. Naval Research Laboratory

Seventy Years of Science for the Navy and the Nation (1923-1993)

D. J. DeYoung

Office of Strategic Planning
Executive Directorate

March 29, 1994

The Naval Research Laboratory (NRL) was officially established on July 2, 1923, as the Naval Experimental and Research Laboratory. In the following seven decades, research efforts have expanded from the two original areas of scientific endeavor, radio and underwater sound, to 19 broad areas that encompass many diverse fields.

NRL is the Navy's Corporate Laboratory and is under the command of the Chief of Naval Research. The Laboratory occupies its original site on the banks of the Potomac River in the southwest corner of Washington, D.C. Since NRL's establishment, the number of buildings has expanded from the original five to more than 170, and the main Laboratory site has expanded from 27.5 to 129 acres. The original group of about 20 employees has grown to more than 3900, including those at the main site and at 14 field sites. On January 14, 1992, the Naval Oceanographic and Atmospheric Research Laboratory (with sites in both Mississippi and California) was merged with NRL as part of the U.S. Navy's post-Cold War research, development, technology, and engineering (RDT&E) consolidation efforts. This merger brought facilities and personnel at Bay St. Louis, Mississippi, and Monterey, California, under NRL management.

NRL has been designated a major shore command and is led by a Navy captain who serves as commanding officer. The director of research, a senior civilian, shares responsibility with the commanding officer for directing Laboratory operations. The Laboratory's overall R&D management structure is built around an Executive Directorate, three principal research directorates and one technology center. This center, the Naval Center for Space Technology, is the only in-house facility capable of designing, developing, and fabricating space systems for the Department of Defense (DoD).

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This report highlights the significance of NRL's unclassified contributions to national security over the past seven decades. It explains how the Laboratory's accomplishments in defense science and technology have had a powerful impact on the nation's military strength and how they have also had a major impact on the other components of national security—economic competitiveness, environmental health, energy security, and public health and welfare.

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PREFACE

The course of history reveals a close and enduring relationship between technological progress and state security. This relationship has never been more vividly illustrated than by the scientific events that led to the dawn of the Nuclear Age and to the climactic end to World War II in 1945. Earlier in this century, Thomas Edison's belief in this link between technology and state security motivated his proposal to establish what became, in 1923, the U.S. Naval Research Laboratory (NRL). For seven decades NRL has fulfilled Edison's hopes through an excellent record of technical achievement. The impact of these accomplishments span from NRL's discovery of the radar principle in the early 1920s, to the invention and demonstration of the first satellite prototypes of the NAVSTAR Global Positioning System, which was so important to victory in the 1991 Gulf War. Today, NRL's multidisciplinary research and development (R&D) program continues to be conducted with an awareness that the problems posed by international competition and conflict can, in part, be addressed by innovative R&D solutions.

As the Corporate Laboratory of the U.S. Navy, NRL's mission is

- to conduct basic research,
- to translate the results of this research into technology, and
- to assist in the transfer of this technology to other Navy and industrial laboratories for incorporation into effective military systems.

The successful transition of these efforts affirms the idea that a sustained and well-managed investment in multidisciplinary defense science and technology leads to a continuous upgrade of national defense capabilities. Specifically, NRL's technical expertise and successful performance of its mission have earned for the Laboratory a world-wide reputation as a center of excellence in discipline-based science and technology, and in space, radar, and electronic warfare systems development. The military impacts of NRL's achievements have supported America's security strategies during the post-World War I era, the years of conflict against fascism in World War II, and the "long twilight struggle" with communism in the Cold War era.

The revolutionary world events of the early 1990s—the liberation of the Soviet Union's eastern European "outer empire", the internal fracture and eventual dissolution of the Soviet Union itself, and the retreat of communism elsewhere in the world—have dramatically changed America's geostrategic position, calling for a reassessment of its security requirements. In addition, U.S. domestic problems—high budget and trade deficits, as well as social, energy, and environmental concerns—are raising doubts about America's ability to compete economically and technologically with foreign competitors and, at the same time, provide a decent quality of life for its citizens. With these foreign and domestic developments in mind, NRL's Director of Research, Dr. Timothy Coffey, recently surveyed the nation's post-Cold War security requirements and identified the opportunities that these new requirements hold for the Laboratory in what is becoming a period of both promise and uncertainty for America in domestic and world affairs:

"...We can expect that economic competition among the world's nations will increase. This increased competition will exacerbate the problem of vanishing global raw material sources...NRL will be expected to be a major player in reconciling what will become increasingly conflicting requirements. Namely, how does one simultaneously maintain an adequate national defense, respond to an accelerating high technology competition, and protect the environment? These conflicting requirements will present some marvelous opportunities for NRL to create advances in science and technology."

It is sometimes said that to know where one is going, it is helpful to know where one has been. In this spirit, this survey of NRL's past contributions to national security has been written. While scientific and technological capabilities are often transitory, America's security interests are enduring. It is these security interests that will continue to drive NRL's decisions regarding future R&D directions. By being ever-aware of these security interests, the Laboratory will continue to serve the nation's vital security interests as successfully as it has over the past 70 years.

Finally, the author notes that much of the information cited in this report has been gleaned from secondary source material, such as *Labstracts* (NRL's official biweekly publication) and laboratory press releases. Although useful as general communication instruments, these secondary sources lack the greater accuracy of primary sources, such as those published in refereed scientific journals. Care has been taken to present an accurate picture of NRL's achievements; however, the reader should be aware that this report is only as accurate as its source documents.

Don DeYoung
Office of Strategic Planning

March 1994

NATIONAL SECURITY AND THE U.S. NAVAL RESEARCH LABORATORY
Seventy Years of Science for the Navy and the Nation
(1923-1993)

INTRODUCTION

This report highlights the significance of NRL's unclassified contributions to national security over the past seven decades. It explains how the Laboratory's accomplishments in defense science and technology have had a powerful impact on the nation's military strength and how they have also had a major impact on the other components of national security—economic competitiveness, environmental health, energy security, and public health and welfare.

1. ELECTROMAGNETIC AND ACOUSTIC WAVE PROPAGATION

Radar

Discovery of the Radar Principle and Invention of the First U.S. Radar

Prior to the development of radar, Navy ships could track other ships or aircraft only by using optical techniques, sound ranging, or primitive radio direction finding. New methods of detection and ranging were necessary. In the autumn of 1922,* in the course of conducting research and development (R&D) on radio direction finders for aircraft, Dr. A. Hoyt Taylor and his associate Leo C. Young noted a distortion of "phase shift" in radio signals reflected from a steamer on the Potomac River. They suggested to the Navy Department that by means of this principle, "destroyers located on a line a number of miles apart could be immediately aware of the passage of an enemy vessel between any two destroyers of the line, irrespective of fog, darkness, or smoke screen" [1]. In short, NRL had made the first detection of a moving ship by radio waves and had, as a result, discovered the radar principle. Limited budgets deferred further in-depth studies in this field, and nearly 17 years were to pass before the Navy installed the first operational radar on its ships.

Eight years after the initial discovery of the radar principle, while experimenting with radio direction-finding equipment in the summer of 1930, NRL scientists observed that reflections of radio waves from an airplane could also be detected. Consequently, a report from the Director of the Laboratory in November 1930 led to orders from the Navy Bureau of Engineering to the Laboratory to "investigate the use of radio to detect the presence of enemy vessels and aircraft" [1].

Between 1930 and 1940, NRL conducted further R&D efforts on the use of radio for detection and ranging, and in 1935 the Committee on Naval Appropriations of the U.S. House of Representatives

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*Radio achievements made in 1922 were accomplished by researchers working for NRL's predecessor organization, the Naval Aircraft Radio Laboratory (NARL). On April 16, 1923, when facilities of the new Naval Research Laboratory first became available, personnel and activities of NARL were transferred to become the major component of NRL's newly formed Radio Division.

allocated $100,000 to NRL for the development of radar. This led to NRL's invention and development of the first U.S. radar, the XAF (installed on the battleship USS *New York* in 1939), and led eventually to its commercial production form, the CXAM. By the time of Japan's attack on Pearl Harbor, 20 radar units were in operation on selected vessels. These radars were cited by Fleet Admiral Ernest J. King for their contribution to the victories of the U.S. Navy in the battles of the Coral Sea, Midway, and Guadalcanal [2].

NRL designed and built the first radar prototypes independently. The RCA Corporation manufactured the first sets built in quantity, followed by the American Telephone and Telegraph Company, which entered the field to design and produce numerous Navy radars, especially for fire control. NRL also made important contributions to the development of the SG radar, the most widely used and effective shipboard radar used during World War II. NRL further shared technical ideas in the radar field with the U.S. Army and Great Britain during the late 1930s and 1940s.

NRL's early radar accomplishments are significant; radar and subsequent developments that have flowed from it are among the foundations of modern military power. Furthermore, as a primary sensor for navigation and surveillance, radar now plays a major role in such diverse areas as the effective operation of civilian transportation systems, weather forecasting, astronomy, and automation, among other uses.

Development of Naval Radar Systems

Following the discovery of the radar principle and the invention and development of the first U.S. radar, NRL established a tradition of excellence in radar R&D that led to other important technological advances. Such achievements in the development of radar systems include:

Duplexer — The use of a pulse technique to detect aircraft and ships was proposed by NRL's Leo Young in 1933. His colleague, Robert M. Page, made important advances over the next few years in the area of transmitters and receivers. He eventually developed the highly important duplexer, which permitted an antenna to be used for both transmitting and receiving. Combined with the duplexer, the pulse technique did away with the separate receiving and transmitting antennas that early radar developers had used. Page and Young received the original patents for the duplexer, an invention that dramatically changed the nature of radar [3, p.178. Gebhard cites R.M. Page and L.C. Young receiving patents 2,512,673 and 2,688,746].

Submarine radar — In 1940, NRL developed submarine radar. This radar enabled a submarine to rise to periscope depth and search for hostile aircraft before surfacing. Aircraft could be detected by the radar out to a range of 20 miles. At that time, this was considered adequate to allow the submarine to submerge before becoming vulnerable to the aircraft's weapons [3, p.186]. This radar became popular with submarine skippers during World War II; units were installed in submarines as quickly as they became available—more than 400 were produced [3, p.186]. The Laboratory later perfected a directional radar antenna for use with the Western Electric Radar System. It was effective enough to be used as a fire-control instrument, allowing several enemy ships to be torpedoed without the submarine being seen.

Plan-position indicator — To provide a polar-coordinate map-like display of targets, NRL originated the radar plan-position indicator (PPI)—the well-known radar scope with the round face and the sweeping hand—between 1939 and 1940 [3, p.193. Gebhard cites as references: "Report of Progress Problem W5-2S," NRL letter to Bureau of Engineering, SS67/36, ser. 135, 26 Feb. 1940; and R.M. Page, Patent 2,770,939]. The PPI is now universally used by military and commercial interests around the world for the display of radar information for such functions as air and surface detection, navigation, air-traffic control, air intercept, and object identification.

Monopulse radar — In 1943, NRL developed monopulse radar, now the basis for all modern tracking and missile control radars. The Laboratory's Robert Page holds the patent on this technique [3, p.219. Gebhard cites R.M. Page as holding U.S. Patent 2,929,056]. The monopulse technique was first applied to the Nike-Ajax missile system, which at the time was the nation's continental air defense system. Subsequently, monopulse radar became the standard radar for U.S. missile ranges. NRL's work in monopulse radar eventually led to the development of the AN/FPS-16, the first high-precision monopulse instrumentation radar. In 1958 this radar was used to guide the launchings of the first U.S. space satellites at Cape Canaveral [3, p.200]. Monopulse radar is still the most widely used technique for military tracking radar because of its high accuracy and relative immunity to electronic countermeasures that degrade other tracking methods.

Airborne radar — Prior to America's entry into World War II, and in anticipation of the German submarine menace, NRL developed the Model ASB. It was the first operational U.S. airborne radar to be widely used for bombing, detection of ships and surfaced submarines, and airborne intercept. This radar saw extensive use during the war, not just by the U.S. Navy and Army Air Forces, but also by the British. It was installed almost universally in U.S. naval aircraft and became known as the "workhorse of Naval Aviation" [3, p.201. Gebhard cites R.M. Page, *The Origin of Radar* (Doubleday & Company, Inc., New York, 1962) pp.171-172] More than 26,000 units were procured (from 1942 to 1944)—the largest procurement of any radar during the war [3, p.201]. The Model ASB was the first radar to be used in carrier-based aircraft and was used in attacking and destroying Japanese ship convoys in the Pacific. It was also effective against Japanese aircraft. It has been said that the ASB "was one of the most successful of all airborne surface search radars" [4].

Periscope-detection radar — NRL's efforts in high-resolution radar, dating from 1950 to 1960, led to the Navy's periscope-detection radar, the AN/APS-116, which was designed and constructed by Texas Instruments, Inc. [3, p.212. Gebhard cites C.O. Olson, "The Investigation of High Resolution Radar Phenomena. Part I - Short Pulse Transmitter," NRL Report 3501, July 1949]. This radar system became standard equipment in the Navy's carrier-based antisubmarine warfare (ASW) system, the S-3 [5].

Over-the-horizon radar — During the late 1940s, NRL foresaw the need to detect moving targets, including aircraft and missiles, at distances and altitudes beyond line-of-sight. Microwave radar as developed during World War II was limited in range by the curvature of Earth. In 1950, while using the pioneering work it had accomplished in radio "skip distance" effect theory (see Section 1: *"Skip-Distance" Effect*), NRL began to investigate the use of radar operating in the high frequency (HF, or short wave) portion of the radio spectrum to extend the range beyond the horizon. This is achieved by the refraction (bending) of radar waves when traveling through the ionosphere, which is located high above Earth's surface. By using the ionosphere to bend the radar energy back to Earth's surface, the range of a radar could be extended out to almost 2,000 nautical miles. By 1955, NRL was operating a low-power HF radar called MUSIC (Multiple Storage Integration Correlation), which demonstrated Earth backscatter at over-the-horizon (OTH) distances and echoes from line-of-sight targets. It also observed nuclear explosions at long range, as well as the launch of rockets [3, p.216]. In 1961, based on success with MUSIC, a high-power, high-antenna-gain OTH radar known as Madre (Magnetic Drum Radar Equipment) was installed at the NRL Chesapeake Bay Division field site. It was able to detect and track aircraft as they traveled across the Atlantic Ocean. The radar also demonstrated ship detection at OTH ranges, sea state, and storm tracking, vectoring of aircraft to an intercept, and warning a naval battle group of approaching aircraft at long range.

Ultimately, NRL's development of OTH radar formed the technical base that led to the Air Force's AN/FPS-118 radar for continental air defense and the Navy's Relocatable Over-the-Horizon Radar, as well as influencing HF radar development in other countries of the world. HF OTH radar is the most cost-effective wide-area sensor available today [6].

Radio

At the beginning of the twentieth century, the U.S. Navy realized that radio communication had great promise for enhancing the tactics and strategy of seapower. The Navy therefore became a principal sponsor of radio electronics and a pioneer in its early development, much of it through NRL's work. NRL's achievements in radio electronics have had a major impact in advancing the operational capability and combat effectiveness of the Navy, as well as that of the other military services of the U.S. and its allies. American industry and the national economy have also benefited greatly by this progress.

"Skip-Distance" Effect

In 1925 NRL discovered the "skip-distance" effect, which could not at the time be explained by the prevailing wave-propagation theory. The effect refers to radio signals, which have disappeared after the "ground wave" dissipates, reappearing at a considerable distance; this distance varies with frequency, time of day, and season. In 1926, NRL's Drs. A. Hoyt Taylor and E.O. Hulburt jointly published a modification of the theory that adequately explained the high-frequency "skip-distance" effect [7] and agreed with experimental data. This seminal work laid the foundation for modern HF wave-propagation theory and led to the Navy's acceptance of HF radio frequencies for Fleet communications [3, pp.44-45].

NRL's work in this area further demonstrated that around-the-world HF transmissions could be obtained through successive reflections from Earth's ionosphere with the proper choice of frequency, time of day, and season. Encirclement of the globe as many as three times in the same transmission and in both directions was observed in 1926. At the same time, reflections of the pulsed HF transmissions from Earth surface prominences, currently called "backscatter," were first observed. These HF "backscatter" observations generated the first concept of detecting and ranging on targets over very long distances. This concept led to the later development of over-the-horizon radar by NRL (see Section 1: *Over-the-Horizon Radar*) [3, p.44. Gebhard cites A.H. Taylor and E.O. Hulbert, "Wave Propagation Phenomena at High Frequencies," *Bureau of Engineering Monthly Radio and Sound Report*, 42-59, Sept. 1925; and A.H. Taylor, "An Investigation of Transmission on the Higher Radio Frequencies," *Inst. Radio Eng. Proc.*, 677-683, Dec. 1925].

Radio Electronics Achievements

1922-1929

NRL's other achievements in the area of radio are numerous, with many being highly critical to national security. They include:

- the first radio broadcast of a presidential address in 1922 when President Warren G. Harding delivered the dedication of the Lincoln Memorial from a transmitter built and installed by NRL's L. Gebhard [3, p.23];

- the first transmission of printed messages and photographs by radio in 1922 [3, pp.67-68];

- the development of the first aircraft radio communication equipment in 1922 [3, p.25];

- the first flight of a radio-controlled pilotless aircraft, the precursor of the radio-guided missile, in 1924 [3, pp.224-225].

- the maintenance of regular communications with the Antarctic base and support ships of Commander R.E. Byrd's expedition to the South Pole in 1929. The Antarctic base and the ships were equipped with NRL-designed and fabricated radio gear. The Laboratory also built the radio equipment used in the first aircraft to fly over the South Pole.

1930-1960

NRL was responsible for developing an aircraft radio homing system in 1937. This system was installed on all Navy aircraft carriers and their aircraft and provided the primary means for the aircraft to navigate back to their carriers during World War II [3, p.273. Gebhard cites A.H. Taylor, *Radio Reminiscences: A Half Century*, 170-171 (1960), AD 775930]. The development in 1943 of a successful countermeasure to German radio-controlled bombs not only jammed the bomb's guidance signals but, on occasion, took control of the missiles (see Section 7: *Electronic Warfare*) [3, p.303]. Remote control units for the first radio-controlled bomb were developed in 1944 [3, p.233. Gebhard cites C.H. Smith, Jr., H.W. Rosen, and C.H. Hoeppner, "The AN/ARW-17 Receiver," NRL Report 2421, Dec. 1944]. Radio communications by using the moon as a passive relay station to reflect transmitted human voice back to Earth was demonstrated in 1954 [8]. NRL developed a very-low-frequency facsimile transmission system; in 1959 this was the first system to provide reliable communications from a single high-power transmitting station in the U.S. to continuously submerged, operating submarines [3, p.147]. This system was later installed on all Polaris ballistic missile submarines.

Satellite Communications

Since its early days, NRL has maintained a continuing interest in extraterrestrial radio phenomena. In connection with its original high-frequency propagation work, NRL was the first to determine the frequency above which radio waves would penetrate Earth's atmosphere and propagate through outer space, making radio communication in space possible [3, p.115. Gebhard cites A.H. Taylor and E.O. Hulbert, "The Propagation of Radio Waves Over the Earth," *Phys. Rev.*, 215, Feb. 1926].

In 1959, the world's first operational satellite communication system, allowing communications from Washington, D.C., to Oahu, Hawaii, was placed into operation by NRL [3, p.116. Gebhard cites RADM F.Virden, USN, "Communication Requirements of Our Navy," *Signal*, 14, 16, 35-36, Dec. 1959]. The public demonstration of this system took place on January 28, 1960 with the exchange of messages between the Chief of Naval Operations and the Commander-in-Chief, Pacific Fleet. Other Laboratory achievements in satellite communication included: the first pictures (facsimile transmitted over a satellite communications system in 1960 [3, p.116]; and, at the request of the U.S. Post Office Department, the first transmission of "space mail" in the form of a facsimile letter over Echo I's satellite communication circuit. This event took place in 1960 and was later commemorated with a special postage stamp issued to herald the advent of satellite communication [3, p.121].

Identification Friend or Foe Systems

An important area of long-term NRL achievement has been in the development of Identification Friend or Foe (IFF) radio systems. In 1937, NRL developed the first IFF system in the U.S., and followed this with a succession of new and improved radio-identification systems for the U.S. and its allies [3, p.251. Gebhard cites A.H. Taylor, *Radar Reminiscences: A Half Century*, 180-181 (1960), AD 775930]. During World War II, these systems allowed the identification of friendly planes and targets on the ground and sea, particularly in poor visibility. Between 1948 and 1960, NRL conducted research on the possibility of deception by an enemy who would be using captured U.S. IFF transponders to appear as a "friend." As a result, the Mark XII system was developed by NRL in collaboration with a Tri-Service effort involving the Army, Air Force, and Navy. This system was the first IFF system to use cryptographic techniques to prevent an enemy from deceiving U.S. forces [9]. Since 1979, NRL has collaborated with Air Force and Army efforts to develop the new Mark XV IFF system, which will replace the Mark XII. The new system, to be installed on Navy ships and in aircraft and antiaircraft systems of all U.S. military services, was urgently required to make efficient use of beyond-visual-range weapon systems [10].

Sonar

Sonar Systems

Underwater acoustic research was begun by the U.S. Navy in 1917 with a small group at the U.S. Experiment Station in New London, Connecticut, to investigate the use of underwater sound during World War I. This group, headed by Dr. H.C. Hayes, was moved to NRL on its opening in 1923. Dr. Hayes and his colleagues decided that the passive sonic devices used in World War I were seriously limited in the detection of enemy submarines. It was their belief that an active echo-ranging sonar, operating in the 20 to 50 kHz frequency range, would provide the best antisubmarine warfare (ASW) system for surface ships. This approach was followed from the beginning of the new Sound Division at NRL, where practically all Navy R&D in sonar prior to World War II was carried out [11].

NRL's first effort was to develop an improved quartz-steel transducer. NRL tests of a 40 kHz transducer in 1926 and 1927 showed a significant improvement in the transducer's efficiency. However, it was decided to seek other transducer designs because of the scarcity of large quartz crystals, obtainable only from Brazil [12]. Extensive research was conducted on each of the components of the new sonar system, from the transducers and signal processing to the mechanical mounting and housing functions. Of particular significance was the development of the streamlined sonar dome to house the transducer. The dome enabled surface ships to make attacks at speeds up to 15 knots. In 1927 a number of U.S. naval vessels conducted tests with the NRL quartz-steel echo-ranging sonar. This was the first practical sonar based on echo-ranging or "pinging" at supersonic frequencies [1, p.171]. P. Langevin a French physicist, had first discussed this possibility in 1918. After a series of tests and at-sea trials, the echo detection equipment, model QB, became the first operating sonar used by the U.S. Navy [13].

Following the QB model sonar, NRL developed the QC and JK/QC sonar systems [14]. Finally in the late 1930s, JK and QB hydrophones were used in research on the protection of harbors and amphibious landing operations. The resulting system was designated the HERALD system. Research on each of these sets of sonar equipment, including the earlier QB system, provided the U.S. Navy's basic underwater ASW capabilities for World War II [15]. During World War II these systems comprised a major group of ASW devices that Grand Admiral Karl Doenitz, commander of the German U-boat fleet, cited as the major reason for Germany's defeat in the Battle of the Atlantic [16].

During World War II, NRL's acoustics R&D was focused primarily on support of the Navy's war effort. This included improvements to existing systems, acoustic countermeasures, and tactical use of ASW systems. An example in the area of tactical use was an analysis made in 1941-42 of American fleet defense against the German U-boat. It was concluded from the analysis of ship loss statistics that the rate of sinking of U.S. and allied ship tonnage was greater than the possible rate of replacement by new construction. Since approximately half of this loss was from submarines, the statistics also indicated that the efficiency of ASW attacks was only about one successful attack in ten. If this situation had continued, the success of the war effort would have been placed in grave jeopardy. After extensive operational analysis, the Laboratory recommended a series of improvements for using sonar during an ASW attack, particularly in speeding up the attack on the target U-boat and in the timing of the weapons deployment [17].

Environmental Acoustics

One of the first accomplishments made by the Laboratory in the early 1920s was the development of the sonic depth finder. It was the first depth finder to be placed in the Fleet for routine service, greatly enhancing both surface and subsurface navigation [18]. In a related area, in 1928 NRL developed a method for seismic exploration by using acoustic sources and receivers. Results of this research have provided geophysicists and geologists with basic tools for exploring for oil and gas and for understanding the nature of the surface and subsurface of Earth [19].

2. SPACE SCIENCE

Solar Studies

In 1946, using a captured German V-2 rocket, NRL scientists obtained the first far-ultraviolet spectrum of the sun [20]. This was the birth of both space-based astronomy and the U.S. Navy's space program. NRL was not alone in early attempts to measure the solar ultraviolet spectrum; Johns Hopkins University's Applied Physics Laboratory attained excellent results 6 months after NRL [20, p.4]. NRL's studies of the sun continued with the first measurement of ultraviolet and X-ray emissions from a solar flare in 1956, confirming the theory that X rays were responsible for radio fade-out. This was important because forecasting the sun's weather enables scientists to more accurately predict the effects of solar storms on civilian and military navigation and communications equipment on Earth. Some of NRL's most notable solar studies are described below.

NRL's monitoring of the sun's weather continued in 1960 with its development and launch of the first orbiting solar observatory satellite, Solar Radiation (SOLRAD) I. Although the SOLRAD program began as fundamental research, the results provided important clues to solar flare predictability. The program demonstrated that solar X rays are the most sensitive indicator of solar activity and are the major cause of sudden ionospheric disturbances in Earth's atmosphere. These solar flux data were transmitted from the SOLRAD satellites to both the National Oceanic and Atmospheric Administration (NOAA) and the integrated U.S.-Canadian North American Aerospace Defense (NORAD) Command. They were also sent to the Naval Communications Command to provide Fleet alerts warning of possible high-frequency communications disturbances.

Subsequent NRL SOLRAD satellites also served as solar radiation monitors—circling Earth, on guard for any unusual solar disturbances that could have endangered the lives of the Apollo astronauts. Special SOLRAD operations for the Apollo 8 moon mission began at the request of the National Aeronautics and Space Administration (NASA) in December 1968 when astronauts first circled the moon and returned to Earth. Later, during July 1969, solar flare forecasts derived from data furnished by SOLRAD 9 were used to safeguard Apollo 11 astronauts and their communications systems during the historic first lunar landing mission [21]. NRL furnished solar radiation data as rapidly as possible to the Space Disturbance

Forecast Center of the Environmental Science Services Administration (now NOAA), which had overall responsibility to NASA for determining the status of radiation hazards to the Apollo astronauts [21]. Timely information was important. Very intense solar radiation could have resulted in the cancellation of certain phases of the lunar missions. The SOLRAD data were particularly important during the periods when the astronauts were either in the lunar module or on the lunar surface. SOLRAD 9 and its follow-on, SOLRAD 10, continued to furnish this critical information throughout the Apollo program as well as the SKYLAB program, America's first orbiting laboratory.

NRL's solar studies continue today with the High-Resolution Telescope and Spectrograph (HRTS). This instrument first flew on the NASA Spacelab 2 mission in 1985 and is scheduled to fly again on NASA's Orbiting Solar Laboratory in the mid-1990s. NRL scientist Dr. J.-D. Bartoe flew aboard the space shuttle on the Spacelab 2 mission. He has the distinction of being the first payload specialist to develop and then operate his own experiments in space—the HRTS and the Solar Ultraviolet Spectral Irradiance Monitor [22].

Radio Astronomy

Since 1950, NRL has been conducting fundamental radio astronomical research with forefront techniques and equipment. One such piece of equipment was the world's first fully steerable microwave parabolic antenna, which had a diameter as large as 50 feet. It was placed in service at NRL in the early 1950s [23]. In 1953, NRL radio astronomers first detected and measured interstellar ionized atomic hydrogen clouds (HII regions) as discrete radio sources, and in 1956 NRL detected the absorption of emission of radio stars by interstellar hydrogen gas. In 1957, NRL made the first accurate radar measurements of the distance to the moon, which gave more accurate information both on the radius of Earth and on lunar topography [24]. These landmark observations were followed by planetary studies marking the first accurate measurement of the surface temperature of Venus and discovery of the radio character of Jupiter and Saturn.

From this base of experience, NRL played a fundamental role in the eventual development and use of the Very Long Baseline Interferometric (VLBI) collaborative observing technique. With this technique, distant stations (antenna sites) are used to achieve expanded synthetic aperture resolution and charting of astrophysical sources. More recent advances in this program lie in the application of radio interferometry to achieve new precision astronomy for Navy time determination, navigation, and geodesy. In fact, NRL technical studies led to the first precise time transfer via satellite in 1970. This was important to the development of the highly accurate NAVSTAR system (see Section 3: *Navigation*).

Ultraviolet Astronomy

On October 10, 1946, NRL's Dr. R. Tousey used a captured World War II V-2 rocket to obtain the first photographs of the sun's ultraviolet (UV) spectrum beyond the atmospheric boundary (see also Section 2: *Solar Studies*). Later, when sounding rockets became available to explore the character of the radiation environment in space, NRL took the lead in investigating the character of the optical background in space. From an Aerobee rocket launched in 1957, NRL discovered that there is an intense nighttime and daytime glow over the whole sky. This glow is emitted or scattered from hydrogen in the extended high atmosphere at a wavelength of 1216 A—the extreme UV range. In 1970, also using an Aerobee rocket, NRL detected molecular hydrogen in interstellar space for the first time [25]. This was a significant finding in that it confirmed theories of star formation from interstellar gas. Although much indirect evidence for the presence of large amounts of molecular hydrogen in space had been accumulated prior to NRL's work, no direct measurement had been made before this rocket flight.

X-Ray Astronomy

In 1948, NRL directly confirmed that X rays from the sun are a principal cause of ionization in the E region of Earth's ionosphere [26]. This pioneering research opened the field of solar X-ray astronomy that the Laboratory explored so extensively in the 1950s (see Section 2: *Solar Studies*) and thus contributed profoundly to understanding physical processes in the solar atmosphere. Practical benefits of this research include an improved understanding of the effects of solar disturbances on radio communication and an improved ability to predict the influence of solar particle emissions on the radiation environment of manned space flight.

NRL's Dr. H. Friedman led the Laboratory's pioneering efforts in X-ray astronomy. In 1969, he received the National Medal of Science, our country's highest honor for scientific achievement, for "pioneering work in rocket and satellite astronomy and in particular for his contributions to X-ray astronomy" [27]. More recently, in honor of this work he received the coveted Wolf Foundation Prize for Physics in 1987. The Wolf Prize committee recognized [28] Friedman and the other two corecipients of the award...

> "as the principal founders of X-ray astrophysics, a new field of astronomical science which has proven to be a prolific source of fundamental discoveries and deeper physical understanding about high-energy processes in the universe. Their work has profoundly influenced every area of astronomical research. All agencies engaged in space science are now developing major orbiting facilities for X-ray observations which will play a vital role in the future of astronomical science."

Radiation Hazards

Radiation presents hazards to spacecraft components. During the 1970s, digital microelectronic components became so small that their logic state could be flipped by ionization from a fast heavy ion or by a proton-induced nuclear reaction. This phenomena, called single-event upset (SEU), dramatically reduces the reliability of microelectronic components used in space [29]. NRL helped reduce the level of this problem by developing semiconductor processing techniques that provided more than a thousand-fold improvement in radiation hardness. A wide range of systems, including DoD missiles and satellites and NASA space probes such as *Voyager*, have benefited from this technology [30].

Another way NRL made major contributions to this problem was by developing means of predicting SEU rates in digital electronic components inside any spacecraft, in any orbit. The Laboratory used its expertise in cosmic ray environments to develop what have become the standard methods for predicting heavy ion upset rates [31]. NRL also made major contributions to the general understanding of SEU and developed standard methods for predicting upset rates resulting from protons in the trapped radiation belts [32].

NRL's expertise in this area has resulted in it serving as the lead laboratory for the Defense Nuclear Agency's SEU hardening efforts. The models and computer codes developed at NRL in the 1980s for SEU rate prediction have been used in the design of all Navy and other DoD spacecraft. These methods have also been used by NASA, the European Space Agency, and the Indian Space Research Organization. In short, SEU rate prediction makes it possible to develop SEU hardening techniques, and to avoid the design errors that have led to expensive spacecraft retrofits and malfunctions. The Laboratory's efforts in this area have continued with SEU microelectronic testing on the CRRES satellite and with environmental experiments aboard NASA's Long Duration Exposure Facility [33].

3. SPACE TECHNOLOGY

The Navy's Lead Laboratory for Space Technology

With the Laboratory's space technology activities dating back to the pre-Sputnik era, NRL is one of the oldest government space technology organizations. By 1987, NRL had been involved in the launch of more than 80 satellites [34]. In recognition of this sustained record of excellence, the U.S. Navy in 1986 formalized the Laboratory's status as its lead laboratory in space technology by officially inaugurating the Naval Center for Space Technology at NRL.

Rocket Programs

In 1945, NRL established the Rocket-Sonde Research Branch to explore the upper atmosphere, the first such program in the U.S. [35]. After World War II, as the only established group ready and able to immediately carry out upper air research, NRL became the prime agency for conducting such research when captured German V-2 rockets were made available. The Laboratory also became responsible for developing the techniques, instrumentation, and devices for carrying out the V-2 missions. Almost without exception, each atmospheric experiment contributed significant information that not only advanced the knowledge of the physics of the upper atmosphere but also helped to launch the era of space exploration (see Section 2: *Solar Studies*). This experience with rockets and scientific experimentation led to the Viking Project and eventually to the selection of NRL to conduct the nation's first satellite program, Vanguard.

The Viking Project

In 1946, NRL directed the development of a new sounding rocket called Viking. It was designed and built by the Glenn L. Martin Company. The rocket motor was built by Reaction Motors Company, the firm that had just constructed the motor for the Bell X-1 aircraft, in which Chuck Yeager broke the sound barrier in 1947 [36]. Viking was the first rocket designed for essentially research purposes and the first to use a gimballed motor to control the direction of flight [35, p.132]. The first successful launch of the Viking took place at the White Sands, New Mexico, proving ground in 1949. In 1950, a rocket was launched from a ship, the USS *Norton Sound*, achieving an altitude of 106.4 miles [35, p.132]. This launching of such a large rocket from the deck of a ship had a very important national security ramification in that it was a step toward the eventual deployment of missiles at sea. In an article describing the Viking launch from the USS *Norton Sound*, Life Magazine observed:

> "...the scientists onboard had reason to be pleased. The Navy members of the expedition were happy too: they had proved for the first time that big rockets... could be launched from the deck of a ship" [37].

In all, 12 Viking rockets were launched by NRL between 1949 and 1954, establishing many milestones: highest altitude of any research rocket at that time (136 miles) [16, p.47]; first measurements of temperature, pressure, and winds in the upper atmosphere; first measurements of the electron density in the ionosphere; and first high-altitude (approximately 100 miles) photographs of Earth. The first high-altitude picture of a hurricane was taken in October 1954 from a Viking rocket. This was the first color photograph successfully taken from such altitudes, and it initiated the interest of the Weather Service in high-altitude weather monitoring [8, p.22].

In 1954, a design study completed at NRL concluded that a multistage rocket, using a Viking as the first stage and an Aerobee-Hi (a smaller, cheaper rocket designed by the Applied Physics Laboratory of Johns Hopkins University with technical help from NRL) as a second stage could reach orbital height and velocity with a small payload. This study was the genesis of the historic Vanguard Project.

Vanguard Project

Between 1955 and 1959, NRL conducted the first American satellite program, called Vanguard. The program was initiated to represent the United States in the International Geophysical Year (IGY). IGY was a cooperative international scientific effort to study the physical properties of Earth. The nation's leaders in science decided to participate in the IGY by placing an artificial satellite in orbit. Following this decision, a competition was held to determine which U.S. government agency would build and launch the satellite. The plan submitted by NRL was selected due, in part, to its success with the Viking program. NRL's pioneering task was to design, build, launch, place into Earth-orbit, and track an artificial satellite carrying a scientific experiment.

With no suitable satellite launching facilities available at that time, NRL constructed the first complete launching facility on Air Force property at Cape Canaveral, Florida [8, p.23]. Since a suitable satellite-tracking system also did not exist, NRL developed the world's first satellite-tracking system (called Minitrack) in 1956. This tracking network became the prototype for the networks used in tracking later Project Mercury missions. It also was later used to determine, by observing orbiting U.S. and Soviet satellites, the upper atmosphere density [38]. Ironically, the Minitrack system first demonstrated its capabilities by tracking another nation's satellite—from October 5 to 26, 1957, NRL accurately predicted and tracked the orbits of the Soviet Union's Sputnik I. Three months later, NRL confirmed and tracked Explorer 1, America's first orbiting satellite launched into orbit by the U.S. Army. Explorer 1 was launched on a previously developed military rocket.

The Vanguard I satellite was successfully launched into Earth orbit on March 17, 1958, 5 months and 13 days after the Soviet Union launched Sputnik I, and about 6 weeks after the launch of Explorer I. Although it was not the first successfully launched U.S. satellite, Vanguard I achieved the highest altitude of any man-made vehicle to that time and established beyond doubt geologists' suspicions that Earth is pear-shaped [39]. It carried two radios and a temperature sensor and was the first satellite to use solar cells as a power source [8, p.23]. Because its predecessors, Sputniks I and II and Explorer I, have since fallen out of orbit, Vanguard I orbits Earth today as the oldest man-made satellite and will remain in orbit well into the 22nd century.

Successfully designing and developing a three-stage rocket, with three brand-new and unproven stages, on such a timely schedule was unprecedented. In fact, experience in the Department of Defense at that time showed that in missile programs it took more than five years from the start of a program to arrive at the first successful launch. The Vanguard team achieved their objective in 2 years, 6 months, and 8 days [16, p.31]. Vanguard II was placed in orbit on February 17, 1959, and was the first satellite designed to observe and record the cloud cover of Earth. As such, Vanguard II was the forerunner of future meteorological satellites [8, p.23]. Eventually, the National Aeronautics and Space Administration (NASA) was created, and all assets of the Vanguard project, including more than 200 NRL scientists and engineers, were transferred to the new space agency. This group of NRL researchers helped start NASA on its highly successful missions.

Space Surveillance

After the Soviet launch of Sputnik I in 1957, detecting and tracking foreign satellites orbiting over the U.S. became a major national security issue. As a result, the Navy Space Surveillance System (NavSpaSur) was developed (1958-1964) by NRL on a "crash basis" for the Advanced Research Projects Agency to detect and track such satellites. NRL was selected to develop this system primarily because of its success in developing the Minitrack satellite tracking network for Project Vanguard (see Section 3: *Vanguard Project*). Unlike the Vanguard tracking system, NavSpaSur was designed to track both satellites that transmitted signals and those that were "quiet". NavSpaSur now consists of nine radar sites stretching between southern California and Georgia and comprises a radar "fence" capable of detecting basketball-sized objects in orbit as high as 7,500 miles above Earth [35, p.133]. The information gathered by this system is used to warn U.S. naval fleet units of periods when they would be vulnerable to detection by foreign satellites.

By 1983, NavSpaSur was a critical element in the North American Aerospace Defense Command's Space Detection and Tracking System and was tracking more than 4966 objects every day. The system by then had also detected and cataloged more than 14,239 orbiting objects since its inception. An upgrade of this system, accomplished by NRL in 1984, should extend the system's operational life for about 15 more years [40].

Navigation

The NAVSTAR Global Positioning System (GPS) is a DoD program to provide precise navigation data to military and civilian users by means of a constellation of 24 satellites. NAVSTAR is based on NRL's TIMATION (TIMe/navigATION) research program, begun in 1964. NRL's R. Easton is recognized for conceiving the idea of the time-based navigational system, which eventually led to the global positioning system [41].

The TIMATION technique was passive, requiring no signal transmissions by the users. In a global operational system based on the TIMATION concept, signals are received automatically from the NAVSTAR satellites and converted by small computer to highly precise position measurements. In demonstrating the feasibility of such a system, NRL conducted basic tests of the TIMATION technique through the use of two small experimental satellites, TIMATION I and TIMATION II.

NRL launched the TIMATION I satellite on May 31, 1967 and the TIMATION II satellite on September 30, 1969. TIMATION I demonstrated that a surface vessel could be positioned to within two-tenths of a nautical mile and an aircraft to within three-tenths of a nautical mile by using range measurements from a time-synchronized satellite [8, p.24]. In short, the TIMATION program proved that a system using a passive ranging technique, combined with highly accurate clocks, could provide the basis for a revolutionary navigation system with three-dimensional coverage (longitude, latitude, and altitude) throughout the world. In 1973, the NRL TIMATION effort was merged with an Air Force program that was investigating similar techniques to form the NAVSTAR GPS program. NRL's TIMATION III satellite was then redesignated the Navigation Technology Satellite One (NTS-1), and was launched in 1974 in connection with the new NAVSTAR effort. NTS-l had the distinction of carrying the first atomic clock into orbit [35, p.134].

The successful launch in June 1977 of NTS-2 as the first NAVSTAR GPS satellite marked the beginning of a new era in navigation and timekeeping. NTS-2 had the distinction of verifying Einstein's relativistic clock shift by measuring the effects of relativity on the frequency of an accurate clock in an orbiting satellite compared to a similar clock on the ground [42]. The NTS-2 spacecraft was also host for a number of small experiments and technology demonstrations. Most prominent was the use of a nickel hydrogen battery as the primary energy storage device.

A primary military objective of the NAVSTAR program is to support the Navy's Fleet Ballistic Missile Program [8, p.24]. In the event of a nuclear strike, strategic missile submarines would obtain last-minute position fixes from navigation satellites to update their inertial guidance systems. Such fixes provide reference points for adjusting guidance systems of the submarine-launched ballistic missiles. For tactical naval power projection operations, NAVSTAR information allows amphibious forces to locate the correct landing zone, day or night. The satellites also significantly improve the accuracy and coordination of artillery barrages, air-to-ground attacks, and parachute supply drops [43]. Naval air strike operation efficiency, in terms of the quantity of munitions and the number of sorties to perform a given mission, is also likely to improve significantly as the result of more accurate positioning of the aircraft. For sea control operations, the ability of GPS satellites to provide common accurate positioning data to a wide variety of weapons platforms improves the ability of the Navy to maintain the level of sea control necessary for effective naval power projection operations.

The aforementioned wartime applications of the NAVSTAR system were put to the absolute test in the 1991 Desert Storm operation. Accurate navigation information was critically important to each of the U.S. military services in the Gulf War. Because of NAVSTAR, such information was available within seconds, whenever it was needed. In fact, the demand for GPS information was so great that the 4,000 GPS receivers that were available when the war began were immediately snapped up, and thousands more had to be provided [44]. The Navy used GPS to pinpoint the location of minefields in the Persian Gulf and to provide midcourse guidance information for standoff land attack missiles. Army and Marine artillery batteries used GPS to locate their positions to within a few meters, and U.S. ground troops used GPS receivers small enough to fit in their packs for accurate and rapid mobility.

GPS promises civilian applications as well. For example, emergency vehicles and delivery vehicles could have GPS receivers linked to electronic map displays to direct them to within a few feet of any address [45]. In the future, this navigation technology may also help ensure that no aircraft ever strays off course and no ship or boat ever runs aground in fog.

On February 10, 1993, the National Aeronautic Association (NAA) selected the Global Positioning System (GPS) Team as winners of the 1992 Robert J. Collier Trophy, the most prestigious aviation award in the U.S. This team was composed of researchers from the Naval Research Laboratory, the U.S. Air Force, the Aerospace Corporation, Rockwell International Corporation, and IBM Federal Systems Company. The citation accompanying the presentation of the trophy honors the GPS Team "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."

The Collier Trophy, established in 1912, is given annually "for the greatest achievement in aeronautics or astronautics in America, for improving the performance, efficiency, or safety of air or space vehicles, the value of which has been thoroughly demonstrated by its actual use during the preceding year." The original Collier Trophy is on permanent display at the National Air and Space Museum of the Smithsonian Institution [46].

Strategic Defense R&D

NRL was tasked by the Strategic Defense Initiative Organization (SDIO) in 1985 to design, integrate, test, launch, and operate a satellite to serve as an instrumented target for low-power ground-based lasers conducting atmospheric compensation tests. In short, this experiment was designed to evaluate whether the atmospheric distortion of a laser beam could be corrected; this would be required for ground-based lasers to become a viable missile defense system. In 1987, the original tasking was expanded to include acquisition, testing, integration, and operation of an instrument that would obtain images of the ultraviolet (UV) emission from rocket plumes. This UV plume instrument, built by Loral EOS Company, could provide data for a system that would be able to better locate a rocket body in relation to its plume for missile defense [47]. This is necessary because the plume emission in commonly observed wavelengths, such as the visible and infrared, can envelop and hide the dark missile, which is the real target for strategic defense systems.

To achieve these objectives, NRL built the Low-power Atmospheric Compensation Experiment (LACE) satellite, which was launched on February 14, 1990. On November 30, 1990, the first of a series of highly successful laser compensation demonstrations was achieved. During a typical experiment, a low-power laser beam was directed at the LACE spacecraft as it passed overhead. Transit through the atmosphere caused the laser beam to be distorted, which resulted in the spreading of the beam at satellite altitudes. This is the same effect that causes stars to twinkle. Adaptive optics techniques were then applied by Massachusetts Institute of Technology's Lincoln Laboratory to compensate for these distortions, thus greatly reducing the spreading of the laser beam [47, p.2].

The second LACE instrument, the UV plume instrument, achieved four successful rocket plume observations out of four launches in its first year of operation. In addition to the rocket plume data, important Earth background data such as aurora, volcanoes, and measurements of emissions from city and highway lighting were also collected [47, p.18]. Data from the LACE satellite's two experiments are extremely important to the SDIO's mission; they could provide valuable data required for the eventual design of future systems providing defense against strategic nuclear missiles.

In 1991, NRL's LACE satellite team received the American Defense Preparedness Association's Technical Achievements Laboratory Award. This prestigious award is given annually to a government or industry laboratory for outstanding R&D. NRL's Director of Research, Dr. T. Coffey, and the LACE program manager, R. Palma, accepted the award for NRL at a ceremony at the U.S. State Department.

4. MATERIALS SCIENCE AND TECHNOLOGY

Nondestructive Testing

NRL's development of gamma ray radiography was an important contribution to the nondestructive testing (NDT) of metal castings and welds. The method was devised by R. F. Mehl in the 1920s, and it entailed the use of gamma-ray radiation as a shadow-graphic technique to detect flaws in cast or welded steels. This technique was first used to ascertain the extent of suspected flaws in the stern post castings of the U.S. Navy's new 120,000-ton heavy cruisers [48]. Upon examination, the stern post castings of these vessels were found to be faulty, and all 10 cruisers of the affected class subsequently had to be repaired to avoid operational failure. During the five-year period before World War II, this NDT technique facilitated the development of improved steel casting processes. By trial and nondestructive examination, the methods used in all stages of the molding, casting, and testing of steel were improved.

This work contributed to American seapower by improving the production of the highest quality steel for armor, ship frames, and fittings. Currently, the American Society for Nondestructive Testing remembers Dr. Mehl with a biannual Mehl Honor Lecture. This lecture is presented at their annual meeting by a speaker selected for outstanding contributions to NDT [48, p.117].

Fracture Mechanics

Fracture mechanics is a field of science and engineering which recognizes that all structures are manufactured with, or will ultimately contain, flaws that govern the eventual failure of the structure. The study of the stresses caused by the flaws, and the material's resistance to failure from them, forms the basis for the field of fracture mechanics—an area of science and engineering pioneered by NRL. In fact, the term "fracture mechanics" was coined and used locally at NRL in the early 1950s [49]. Fracture mechanics permitted, for the first time, the capability to calculate the strength of structures containing defects or flaws that inevitably occur in fabrication or during service operation. The net result of these new design principles increased the reliability of structures as the result of improved design capability and an improved predictive capability of in-service damage. Prior to these techniques, the primary way to determine the structural integrity of structures was by gamma ray radiography, which had been devised by NRL's R. F. Mehl in the 1920s. Today, fracture mechanics has become a science that has been applied throughout the world in the design of any structures where sudden, catastrophic failure would cause loss of life or other serious consequences. Notable examples are nuclear reactor pressure vessels, aircraft and missiles, and tanks for storage of toxic or flammable materials.

NRL R&D conducted by G.R. Irwin, J.A. Kies, T.W. George, and W. Pellini from 1937 to 1971 led to the development of fracture-safe design principles, thus solving an engineering problem that had baffled the best technical talent for decades. The NRL fracture research program was begun during a crisis stemming from the catastrophic failures of a considerable number of welded cargo vessels and tankers. During World War II, roughly 1,200 of approximately 5,000 welded ships built during the war on a crash basis suffered failures with various degrees of severity [50]. After the war, NRL solved the problem of brittle fracture in steel ships, by using experimental methods and by developing engineering approaches to materials selection.

In general, NRL's efforts in the field of fracture mechanics can be divided into those related to science, those related to engineering, and those related to both science and engineering.

Scientific Principles

NRL's Dr. G.R. Irwin is recognized as the pioneer of modern fracture mechanics. During his tenure as superintendent of NRL's Mechanics Division he developed the scientific principles for understanding the relationships between applied stresses and cracks or other defects in metallic materials. Beginning with Griffith's basic work on the fracture of glass, Irwin developed, around 1947, the concept that fracture toughness should be measured in terms of resistance to crack propagation [51]. Critical values of the stress intensity describing the onset of fracture, the onset of environmental cracking, and the rate of fatigue crack growth were established later.

To illustrate the significance of these groundbreaking scientific developments, two events can be cited. The first event was the formation of an American Society for Testing and Materials (ASTM) Committee on Fracture, which dealt almost exclusively with standardization of the applications of fracture mechanics as introduced by Irwin's work. The second event was the U.S. Air Force's use of fracture mechanics to design military aircraft following fracture problems experienced with the F-111 fighter bomber. The Air Force applied the term "structural integrity technology," which was the application of fracture mechanics established by Irwin and others in NRL's Mechanics Division and developed further by aerospace companies and universities [48, p.77]. The Air Force required materials property data and design analysis based on this technology.

As a result of Irwin's scientific work, fracture mechanics is now taught in many graduate schools and remains an active field of R&D today. The NRL procedures are now "standard doctrine" for naval engineering; the NRL reports issued on these procedures were at one time used as textbooks in universities [52]. Furthermore, the impact and significance of these procedures pertain to all types of metal structures—submarines, aircraft, fast surface ships, etc.

Engineering Principles

While Irwin was concerned primarily with the basic science of fracture using mechanics methods, W.S. Pellini in NRL's Metallurgy Division established methods for prevention of fracture based on experimental methods. Pellini developed engineering approaches for design and material selection in structures based on metallurgical principles. The most prominent example is materials for submarine pressure hulls, which had to withstand local deformations from explosive attack without crack extension. Pellini and his colleagues worked with Navy ship and submarine materials and design offices to develop methods for evaluating materials, weldments, and welding processes. These methods, based on modeling, established the requirements for qualifying welds, welders, and new companies for the construction of submarine pressure hull structures. The Dynamic Tear Test, the Drop-Weight Nil-Ductility Transition Temperature Test (DWT-NDT, standardized by the ASTM in 1963 and used with the Fracture Analysis Diagram for design of steel structures over the entire world), the Explosion Bulge Test, and the Explosion Tear Test, were all incorporated into the Navy's materials procurement and fabrication specifications for construction of critical submarine and surface ship components [48, p.123].

In particular, the DWT-NDT proved that the fracture resistance of HY-80 steel was superior to conventional steels. The fully plastic performance of welded HY-80 plates in the Explosion Bulge Test convinced the Navy that HY-80 should be used for submarine hulls and for any other critical application [48, p.123]. In practice, the evaluation of higher strength alloys, such as HY-80 and HY-100, by fracture mechanics methods has permitted the reliable deployment of deeper running U.S. submarines. In addition, two Navy Deep Submergence Rescue Vehicles were put into the fleet in 1971 and 1972 with pressure hull material certified to be reliable as measured by fracture mechanics methods.

A unique project related to the engineering fracture safety efforts was developing a method for bomb disposal. This was accomplished in cooperation with the Washington D.C. Police Department, which required a method to safely and quickly dispose of bombs found in public buildings. NRL's solution was a containment vessel, open at the top, which could withstand the explosion and vent the force directly upward. Two such vessels were built and mounted on trucks by the Police Department. One was tested by detonating an explosive package in the truck-mounted vessel. The explosion deformed the vessel and bent the truck frame, but the vessel did not fracture, which was the desired result [48, pp.24-25].

Combined Scientific and Engineering Mechanics

The two fracture efforts—basic research and engineering mechanics—had much in common. One of the foremost was the use of fracture mechanics principles to describe environmentally influenced crack growth, also known as stress corrosion cracking (SCC). This method was developed jointly by J.A. Kies in the Mechanics Division and B.F. Brown in the Metallurgy Division about 1965 [53]. This method was to have a long-term impact on materials applications for service in different environments, particularly on the Navy's criteria for new metals.

In 1964, in a controversial incident, NRL could not convince the Navy that SCC could be a problem for titanium alloys, even though the Laboratory produced data and samples of material that were very susceptible to seawater SCC. The material was a titanium alloy, Ti-7Al-2Cb-1Ta (721), which was being developed for submarine pressure hull use. In this alloy, NRL found that under the right conditions crack growth was so rapid that cracks on the order of inches in length could develop in minutes [48, p.30]. The Laboratory reported its findings in a December 1964 Quarterly Progress Report, however NRL's judgment was not believed [54]. The issue was resolved when two small plates of welded 721 and some small models were left outside on a dock. When it rained, they cracked from the combined action of residual stress and water. This accidental demonstration of the effects of SCC convinced the Navy to stop the 721 program, which had progressed to the rolling of large plates to demonstrate mill capability. Titanium, as a submarine hull material, never recovered the momentum it had at the time. However, the continued use of 721 on a large scale would have been a disaster for the U.S. Navy.

Through related research it was also discovered that two other developmental materials, HY130 and Ti-811, had some sensitivity to SCC. This fact has been the principal impediment to HY130's introduction into the construction of ships and submarines. It also was responsible, in part, for the cancellation of the government-sponsored Supersonic Transport Program, which would have extensively used Ti-811 in the aircraft's engines and airframe [48, pp.30,135; 53]

Other Selected Applications

By using the principles developed on fracture-safe design, NRL helped solve many other important military and commercial problems. Some of these applications are discussed below.

Commercial aircraft fuselage fractures—NRL used fracture-safe design principles to analyze and solve failures in pressurized aircraft cabins to avoid aircraft losses such as those experienced by British DeHavilland Comet aircraft between 1953 and 1954 [55]. In fact, fracture mechanics principles first gained international recognition when they were used to explain the failure of these aircraft [56].

Polaris missile failures—In the case of the Polaris submarine-launched ballistic missile, NRL was given the main responsibility for solving the Polaris program's problem in which too many of the welded ultra-high-strength steel rocket chambers broke during static testing. This problem threatened a serious risk to the timetable of America's first program to place part of its strategic nuclear retaliatory force at sea. NRL solved the Polaris problem in 1958 and later participated in the successful effort to launch the second-generation Polaris SLBM in 1960. The Minuteman intercontinental ballistic missile program, phased about one year behind Polaris, also encountered fracture problems and received some help from NRL. A decade later, in the 1970s, NRL made recommendations regarding design criteria and proof loading for the missile-handling gear of U.S. strategic ballistic missile submarines [49, p.36; 55].

Nuclear power reactors—Another remarkable example of the application of the fracture technology developed at NRL was the participation of the Metallurgy Division in the Heavy Section Steel Technology program conducted by the Nuclear Regulatory Commission (NRC). The technical issue was to determine the safety of nuclear reactor pressure vessels fabricated from 12-inch-thick steel as a function of thickness and temperature. NRL's Pellini and F.J. Loss built the apparatus and conducted experiments on full-thickness specimens to demonstrate the safety of the vessels. The program lasted several years and attracted international attention. Currently, the ASME Code rules for the operation of nuclear pressure vessels are based on the results of that program [48, p.127]. In addition, all military and civilian power reactors that feature a steel pressure shell are designed or operated, or both, on these principles developed by NRL [57].

Aircraft carrier propellers—For more than forty years, the manganese bronze propellers on U.S. aircraft carriers have been cracking after only short periods of service, necessitating drydocking of the ships. Repair procedures required rewelding the cracks and relieving the propeller stress before placing both the propeller and the ship back into service [58]. However, in 1983 NRL was asked to perform a failure analysis of the propellers from the USS *Carl Vinson* and the USS *Independence* [59]. After collecting samples, visiting commercial heat treaters and Navy yards, and performing the analysis, NRL concluded that the stress relief treatments were actually adding stresses. Two NRL reports solved this problem and resulted in a change of procedure [60]. The adoption of the Laboratory's recommendations are now apparent throughout the Navy community; the yards have scrapped their previous procedures, built new buildings, and are using the tighter controls and modified temperatures suggested by NRL. The monetary savings are roughly $100,000 per repair [58], but the value to national security that results from keeping the Navy carriers at sea cannot be calculated.

Solid-State Dosimetry

NRL pioneered the field of solid-state dosimetry in the late 1940s and continued a leadership role in the evolution of the science and applications of ionizing radiation measurement over the next two decades. The first result of this work was NRL's development of silver-activated glass dosimeters that were accepted as the standard personnel radiation monitor in the 1950s [61]. In 1960, NRL's research in this area yielded the first successful thermoluminescent dosimetry system, which displaced the photographic film badge as the standard for radiation workers all over the world [62]. Those radiation dosimeters now provide the military with a diagnostic tool for radiation exposure as well as serve medical uses in areas such as clinical radiology and cancer treatment [63].

Materials Safety and Durability

Radiation Damage of Metals

In the early 1960s, NRL demonstrated the potentially severe embrittlement of nuclear reactor steels to be a function of neutron exposure and irradiation (service) temperatures. While emphasizing light water reactor pressure containment steels and their modes of failure after neutron exposure, other properties of other reactor component alloys were studied as well. Broad interest in NRL's work led to support by the Atomic Energy Commission and the Army. The results of this program were presented in various media, and the work of the Laboratory became well-known. This work is believed by most nuclear safety authorities to be the primary basis for assurance against catastrophic failure of radiation containment. In 1975, a definitive book, *Neutron Irradiation Embrittlement of Reactor Pressure Vessel Steels* (International Atomic Energy Agency TRP 163), was published and became a landmark guide for specialists around the world [48, p.131].

Solving the radiation embrittlement problem in reactor pressure vessel steels eventually led to the production of radiation-resistant steels that are applied in new reactors throughout the world and in the assurance of reactor containment safety in older reactors. In 1967, NRL developed the first laboratory quantities of a steel that was insensitive to neutron radiation embrittlement and later developed criteria for the U.S. steel industry's use in manufacturing the steel on a commercial scale [64]. The use of this steel greatly reduces the potential for fracture resulting from neutron-irradiated embrittlement. This development was important to the nuclear power industry because one large commercial nuclear power plant represented a financial investment in 1970 of as much as $100 million [52]. However, the greatest significance of this accomplishment is in increased safety levels, since an accident involving the fracture of the containment vessel to a nuclear reactor could result in incalculable damage.

Sonar Dome Rubber Windows (SDRW)

SDRWs are steel-wire-reinforced neoprene structures that provide a hydrodynamic shape and separate the sea from the sonar array on the bows of several classes of ships. The SDRWs weigh approximately 19,000 lb, are about 37 ft long, 21 ft wide, and 9 ft high, and have a wall thickness between 1 and 8 in. [65]. In 1971, SDRWs were introduced into the U.S. surface combatant fleet as a replacement for steel sonar domes. Rubber is preferred to steel because rubber allows the sonar to have a longer effective range than steel. However, by 1981 the Navy had become concerned because the new 10-ton rubber domes had been failing because of unknown causes. By 1983, NRL determined the cause of the SDRW failures to be corrosion fatigue of the steel wire cord reinforcement material. By solving this problem the Navy was able to achieve higher fleet operational readiness, acquire an improved means for monitoring the operating conditions of the SDRWs, and achieve lower costs because unscheduled drydocking for SDRW replacement was avoided.

In a ceremony held at the Laboratory on October 23, 1987, NRL's C. D. Beachem received a citation from the Chief of Naval Research for determining the cause of the SDRW failures. The citation noted that "the cost savings that have resulted to the U.S. Navy as a result of Mr. Beachem's outstanding failure analysis accomplishment are in the millions of dollars" [66].

Corrosion Research

Important accomplishments have been made by NRL in the general area of corrosion research related to aircraft structures, boilers, and hulls. Research in these areas has established a position of leadership for NRL, based on a steady flow of superior work. In particular, between 1950 and 1960, NRL developed the cathodic protection system for ships, allowing the U.S.'s large "mothball" fleet to rest in floating storage for years without danger of hull destruction through electrolytic corrosion [67]. The Navy's Bureau of Ships adopted this system as standard for some 1500 ships. The installation costs have been judged to be from one third to one quarter the cost of less desirable commercial units available at the time [50].

Superconductivity Research

Superconductors, which operate at cryogenic (near absolute zero) temperatures, are known to transmit electrical current with no direct current resistance losses and permit much smaller systems to be used than are needed with conventional conductors.

NRL has had a continuous history in superconductivity research since 1948, when scientists here began investigating the electromagnetic response of superconducting materials. During the 1950s and 1960s, NRL's research focused on fundamental properties: searching for new materials and probing the basic mechanisms of the phenomena. It was during this time period that NRL established an international reputation for research in superconducting materials by discovering superconductivity in the elements iridium (T_c = 0.10 K) and tungsten (T_c = 0.015 K) and in the compound germanium-tellurium (GeTe) at temperatures near 0.3 K [48, p.57]. This latter discovery in 1967 takes on great historical significance since it was the first low carrier concentration superconductor ever found, and confirmed a theoretical prediction made in 1964. Interest in the low carrier superconducting materials continued at a low level of interest throughout the world until this class of materials led to the Nobel-prize-winning discovery of high-temperature superconductivity in low carrier density cuprate oxides in 1986 by IBM researchers.

In the 1970s and 1980s, NRL's program expanded to include both theoretical studies and applied efforts. During this period, NRL developed techniques for fabricating superconducting wire from brittle materials and for making quality thin-film superconducting materials for a variety of device applications. In 1975, NRL developed a superconducting composite wire that was superior in critical-current carrying density to any superconductor known at the time. In 1977, NRL improved the critical current density of the wire by 60%, while the earlier 1975 development was awarded a patent. This work on wire development continued until 1982. However, work was later re-started to develop wires composed of the new high-temperature superconductors [68].

NRL continues superconductivity research to the present. After the high-temperature superconductivity breakthrough by IBM in 1986, NRL was well positioned to respond to the rapidly evolving scientific advances. By March 1987, NRL had isolated, identified, and established processing procedures for the first superconducting material with a transition temperature over 90 K [48, p.62]. This discovery led to the filing of a patent application for the material. In August 1987, NRL was tasked to chair the Naval Consortium for Superconductivity (NCS), which was instructed to develop a Superconductivity Program to focus the Navy's investment in the most important areas. The Navy has many potential uses for superconductivity, including motors for ship propulsion, magnetometers for underwater ocean surveillance, and detectors of electromagnetic radiation. One area of potential application for superconductors that is under investigation by NRL is space systems, specifically the development of high-temperature superconducting components and devices operating in the reduced-temperature environment of space satellites. NRL plans to conduct the first meaningful high-temperature superconductor experiment in which the devices are operated in space. This program has been nationally recognized as one of the most aggressive programs in the world for promoting systems applications of superconductivity [48, p.63]. Another technology under investigation is the Superconducting Quantum Interference Device, or SQUID, which could be used to detect submarines and mines.

Ion Implantation Technique

In 1977, NRL researchers devised a surface modification technique for developing new materials with unique and extraordinary properties by forcibly implanting ions (electrified atoms) into ordinary materials. The new properties can be physical, chemical, electrical, optical, or mechanical. Ion implantation offers broad new areas of applications including corrosion-resistant ball bearings, wear-resistant sliding bearings, and radiation-resistant semiconductor devices [69].

In 1986, ion implantation of gas turbine aircraft bearings was demonstrated on an industrial scale as a result of the successful completion of a Manufacturing Technology program by NRL and Spire Corporation. This project provided the impetus for making ion implantation a viable industrial technology for the surface treatment and modification of critical components of naval equipments that are subject to degradation by corrosion and wear. The program successfully demonstrated ion implantation processing for several components for which service lifetime can be extended by 200% or more, with attendant decreases in life cycle costs. Demonstration components included helicopter rotor hingepin bearings, gas turbine aircraft bearings, helicopter gearbox bearings, beryllium alloy gyroscope bearings (used in missile guidance systems such as the MX), and printed circuit board drills. Other applications explored by Spire Corporation included kneejoint prostheses and the liquid oxygen pump for the space shuttle main engine [70].

More recently, in 1991, NRL assisted a defense contractor by using ion implantation to improve the performance of an experimental vibrating beam accelerometer (VBA). The VBA is a guidance instrument undergoing development by both the U.S. Navy and Air Force. It will result in an increase in guidance reliability and accuracy, as well as a reduction in the weight of guidance systems [71].

Permanent Magnet Materials

In 1980, NRL's N.C. Koon and B.N. Das were the first to examine the magnetic properties of rare earth-iron-boron (R_2-Fe-$_{14}B$) alloys, which showed promise for permanent magnet use [72]. NRL scientists did the first work on these materials and hold the fundamental U.S. patents. The NRL patents have been licensed to several firms, and products are being offered commercially. Since 1983, commercial alloys based on R-Fe-B have been in commercial production, and by 1985 these materials provided almost twice the magnetic energy density of the best materials previously available [73]. They are eventually expected to cost much less than the older materials because they are made from less expensive and more abundant elements.

These new magnet materials have had a tremendous impact in the concept and design of devices that use a magnetic field to produce motion. These materials promise to be useful by both the military and commercial sectors for improved microwave tubes; sensors; powerful, lightweight, electric motors and generators; computer peripherals; and faster, more compact actuators.

5. ENERGY-RELATED SCIENCE AND TECHNOLOGY

Nuclear Science and Technology

The Manhattan Project

NRL was the first research center that General Leslie Groves visited when he took charge of the Manhattan Project in September 1942. The Laboratory at that time had the distinction of being the first U.S. government agency to sponsor uranium research (in 1939) [74], work that resulted in the first successful separation of uranium isotopes by the liquid thermal diffusion process.

NRL's process of liquid thermal diffusion was one of the three methods that the Manhattan Project used to obtain the enriched uranium needed to form the first atomic bombs. In its early stages, the project used two uranium-enrichment methods, but in 1944 the bomb project reached a technical impasse. The project's director, Dr. Robert Oppenheimer, then became aware of NRL's research using liquid thermal diffusion as a method of separating uranium isotopes, and he subsequently urged its use in the Manhattan Project. After the war, in describing to Congress the importance of NRL's methodology to solving the project's impasse, General Groves recalled the moment he realized the importance of liquid thermal diffusion:

> "Dr. Oppenheimer ... suddenly told me that we had (made) a terrible scientific blunder. I think he was right. It is one of the things that I regret the most in the whole course of the operation. We had failed to consider (thermal diffusion) as a portion of the process as a whole" [75].

The Laboratory's contribution was accomplished by a team led by Dr. P. Abelson at NRL's main site and at a larger pilot plant built at the Philadelphia Naval Shipyard in 1940-1941 [76]. In 1944, the Manhattan Project had used NRL's pilot plant as a model for the construction of a similar plant at Oak Ridge, Tennessee, that was critical to the project's success [77]. During part of 1944 and 1945, NRL's team at Philadelphia shipped 5,034 lb of enriched uranium to the Manhattan Project at Oak Ridge—a substantial contribution to the atomic explosions of 1945 [78].

Finally, as a historical footnote to NRL's involvement in the Manhattan Project, Lieutenant (eventually Rear Admiral) W.S. Parsons USN, who armed the atomic bomb for the flight over Hiroshima, had been a member of NRL's wartime research group, working on monopulse radar [1, pp.140,444].

Nuclear Submarine Propulsion

It is a matter of record that NRL was the first U.S. government agency to undertake the study of atomic power. The use of nuclear power to propel submarines underwater was first proposed by an NRL physicist, Dr. Ross Gunn, in 1939, soon after fission was discovered [79]. In 1946, NRL scientists P. Abelson, R. Ruskin, and C. Raseman drew up a preliminary engineering design and recommendations for adapting nuclear power for submarine propulsion. Their plans were forwarded to the Bureau of Ships and the Chief of Naval Operations, thereby contributing to the development of the first atomic-powered submarine [80].

Detection of the First Soviet Atomic Test

Following the U.S. Bikini atoll atom bomb test, NRL became involved in developing the means for technical surveillance of Soviet nuclear weapons development. The Laboratory established a network of stations to detect radioactive fallout from the first Russian nuclear explosion. In 1949, NRL detected the first atomic blast by the Soviet Union [16, p.54; 20, p.5]. By chemical analysis of the fissionable material in rainwater, the Laboratory was able to fix the date of the first explosion. NRL's evidence, combined with evidence from other monitoring agencies of the government, led to President Truman's announcement to the world that the Soviet Union had exploded an atomic device, thus ending America's brief monopoly on atomic weapons.

High-Altitude Nuclear Explosion Effects

In 1963, the U.S. and U.S.S.R. signed the Partial Nuclear Test Ban Treaty, thereby agreeing to ban all atmospheric nuclear tests. A major impetus for the treaty grew out of worldwide concerns over radioactive fallout. Although the treaty offered unequivocal benefits for environmental protection, a military imperative remained to understand high-altitude nuclear explosion (HANE) effects. With high-altitude tests banned, it was necessary to pursue other alternatives.

In response to this national security requirement, NRL pioneered the theoretical basis and development of computer simulation models of a multitude of disruptive effects that occur in the aftermath of nuclear explosions in the upper atmosphere and ionosphere [81]. After a nuclear explosion in the atmosphere, a variety of plasma processes cause enhanced density and structuring to occur over thousands of square kilometers and persist for hours after a detonation. These processes are important to understand because they severely disrupt communications, sensors, and other space- and Earth-based military systems. In fact, the greater technical understanding of these phenomena was a contributing factor in the eventual political decision to terminate the Safeguard antiballistic missile program in the early 1970s.

In 1970, NRL began the first laser experiment to test many of these effects in the laboratory. This experiment produced the first confirmations of many important HANE phenomena and discovered many new phenomena that were not included in the theoretical or computer simulation models [82].

Fluid Dynamics

In the late 1960s, NRL conducted theoretical and computational investigations of HANE for the Defense Nuclear Agency. During 1970 and 1971, in the process of performing this work, NRL scientists developed an entirely new technique for solving fluid dynamic continuity equations on a computer. The technique, Flux Corrected Transport (FCT), made possible accurate calculations of shock and steep gradient phenomena by eliminating the oscillations, ripples, and numerical diffusion that had plagued all other techniques for decades. This improvement has been adopted by more than 500 computational laboratories, universities, and companies dealing with fluid flow problems [83].

In addition to the HANE research, FCT has been used in missile silo design, naval oceanography, nonacoustic ASW, and atmospheric communications research. Other applications include research in civil hydrodynamics and water resources, mine safety, atmospheric pollution transport, supernova explosions, solar weather prediction, laser and ion-beam fusion, and aerodynamics [84]. With 250 citations, the original paper on FCT was NRL's most cited publication during the period between 1973-1988 [85].

Pulsed Power Physics

NRL has established a history of leadership in high-power (10^{12} W) pulsed power research, beginning with the *Gamble I* facility. Completed in 1968, *Gamble I* was the first high-power, low-impedance generator to use demineralized water as a capacitive energy-storage medium at high voltage. The success of the *Gamble I* generator led to funding and completion of *Gamble II* in 1970, which was the most powerful generator of its kind in the world. Its output power ($\sim$TW) was greater than the combined electrical power capacity of the U.S. The *Gamble* generators are the prototypes for all modern high-power, low-impedance devices now in existence at private industry laboratories and at both DoD and Department of Energy laboratories [86].

Pulsed power generators were originally developed to provide intense X-ray sources for simulating nuclear weapon effects in the laboratory to supplement underground testing. Military electronics are exposed to this radiation to assess their survivability in a real nuclear environment. Pulsed power generators, such as *Gamble II*, are also used to generate high-power ion beams for applications that include imploding inertial confinement fusion (ICF) targets, material modification, and intense energy deposition in surface layers to simulate exposure to soft X rays from weapons.

High Voltage Technology

During the 1980s, the Navy's fleet of aircraft experienced an increasingly severe problem with wiring-related fires caused by unforeseen defects in the insulating material on the wires. In 1988 alone, 61 wiring fires were reported in the F-14, F/A-18, A6, EA6B, and E2 aircraft. One Navy estimate found that 143,641 wiring failures occurred during one year of naval aviation; for every flight-hour off-deck, nearly one hour of unscheduled wiring maintenance was required; 807,418 man-hours were spent on unscheduled wiring maintenance, which was 8.6% of all aircraft maintenance man-hours for the same period; and the mean flight hours between failures was 11.4 hours [87]. Most importantly, however, such wiring-related fires can result in catastrophic system failures with possible loss of aircraft and crew. In response to this serious situation, NRL was asked to investigate the wiring failure modes and to provide guidance for solutions.

NRL's work led the Navy to ban this type of wiring in all of its future aircraft. One test conducted by NRL found that the insulated wiring frequently burst into flames when hit by a projectile simulating a bullet or missile attack, thus raising concerns about a military aircraft's chances of surviving combat [88]. The other military services, as well as commercial aircraft companies, have now become more concerned about the use of this type of insulation. Since it is impractical to remove all such wiring in all naval aircraft at one time, NRL, in collaboration with a private company, has developed a technique to measure insulation aging and remaining useful life for all wires under the same environmental conditions. This technique allows maintenance managers to schedule wire replacement on an as-needed basis [89]. Clearly, NRL's investigation into the causes of wiring-related failures has had a major impact on the flight safety and efficiency of operations for all existing and future Naval aircraft, as well as an impact on other military and commercial aviation.

6. CHEMISTRY

Submarine Atmospheric Habitability

NRL's work in this area began in 1929 following two submarine disasters. A special Submarine Board appointed by the Secretary of the Navy recommended that NRL undertake the study of hydrogen detection and removal, elimination of carbon dioxide, ventilation of batteries, and development of fire extinguishers for submarines. This early work resulted in the gradual development of lithium hydroxide as a carbon dioxide adsorbent, the chlorate candle as an emergency source of oxygen, superior storage batteries, and improved analytical techniques [16, p.68].

Between 1950 and 1956, as the age of the nuclear submarine emerged, the requirement grew for extending the capabilities of closed-cycle atmospheres for periods up to 90 days. The need for new atmosphere habitability capabilities was especially evident when NRL participated in the first scientific cruise of the nuclear submarine USS *Nautilus*. New requirements discovered on the cruise included the continuous replenishment of oxygen, and the removal of carbon dioxide, hydrogen, carbon monoxide, and numerous other pollutants such as hydrocarbons from paint solvents. In response to these critical needs, NRL research sparked the development of a continuous carbon dioxide adsorbing system; a special catalytic system for burning carbon monoxide, hydrogen, and hydrocarbons; a composite analyzer for the principal atmospheric gases; electrostatic precipitators for eliminating smoke and other aerosols; and an electrolysis system for decomposing water to provide a continuous supply of oxygen [90].

In 1975, NRL developed the Central Atmosphere Monitor System (CAMS), which allowed submarines crews, for the first time, to reliably monitor the air aboard their boats [91]. CAMS is a combination carbon dioxide detector and fixed-collector mass spectrometer that monitors hydrogen, water, nitrogen, carbon monoxide, oxygen, carbon dioxide, and refrigerant gases. The system became the first submarine air monitor to be "service approved" and was subsequently installed on all U.S. Navy nuclear submarines [92]. NASA also uses a variant of this system for manned space vehicles. Each of the above systems developed by NRL now has its counterpart, either in civilian air pollution control systems, medical research, or in the national space program [93].

Fire Suppression

Purple-K-Powder

In 1959, a series of original investigations by NRL in the area of chemical flame extinction gave birth to the discovery of a new, dry chemical agent called potassium bicarbonate powder. Powdered bicarbonate of soda as a flame-halting agent had been used for many years, but its action had never been satisfactorily explained. Working with other investigators, NRL conducted fire tests with many powdered substances that helped explain the chemical actions involved. This work came to the conclusion that the simple substitution of the potassium ion for sodium extended the flame-quenching efficiencies of the chemical powders by a factor of two. American industry was called in at that point, and the new highly effective product, called Purple-K-Powder by its NRL discoverers, became used throughout the Navy and in U.S. municipal and industrial fire protection operations, and thereafter throughout the world [16, p.44].

Aqueous Film-Forming Foam

Beginning in the early 1960s, NRL conducted research on fire suppression that eventually led to one of the most far-reaching benefits to worldwide aviation safety—the development of aqueous film-forming foam (AFFF). AFFF rapidly extinguishes hydrocarbon fuel fires. It has the additional property of forming an aqueous film on the fuel surface that prevents evaporation and, hence, reignition of the fuel once it has been extinguished by the foam. The film also has a unique, self-healing capability whereby scars in the film layer caused by falling debris or firefighting activities are rapidly resealed. This firefighting foam is now used on all U.S. Navy aircraft carriers and by major airports, refineries, and other areas where potentially catastrophic fuel fires can occur. In 1979, this NRL-developed fire suppressant was in use at more than 90 airports in the U.S. alone, as well as in many civilian fire departments [94].

In 1987, AFFF was the primary agent used to prevent a major fire disaster in Fairfax, Virginia. The incident happened on June 11, 1987 when a construction bulldozer ruptured an underground gasoline line. The accident left a gaping hole in the pipeline, spewing thousands of gallons of the highly flammable liquid and vapors over a wide area, and caused the evacuation of an entire community. AFFF was promptly furnished by fire officials from Dulles International Airport, Bolling and Andrews Air Force Bases, Ft. Belvoir, and the Quantico Marine Corps Base. Officials reported that a total of 4,375 gallons of AFFF and two other types of foam were used at the spill site. In a letter to NRL, the Public Information Officer for the Fairfax Country Fire and Rescue Department stated,

> "It was clearly a miracle that no ignition source reached the thousands of gallons of gasoline that spewed from the broken pipeline. Had that happened, the entire community of Singleton's Grove would have been engulfed in flames, and numerous lives undoubtedly would have been lost" [95].

The initial concepts for AFFF came from NRL's R. Tuve and E. Jablonski, who patented the first formulation, and their coworkers, H. Peterson and R. Neill. Although NRL was responsible for the original concepts and formulations, it was necessary to elicit the aid of the chemical industry to synthesize the fluorinated intermediates and agents to achieve improvements in formulations. The Minnesota Mining and Manufacturing Company, now 3M, contributed considerably to the success of the development of AFFF.

Nonskid Coatings

Nonskid coatings are used on the flight decks of aircraft carriers to provide traction for personnel, equipment, and aircraft. However, these coatings wear out quickly, often in less than six months. This happens because the deck coatings are inevitably damaged by the tailhooks of landing aircraft in the course of flight operations. This wear and damage to the carrier deck also creates hazards for potential aircraft engine damage or failure as the result of the dislodged deck fragments [96].

In 1982, the Naval Sea Systems Command responded to continuing complaints from the Fleet regarding the short service life of these coatings by establishing a program at NRL to improve the coatings. The NRL effort led to improvements that resulted from more reliable testing and quality control methods for current materials, and the identification of new commercial coatings of improved performance. The carrier decks were resurfaced at least twice a year with the old coatings, at an approximate cost of $3 million [97]. Therefore, the more durable new coatings will increase the availability periods of the Navy's carriers and will reduce the frequency of the costly recoatings. The durable coatings will also save the Navy millions of dollars annually in aircraft engine repairs.

Molecular Structure Analysis

The Laboratory has produced two Nobel Laureates, Drs. J. Karle and H. Hauptman. Each received the Nobel Prize for Chemistry in 1985 for devising direct methods that used X-ray diffraction analysis to determine crystal structures. The seminal research paper for this work, "The Phases and Magnitudes of the Structure Factors," was published in 1949 [98]. The major scientific events leading to the development of these new methods were: quantitative molecular structure analysis in 1948; foundation mathematics for the X-ray phase problem in 1949; and the first general procedure for solving crystal structure problems in 1963 [99]. The many years spanning from these early research events to the eventual award of the Nobel Prize illustrate the time that is often required before the impact of basic research becomes apparent and recognized.

X-ray diffraction analysis involves determining the arrangement of atoms in crystals from which the molecular formula is directly derived. Determination of the molecular structure is important in that once the structural arrangement is understood, the substance itself can then be synthesized to produce useful products. This research on atomic and molecular-level structures occupies an almost unique position in science because the information it provides is basic to other fields of research. In fact, many phenomena in the physical, chemical, metallurgical, geological, and biological sciences are interpretable in terms of the arrangements of atoms in the substances under study [16, p.86].

Dr. Karle still leads a research team at NRL, the Laboratory for the Structure of Matter (LSM), after 45 years of government service. His research group plays a large part in the Navy's energetic materials research program, which focuses on making safer and/or more powerful explosives and propellants. Hundreds of new materials have been synthesized in Navy laboratories, and more than 300 have been analyzed by the LSM. These new compounds include energetic compounds that match or even exceed, in some useful property, all energetic materials now being used (such as RDX and HMX). For example, one new material, known as CL20, exceeds HMX in energy content, and is being investigated and tested. LSM/NRL has participated extensively in this effort, first by determining its novel molecular structure, and later by examining more than 20 variants of CL20 to monitor the effect of changes in reaction conditions and crystallization procedures on the properties of the final product. Research such as this will enable improvements in performance, coupled with increased safety, in the next generation of naval ordnance [100].

Methodologies for determining molecular structures are major contributions to science and technology. For example, they form the basis for the computer packages that are used intensively in pharmaceutical laboratories and research institutions worldwide for the analysis of more than 10,000 new substances each year. In addition, a significant portion of structural research has a direct application to public health. Applications include the identification and characterization of potent toxins found in animals and plants, antitoxins, heart drugs, antibiotics, antiaddictive substances, anticarcinogens, antimalarials, opioids, and radiation-damaged components of DNA [100].

7. ELECTRONICS SCIENCE AND TECHNOLOGY

Much concern over technological competitiveness has been directed toward electronics because it is essential to the nation's military and economic performance. Admiral B.R. Inman, former director of the National Security Agency and deputy director of the Central Intelligence Agency, has explained the pervasive impact of electronics in the following way:

> "The electronics industry has been likened to a food chain. The survival of each unit in the chain—materials, manufacturing equipment, semiconductors, circuit boards, computers, software, and systems—is critical to all of the other elements. For example, semiconductors depend on materials and manufacturing equipment. Access to leading-edge semiconductor technology, in turn, is essential to the success of all of the technologies further up the chain. A lag in access to this technology ultimately means a loss of competitiveness for the businesses that rely on this technology" [101].

Specifically, electronics underpins many important military systems technologies—radar, sonar, space systems, information systems, optics, electronic warfare, etc. (In addition to this section, many of NRL's early electronics accomplishments are described in Section 1; additional achievements are found within other sections as well.)

Electronic Warfare (EW)

When the Germans unleashed their radio-controlled glide bombs at the U.S. Fleet in 1943, antimissile electronic countermeasures became a matter of major importance to the Navy [16, p.57]. In fact, the problem of German guided missiles presented serious difficulties to the Allied war efforts as a whole. Subsequently, the American countermeasures program came to be centered at NRL, as well as at the Airborne Instruments Laboratory of the National Defense Research Committee [1, p.34].

To combat the new German threat, the U.S. destroyer escorts *Davis* and *Jones* were fitted with NRL-developed intercept receivers, signal analysis equipment, and recorders to determine the radio frequencies and the types of guidance modulation used by the enemy. This effort was successful when NRL used the data gathered by the destroyers to build a countermeasure to the bombs. In the Sicily campaign—and later, in the Normandy invasion—NRL-constructed equipment not only protected Allied ships by jamming the German signals but on several occasions apparently took control of the air-dropped missiles and diverted them harmlessly into the sea. NRL also designed towed-radar decoys, which were used to lead the Germans to believe the Allied landing was directed at Pas de Calais instead of Normandy [3, p.303; 16, p.57].

NRL's efforts in electronic warfare continue to the present time, although much of this work has been of a classified nature and cannot be discussed in this report. There are, however, some unclassified examples that can be mentioned.

Decoys and False Targets

Airborne Active Expendable Decoy—During the late 1970s, NRL supported a Defense Science Board Monopulse Countermeasures Study. The results of this study led to funding for the development of the Airborne Active Expendable Decoy (AAED), which is an electronic device designed to counter modern radar-guided antiaircraft threats. The towed version of the AAED (the AN/ALE-50) was subsequently developed as an "end-game" countermeasure. In this regard, the decoy acts as a seductive alternate target that attracts the radar or missile seeker away from the defended aircraft and onto itself. During 1988-1990, in the joint Navy/Air Force Multi-Service Decoy Program, flight-worthy devices were tested and proved to be extremely effective. The system was then scheduled to go into production on the A-6E, followed by installation on numerous other aircraft (including the F/A-18, AV-8B, and P-3C). This decoy system, when combined with maneuver, deception, and other electronic countermeasure techniques, seriously degrades the ability of an adversary to attack and destroy U.S. aircraft [102].

Super Rapid Blooming Offboard Chaff—NRL-led improvements in chaff subpayload packaging and deployment techniques, developed in the early 1970s, made possible the development of the Super Rapid Blooming Offboard Chaff (SRBOC) decoy system. This system has been installed on more than 300 U.S. Navy ships as well as on ships of a number of foreign navies. Versions of SRBOC have also been installed onboard many of the U.S. Navy's aircraft carriers [103].

The SRBOC system consists of the MK 36 Decoy Launching System (DLS) and the MK 182 Mod 1 seduction chaff decoy, and is the follow-on to the RBOC decoy system. Successful Technical and Operational Evaluations were completed during 1976, with production beginning in 1977. More than 40,000 SRBOC (both MK 182 mods 1 and 2) chaff decoys have been produced for the Navy. The follow-on to the MK 182 SRBOC seduction chaff decoy, the NATO Sea Gnat seduction (MK 214 Mod 0) and distraction (MK 216 Mod 0) chaff decoys are also deployed from the MK 36 DLS [103].

Torch Decoy—NRL was tasked with developing new concepts for infrared decoys for surface ships when a counter-countermeasure capability was discovered in threat anti-ship missile guidance units that greatly reduced the effectiveness of the existing Torch decoy. In 1988, the Laboratory's Tactical Electronic Warfare and Chemistry Divisions jointly developed and characterized a modified Torch round that provided improved performance against all known infrared-guided anti-ship missiles [103].

Threat Simulators

Generic Missile Seeker Simulator Program—Development of the AN/ALQ-170 Anti-Ship Missile (ASM) seeker simulator was begun in the late 1970s. The AN/ALQ-170 provided the Fleet with a simulator capable of exercising the Navy's EW systems and ascertaining their effectiveness in an operational situation. The system's original design included the simulation of 10 ASM threats. However, because of the rapid proliferation of ASMs worldwide, the system incorporated an array of new threat variants requested by the various Fleet commands. Additionally, under the Effectiveness of Naval EW Systems (ENEWS) program, NRL has the responsibility to provide intelligence updates to the system [103].

ALQ-170 activities at NRL are centered around two Engineering Development Models (EDMs) that serve as R&D test beds for software and hardware improvements. The EDMs are also used extensively by the EW R&D community to evaluate the performance and effectiveness of new and upgraded EW systems. Flown onboard NRL's EP-3B Flying EW Laboratory, the ALQ-170 has become the workhorse for the Navy's EW RDT&E community. As the effectiveness of ASMs becomes increasingly lethal, the burden on EW grows, as does the requirement to develop hardware simulations that represent the validated threat. The ALQ-170 Program is poised to meet this challenge. NRL is currently directing a major effort to expand the utility of the ALQ-170 through the design and development of a laboratory version, referred to as the Functionally Versatile Seeker. This system, when complete, will provide a laboratory equivalent of the ALQ-170 and play a major role in the expanding process of threat simulator validation [103].

Tactical Electronics Warfare Environment Simulator—An area of long-term NRL achievement includes the development of RF threat simulators. During the late 1970s, NRL's Tactical EW Division developed the technology for an advanced real-time radar environment simulator for laboratory test and evaluation of modern ESM systems. The most significant aspect of the Tactical Electronics Warfare Environment Simulator (TEWES) was its ability to generate a near real-world dynamic RF environment, consisting of up to a thousand simultaneous signals, with a combined pulse density of one million pulses per second [104]. With this level of unprecedented performance in simulation, laboratory evaluation of modern EW/ESM systems could be conducted prior to costly at-sea and/or flight-testing investments, thereby allowing new system developments to transition to the U.S. fleet in reduced time and cost.

In recent years, the TEWES technology has been dramatically enhanced to include complex features for simulating real-time battle force engagements in three-dimensional space. TEWES technology is widely used and has been applied to virtually every major Navy EW program currently in the Fleet or under development. Many TEWES have also been built and procured by other DoD organizations. This technology has revolutionized the development and fielding of new and upgraded defense systems and dramatically increased Fleet combat readiness.

Ship Infrared Signature Measurement Facility—NRL has been responsible for the development of an airborne infrared (IR) ship signature facility that is the centerpiece for quantifying IR signatures of U.S. ships. This facility is recognized internationally as the most technically sophisticated airborne measurement system available. The system is used extensively by the U.S. Navy and by several foreign governments to create a comprehensive database for ship architects and EW system designers. The IR ship signature database was used to support the production decision of the Torch 186 Mod 2 IR decoy (see Section 7: *Torch Decoy*) [103].

Electronic Materials and Device Fabrication

Single-Crystal Gallium Arsenide

In the late 1970s, NRL developed a new and inexpensive technique for compounding and growing single crystals of gallium arsenide (GaAs) of high enough purity to be used for microwave and millimeter-wave devices and integrated circuits. This development was important because transistors and microcircuits made of silicon, the most common semiconductor material used, operate poorly at microwave frequencies. NRL developed the basic process, demonstrated the principles for achieving the high-purity semi-insulating GaAs substrate, and was instrumental in transferring the technology to industry [105].

The NRL technology was adopted by major U.S. industrial firms, such as Rockwell International, Westinghouse, and Hughes Research, and by international firms as well. According to a major manufacturer, the LEC method was expected to decrease the production cost of each GaAs wafer from $3500 to $1000 by 1990 [106]. A 1986 study further estimated that this technique would save the Department of Defense $560 million between 1979 and 1989 [107]. Such cost reductions in wafer production are important because they also lead to reductions in the costs of microwave and millimeter-wave devices and integrated circuits vital to military systems. The availability of GaAs substrate devices has stimulated military advances in space communications and space-borne phased array radar. These devices are currently used on F-14 and F-18 aircraft, as well as on the Sparrow, AMRAAM, and Phoenix missiles. Nonmilitary applications include satellite-to-home television, high-rate data processing, and communications.

Microlithography

NRL developed a new lithographic technique for fabricating ultra-high-resolution patterns on a variety of solid substrates. The approach for this lithographic method was derived from determining the optical sensitivity of biological molecules. Monomolecular films are exposed and developed to high resolution by using this approach. In 1989, the Shipley Company licensed the work and entered into a Cooperative Research and Development Agreement (CRADA) with NRL to further develop this lithographic technique [108].

The ability of a government laboratory to enter into a CRADA with a private company was established by Congress in the Federal Technology Transfer Act of 1986. This legislation promotes the timely transfer of technology from government laboratories to the private sector. Shipley's expertise in photoresist fabrication and metallization provides the additional resources to bring the technology from the laboratory into the manufacturing environment. This technology has the potential of significantly impacting the commercial sector, while providing the technology base for the development of the next generation of more sophisticated electronics necessary for the nation's defense. It is also potentially much cheaper and less toxic (cleaner environmentally and safer for labor) than conventional technology used in this country and Japan [109].

8. ENVIRONMENTAL/BIOLOGICAL SCIENCE AND TECHNOLOGY

Atmospheric Science

Ozone Measurements

During the late 1940s to early 1950s, an NRL research group measured ozone by means of solar spectrographs carried aloft by rockets. In doing so, NRL was the first to experimentally determine the vertical distribution of ozone above those altitudes reached by balloons. Through these tests, NRL found a vertical distribution of ozone in good agreement with the result of photochemical theory [110].

East Coast Acoustic Phenomena

In the winter of 1977-78 many residents of Nova Scotia, coastal New Jersey, New York, and South Carolina were disturbed by loud, explosion-like sounds. In most early reports, the probable causes of the events were thought to be either man-made or noncatastrophic quirks of nature. Conjectures in the news media postulated a range of possible causes including supersonic aircraft, artillery firing, the explosion of large methane bubbles, meteor fireballs, Earth tremors, the detonation of tens of tons of dynamite, and even unidentified flying objects. Although the sounds were detected by scientific instruments, neither the Central Intelligence Agency (CIA) nor the U.S. Air Force found a satisfactory explanation of their nature and origin. On December 30, 1977, the White House called on DoD to investigate the cause of the events. Consequently, scientists at NRL were directed to form a multidisciplinary team to investigate the occurrences in coordination with the CIA.

After collecting the available information, the NRL team was able to rule out one-by-one such candidate sound sources as nuclear and underwater explosions, earthquakes, missile launches, meteorites, and other possible causes. By use of modified acoustic propagation computer codes, the NRL investigators were able to calculate the location and altitude of the sources of these disturbances. By correlating military flight information with the sonic data, the Laboratory investigators proved that specific offshore supersonic military and Concord flight operations caused the disturbances when they coincided with special atmospheric weather conditions that formed sound ducts. The military aircraft flight activities were subsequently moved to less sensitive areas and altitudes, thus alleviating the problem [111].

Deep Ocean Research

Search for the USS Thresher

On April 10, 1963, the nuclear submarine USS *Thresher* (SSN 593) was lost in deep water 260 miles east of Boston, Massachusetts, with all 129 crew members aboard. The loss of the submarine and its crew was a great shock to the Navy and to the country. Immediately after *Thresher's* loss, Navy Task Group 89.7 was formed as a search and rescue team [112]. NRL's technical capabilities were required by the Task Group to locate and photograph the lost vessel. This was necessary for determining the reasons for the loss, thereby averting future losses.

NRL joined the search effort aboard two vessels. The USS *Rockville* (PCER 851), equipped with a unique, trainable hull-mounted sonar, departed with one NRL team on 12 April to join three other naval vessels for an acoustic search of the sea floor [113]. The other NRL team left in May aboard USNS *Gilliss* with a cable-towed, slow-scan television camera and more conventional camera gear to investigate the most promising bottom acoustic targets found earlier [114]. Later in the summer the bathyscaphe *Trieste* took photographs of large pieces of wreckage and recovered a piece of copper pipe inscribed "593 BOAT," thus confirming the debris as that of the *Thresher*. During this operation, *Trieste* was tracked by *Gilliss* using an acoustic system developed by the University of Washington. In August, *Gilliss*' cameras photographed a two-ton mushroom anchor later identified as *Thresher's* [115]. By this time NRL had successfully applied deep-towing technology, developed years earlier for underwater acoustic research, to the deep-sea floor search for the *Thresher*. However, the search was terminated in September 1963 with the onset of bad weather.

On May 18, 1964, Task Group 168.1 began new search operations. To augment its search capability, NRL had acquired USNS *Mizar*, a retired cargo ship ideally suited for conversion to the search mission. An improved underwater tracking system was also installed aboard *Mizar*, and a cargo boom was rigged for launching and towing the deep-towed instrument vehicle, or "fish" as it was called. NRL's "fish" was about 9 ft long and 3 ft wide, and weighed about 1000 lb. Instruments aboard this vehicle included a set of three cameras to photograph the wreckage, a side-looking sonar to probe beyond camera range, two strobe lights, a magnetometer to locate the *Thresher* pressure hull, a transponder, a sonar pinger to measure the "fish's" altitude, and a telemetry system. This unmanned vehicle, towed by *Mizar*, made the initial detection of the *Thresher* hull after only eight hours of bottom operations. *Mizar* thereafter revisited and rephotographed the hulk area by use of the tracking system and by turning on cameras whenever magnetic anomalies were detected. Later that summer, *Mizar's* underwater tracking equipment and underwater telephone were used to guide the submersible *Trieste II* to a position directly on top of *Thresher's* hull. NRL's photographs were later assembled into a photomosaic of most of the major parts of the sunken submarine [116].

The January 1966 installation of a center well in *Mizar* added greatly to her deep-ocean search capability. The well permitted the "fish" to be launched in a controlled fashion and to be towed from a point close to the centers of pitch and roll. This minimized the motions imported to the tow cable and permitted operations during rough sea conditions that would shut down operations aboard more conventional vessels. Once the "fish" had been retrieved, the well doors were slid closed, and the "fish" was lowered to rest on the doors. The covered well deck then became a protected area where the instruments could be serviced in preparation for the next lowering. *Mizar's* center wel! was another concept that was a refinement of NRL's earlier acoustic research. The result of these innovations was an unparalleled decade of successful deep-ocean search missions by NRL [113].

Search for the USS Scorpion

After NRL's success in locating the *Thresher*, the Laboratory was called on to locate and photograph the USS *Scorpion* (SSN 589) in 1968. An NRL-developed wide-angle underwater camera extended the capabilities of the "fish" during this mission and those that followed. This search was successfully completed after five months when NRL photographed the *Scorpion* hulk on October 28, 1968 in about 10,000 ft of water, 400 miles southwest of the Azores [113].

In 1980, NRL's emergency search mission was transfe. ed to other Navy organizations and the Deep Ocean Search System was deactivated. To various degrees, NRL-developed ocean search technology now resides at the Naval Oceanographic Office, Submarine Group One, the Navy's Supervisor of Diving and Salvage, the U.S. Geological Survey, and several foreign governments. The U.S. private sector has also adapted the technology for tethered inspection systems for the offshore petroleum industry, and several companies have used this technology to perform deep-ocean searches and recoveries for the Navy, NASA, and the airlines [117].

Blood Surrogate Research

NRL has been conducting research on developing techniques for the synthesis of durable, rugged lipids. Lipids are naturally occurring substances that "self-organize" into double layers that make up membranes of living cells. Both naturally occurring and synthetic lipids can be chemically modified. As modified by NRL, these materials have the potential for being applied in new electronic materials, optical elements, acoustic sensors, biological hybrid detection systems, and oxygen and drug delivery to the body [118].

In 1985, synthetic red cells based on the concept of liposome-encapsulated hemoglobin (LEH) were developed at NRL as a potential blood surrogate. In principle, hemoglobin solutions were added to a mixture of dry phospholipids and cholesterol, and the dispersion was extruded under high pressure through narrow channels. The resulting liposomes lacked the blood group antigens, theoretically rendering them "universally" acceptable for transfusions. The blood surrogate was also storable up to 10 times longer than regular blood. Work is underway at NRL to extend the storage lifetime of LEH by freeze-drying; to transfer LEH technology to industry for manufacturing; to establish manufacturing and quality control standards; and to study LEH's physiological effects. The red blood cell surrogate research is directed toward improved methods of combat casualty care. It is hoped that this development may also be used in domestic emergency trauma care, as well as in surgical procedures requiring multiple transfusions [119].

Thin Organic Films

From 1961 to the early 1980s, NRL conducted basic research on the nature and effects of surface-active organic substances at critical interfaces in the marine environment. This research generated three spinoff applications that used nontoxic, monomolecular, aquatic surface films: to control and confine spilled petroleum oils; to function as radar-detectable seamarkers for the search and rescue of personnel and machines lost at sea; and to control mosquito larvae and pupae in their breeding sites [120].

Oil Spill Control

NRL discovered that certain surface films applied around an oil spill prevented its spreading and maintained the spill in a thick layer, thereby enhancing the efficiency of oil-recovery operations. In 1970, NRL demonstrated the first successful containment of an oil spill at sea by using a monomolecular surface film. On Environmental Protection Day, June 27, 1972, NRL demonstrated the film at the U.S. Naval Academy before high-ranking attendees representing the navies of 33 nations. The keynote speaker for Environmental Protection Day was Jacques Cousteau who, as an advocate of maintaining the cleanliness of the world's oceans, expressed great interest in the NRL oil-control demonstration [121]. Following approval from the Environmental Protection Agency, this oil-spill control method was fully incorporated into Naval fleet and facility pollution control and recovery programs for harbors and bays. It has also been adopted in the private sector by several petroleum companies. W.D. Garrett, one of the NRL researchers responsible for this work, was appointed by the United Nations World Meteorological Organization as a member of a group of experts on marine pollution monitoring [122].

Seamarker Development

NRL research demonstrated that the one-molecule-thick films on water were readily detectable, both visually and by radar, with radar providing nighttime and poor weather detectability. The films were useful as seamarkers because the films dampen wave action over a wide area of the water surface, thereby producing a highly visible artificial sea slick under a variety of environmental conditions. W.D. Garrett and W.R. Barger patented this invention as a chemical sea surface marker in 1972 [123]. In developing this product, they made comparative studies with the standard Navy dye marker. When the sea slick and dye were used in combination, the detectability of the resulting marker was greater than that of either component used alone. This is because the dye-only marker is barely visible at certain angles of viewing where the NRL-developed marker slick is obvious. At certain other angles, where the NRL slick was difficult to see, the dye stripe could easily be observed [124].

This work attracted the interest and funding support of the U.S. Coast Guard between 1975-1976 when it sponsored additional research leading to the development and patent of practical prototype markers. This new technology updated earlier seamarker technology developed by NRL in 1939 for personnel adrift at sea. (These earlier NRL seamarkers were responsible for saving the lives of more than 150 persons during World War II [125].)

Mosquito Control

While testing monomolecular surface films for their usefulness in controlling oil spills, NRL researchers realized that these substances might also be effective in controlling mosquitos. NRL then conceived and developed an approach that uses selected film-forming agents that have maximum impact on water surface properties that are critical to mosquito survival. (Mosquito larvae and pupae are highly dependent on the properties of the water surface in their breeding sites.) This new approach may have a great impact on controlling disease, particularly since the use of DDT has been terminated in this country, and other pest-control chemicals such as aldrin and dieldrin have been greatly curtailed [126].

NRL's new agent differs from other pest control substances in that it kills by physical means, not by toxic means. A thin film of the substance is spread on the surface of the water after which immature mosquitos in the pupal and larval stages die from drowning, since the surface film keeps them from attaching to the water's surface where they breathe and feed. This control method has proven effective against mosquito genera, which are carriers of debilitating tropical diseases, including malaria, encephalitis, and dengue fever. In 1984, the nontoxic mosquito-control substance gained Environmental Protection Agency approval and is currently being manufactured by a chemical company under license from a U.S. Navy patent on this invention. The substance is now commercially available to mosquito control districts across the U.S. [127].

Biologically Based Sensors

NRL has also investigated biologically based sensors. For example, NRL responded to the needs of the U.S. Fleet during the Operation Desert Shield/Storm by adapting a laboratory biosensor to detect biological warfare agents. The assays were sent to the Gulf in January 1991, and 10 biosensors were built for subsequent deployment. The new sensor system was 10,000-fold more sensitive than previous detectors, and it immediately became an essential component of the U.S. Central Command's biodefense system [128]. Since the end of the war these sensors have been used to develop additional tests for the rapid detection of potential biological warfare agents. The detection system under development is the only automated system being developed specifically for use in the Fleet [129].

A second type of biosensor has been developed for detecting explosives and drugs of abuse. This biosensor was developed by NRL in 1990 and patented in 1991 [130]. The patent for this biosensor was subsequently licensed to U.S. Alcohol Testing of America (USATA) and a Cooperative Research and Development Agreement was established to develop portable commercial instruments for on-site drug detection. This instrument can be operated by personnel who lack scientific training and can be used outside a laboratory environment. According to the president and chief executive officer of USATA,

> "...this technology will be effective in the nation's war on drugs. The timing of this agreement is of extreme benefit, as the need for less expensive and more efficient drug testing is rapidly expanding" [131].

In recognition of this successful transfer of technology, NRL's F. Ligler and A. Kusterbeck were honored with the 1992 Technology Transfer Award for Drug Enforcement by the Office of National Drug Control Policy.

9. OPTICAL SCIENCE AND TECHNOLOGY

Camouflage Techniques and Visual Aids

On the eve of World War II, NRL had determined the best type of protective coloring for all classes of naval vessels and had written the first edition of the *Handbook of Camouflage*, which became a Bible on the subject. It was carried aboard all ships throughout the war [132]. During the war, NRL capitalized on its finding that red light does not decrease the eye's adaptation to darkness as does blue or white light. This resulted in an immediate change throughout the Fleet to the use of goggles, flashlights, and other optical devices designed to receive or emit red light. In addition, fluorescent materials excited by ultraviolet light and phosphorescent materials, which glow for some time after the light stimulation has been turned off, were also developed for visual aids. Two examples were the fluorescent coveralls and signal flags that made Navy crewmen visible to pilots at much greater distances than had previously been possible. Prior to the war, the Laboratory also developed a successful coloration for Naval aircraft, giving them a lowered visibility [16, p.5].

During the Vietnam War in the 1970s, U.S. Marine and Naval units expressed dissatisfaction with ultraviolet light systems used for night map readings in the combat environment. The complaints were that lights in the old system were fragile, had a short life, and experienced leakage of light. In response to this need, NRL developed new units that provided the user with night map-reading capability while maintaining personnel safety in a hostile environment and preserving night vision ability. Six of the units were tested for approximately six months in actual Vietnam combat situations. All were returned intact and operable; reportedly they had operated flawlessly [133].

Fiber-Optic Systems Development

Future Navy needs in sonar arrays require large increases in sensitivity to address the possible threat of quieter submarines. Optical fiber sensors have been shown to be capable of providing this required sensitivity for use in new acoustic sonar systems under development, such as the All-Optical Towed Array (AOTA).

A highly successful sea test of the AOTA was completed in 1989. This test included new high-scale factor fiber-optic hydrophones and fiber-optic heading, temperature, and depth sensors. The self-noise performance of the new hydrophones surpassed all expectations, and the excellent results of the sea test received widespread recognition throughout the Navy ASW community. The Space and Naval Warfare Systems Command's Towed Array Technology Assessment conducted in 1988 concluded that the successful development of AOTA could reduce the cost of future towed arrays by a factor of five [134].

Laser Research

In 1965, NRL was chosen (along with the Air Force Weapons Laboratory, Kirkland Air Force Base, New Mexico) by the Defense Advance Projects Agency to be responsible for developing High Energy Laser (HEL) Technology. Over time, NRL has developed solid-state lasers, electric discharge and electron beam pumped gas lasers, and chemical lasers.

Glass Laser Development

NRL's early solid-state work concentrated on scaling-up and modeling the neodymium glass laser. In the late 1960s, NRL constructed the first U.S. high-power glass laser, called Pharos, and in the early 1970s developed the most successful disk amplifier design. The disk amplifier development allowed lasers to be constructed with very large apertures, hence high energy, and is the basis for all such powerful systems used in inertial confinement fusion (ICF) development. The largest system, in use today at the Lawrence Livermore National Laboratory, was largely designed by people who were drawn from NRL. The NRL Pharos laser has been used for studies in ultra-high energy density systems and has been the source of many important findings in ICF development and high-altitude nuclear effects research [135].

Chemical and Gas Lasers

The work at NRL on chemical and gas dynamic lasers was pursued jointly with Cornell University in the early stages and led to eventual demonstrations of deuterium fluoride (DF) chemical lasers as well as the DF-CO_2 transfer laser. In 1973, NRL installed a powerful gas dynamic CO_2 laser, which was built by AVCO Corporation for NRL, at the Laboratory's Chesapeake Bay Facility. With this device, NRL explored much of the early HEL target interaction phenomenology as well as optical propagation issues. NRL's optical propagation model was the first model to correctly treat the mutual interactions of powerful laser beams and the atmosphere, which is important in assessing the feasibility of laser strategic defense systems, as well as other systems [136].

The chemical laser activity rapidly outgrew the site limitations at NRL and led to a series of devices at contractor and government facilities. In 1982, this culminated in the MIRACL (MidInfrared Chemical Laser) device, which is now at White Sands as part of the Sealite prototype HEL system. NRL provided technical support to the Naval Sea Systems Command, and later the Space and Naval Warfare Command, in the development of this class of laser as well as diagnostics for the device [136].

Electric Discharge and Electron Beam Pumped Gas Lasers

In 1976, NRL reported the first demonstration of a new class of lasers, the rare gas-halide excimer laser [137]. It was found that the noble gases, which do not form stable molecules in the ground state, can form stable excited states with halogen atoms and that some of these species can lase to the ground state as powerful visible or ultraviolet lasers. Initially all of these lasers were excited by using powerful pulsed electron beam sources, but with careful optimization it proved possible to develop efficient discharge excitation sources. In 1985, this effort culminated with the demonstration of a reliable device having an output of 70 joules at an efficiency of greater than 1% with xenon chloride (XeCl) as the laser species. This laser represented an order of magnitude increase in size and energy from what had been state of the art at the start of the NRL program; at that time it represented the largest discharge pumped excimer laser yet demonstrated.

This work led directly to the first technically viable laser for submarine communications, a discharge pumped XeCl laser frequency-shifted in lead vapor to the blue region of the spectrum. It also formed part of the technical basis for devices such as the kilojoule NIKE laser presently under construction at NRL for the DoE Laser Fusion Program [136].

Solid State Lasers

In the 1980s there was a rebirth of enthusiasm over solid state lasers for many low- and medium-power DoD applications. One of the major causes of this was the emergence of powerful, efficient, and relatively cheap laser diode sources. NRL had been involved centrally both in developing powerful diode sources and new types of diode pumped solid state lasers.

A spin-off from the infrared solid state laser work was the CTH:YAG (chromium-thulium-holmium:YAG) flashlamp pumped laser. In experiments and modeling of the erbium-thulium-holmium laser scheme used at low temperatures, it became clear that at higher temperatures deleterious energy transfer processes involving erbium ions were the source of the poor performance. Substitution of chromium for the erbium allowed efficient flashlamp pumped long-pulse operation of the laser [136].

This laser has come into use for arthroscopic surgery. In 1986, NRL and the National Institutes of Health (NIH) demonstrated that a combination of an NRL-designed erbium laser and zirconium fluoride glass fibers held promise for new kinds of microsurgery. The NRL laser emits short, infrared light pulses that are absorbed by the water in tissue and bone. By varying the total energy in each pulse, experts at NIH have shown that they can remove a surface layer of tissue as thin as one ten-thousandth of an inch with no apparent damage to cells lying just below those destroyed. Thus in microsurgical applications, a single cell layer can be removed with each pulse. This allows much less invasive procedures to be used for major arthroscopic reconstructive surgery than previous surgical techniques [138].

NRL also developed a glass fiber that provides a means of delivering these particular infrared pulses. The fiber is as fine as a human hair and yet is able to carry enough energy to cut bone and soft tissue deep inside a patient. It is envisioned that this fiber could be threaded into an atherosclerotic artery to remove a blockage otherwise treatable only by major surgery. Future applications may include neurosurgery, ophthalmology, and cardiology. NIH, after having examined competing laser microsurgery approaches, is enthusiastic about the future for NRL's technology [138].

The full potential of diode lasers and the diode pumped solid state laser has yet to be realized. It is clear, however, that in the near future this technology will replace older gas laser technology for low-and-medium power laser applications because of large improvements in efficiency, compactness, and reliability.

Infrared Detection

The infrared guided missile has become one of the primary threats to U.S. Navy aircraft. Navy pilots have had no effective means to detect the approach of infrared guided missiles except visually, which is practically impossible [139]. To meet this need, the Fly's Eye program is focused on the development of an infrared threat warning system that is capable of detecting both IR and RF guided missiles and other aircraft [140]. This program is based on a concept developed at NRL. In 1989, this program for the first time verified an IR threat warning system. In 1990, eight NRL researchers were honored with Navy Awards of Merit for Group Achievement for their work in the program. The program's approach has also been adopted by two industry teams in a competitive program and was selected by new Navy and Air Force aircraft programs [141].

SUMMARY

With the collapse of the Soviet empire and the demise of Soviet communism as a crusading and expansionist ideology, America's emphasis on massive weapons development programs has become less suited to the new strategic environment. One of the greatest differences between the realities of the Cold War and the current international situation is that our nation now possesses more time to develop military technology. Time was not available during the "long twilight struggle" with communism, a period when America's armed forces fought to contain a threat that posed a clear and present danger. The urgency of that struggle demanded rapid weapons development. By contrast, in the evolving postwar era the military threat to vital U.S. interests is neither clear nor present, and the Gulf War proved clearly that America has the preponderance of military force required to enforce national goals and policies.

The U.S. can now afford to use time to its advantage. One way to do this is to pursue defense technology-base projects. These are the programs that guard against "technological surprise," provide the foundation for future innovation in defense weapons systems and support technology, and generate dual technologies that enhance national economic competitiveness. As this report has shown, technology-base programs are also what NRL has excelled in over the past seven decades. During this period, NRL's achievements have supported each of our nation's security strategies—the post-World War I strategies of the 1920s and 1930s, the confrontation of fascism in the 1940s, and the containment of communism from the late 1940s through the early 1990s. The national security strategy that is now evolving after the collapse of the Soviet empire will similarly be supported and strengthened by the scientific and technological programs of the U.S. Naval Research Laboratory.

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This report has been heavily referenced so that future attempts at documenting NRL's accomplishments may begin from a broad base of material. Therefore, the following references serve a twofold purpose: they substantiate the claims made in this report, and they provide additional bibliographic sources for future historiographic efforts.

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