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EVOLUTION OF THE DEPARTMENT OF DEFENSE MILLIMETER AND MICROWAVE MONOLITHIC INTEGRATED CIRCUIT PROGRAM

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ABSTRACT

The Millimeter and Microwave Monolithic Integrated Circuits (MIMIC) program had its origins in the concern of the smart weapons community for the affordable production of millimeter wave missile seekers, but the broad-based applicability of the technology to radar, communications, countermeasures, and counter-countermeasures was recognized in the formulation of the program. The program was initiated in the turbulent 1980s during the period of high technology trade deficits (and the defense buildup) that created an atmosphere of crisis leading to searching examinations of the reasons for the defeat of the United States in the global marketplaces.

The resultant initiatives by the Congress, the Executive and the private sector created a favorable climate for the execution of the program that featured a unique architecture in which goals were framed in system terms to provide the linking mechanism between materials research, device design, modeling simulation and testing leading to application in the four military application areas cited. The program provides a useful model that could be applied to other programs designed to achieve either civilian or military objectives.

The report traces the evolution of the technology from program formulation when the market was principally military to completion when the market was principally commercial, leaving the semiconductor industry well positioned to cope with the defense cutbacks and downsizing. The report concludes with an analysis of the elements that made the program a success.

SUBJECT TERMS

Millimeter Seekers; Gallium Arsenide; Microwave; Integrated Circuits; Millimeter and Microwave Monolithic Integrated Circuit (MIMIC); Smart Munitions; Radar; Communications; Countermeasures; Counter-Countermeasures; Field Effect Transistor (FET); Metal Semiconductor Field Effect Transistor (MESFET); High Election Mobility Transistor (HEMT); Hetrojunction Bipolar Transistor (HBT); Baseline Seeker; Manufacturing Methods and Technology (MM&T); Dual-Use Technology; Metrology and Standards; Global Environment; Science Policy

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I. INTRODUCTION AND SUMMARY

The purpose of this report is to trace the evolution of the Microwave and Millimeter Monolithic Integrated Circuit (MIMIC) Program and examine the elements of the program that made it a success. In order to tell the story completely, it is necessary to trace the formulation and execution of the program in the turbulent environment of the 1980s defense buildup and the beginning of trade deficits in the high technology industry including semiconductors. The program provided a unique architecture in which program goals were framed in system terms to provide the linking mechanism between materials research, device design, modeling, simulation, and testing leading to applications in four major areas of high technology: radar, communication, countermeasures and counter-countermeasures, and smart weapons. The program featured both structured and unstructured parts with feedback loops that generated the motive force for compressing the innovation process, thus providing a valuable model that can be applied to other military or civilian programs for achieving national objectives. Although the MIMIC program found application in four broad areas, it had its origins in the area of smart weapons; therefore, an additional purpose of this report is to present this early history that has not been treated fully.

The United States (U.S.) emerged from World War II as a world power with no rival in industrial might and scientific and technical leadership, but this led to complacency in the early postwar years. This complacency continued in the 1950s and 1960s, and did not disappear in the 1970s as trade deficits were mounting, since the Nation took comfort in the fact that it was the world leader in science and technology. However, the loss of the U.S. position in the global marketplace in high technology industries in the 1980s, brought about searching re-examinations of what was wrong with the entire product development cycle in various industry segments including semiconductors. In a 1988 report to the Secretary of Defense from the Under Secretary of Defense for Acquisition, the weakness in defense industrial competitiveness was attributed to flawed management theory and practices, the low status of manufacturing in American society, and inadequate attention of engineering schools in American universities to design and manufacturing. [1] The Executive Department, Congress, and the private sector launched a wide range of initiatives to cope with fragmentation of policy on the national level, correct weaknesses in educational institutions, encourage technology transfer, promote partnerships between public and private sector institutions, and fine tune the science policy framed by Vannevar Bush at the close of World War II. [2]

Section II of this report traces World War II origins and the flow of technical innovations in both hybrid Microwave Integrated Circuits (MIC) from the mid-1940s, to the early 1980s when the formulation of the MIMIC program began. An early effort to apply some of the emerging solid-state technology in a millimeter wave terminal homing missile seeker is described in Section III. This was the result of cooperative efforts between the Millimeter Wave Team at the Army Ballistic Research Laboratories, the Air Force Armament Directorate, the Electronics Technology and Devices Laboratory, and the Advanced Sensors Directorate at Redstone Arsenal, Alabama. The same year that laboratory and field-testing was conducted on the baseline seeker, a Manufacturing Methods and Technology (MM&T) program was formulated that led to a program that is presented in Section IV. The completion of the MM&T program in 1983, led to a study at the U.S. Army Missile Command (MICOM) of MICs and MIMIC Independent Research and Development (IR&D) programs in the industrial base with the result that 40 companies were found to be working in the field, but projects in manufacturing process development were limited in scope.

The IR&D analysis was followed by a more detailed analysis that led to the establishment of the Monolithic Millimeter and Microwave Initiative (M^3I) Committee presented in Section V, along with MIMIC analyses conducted by other institutions presented in Section VI. In August 1984, the Advanced Sensors Directorate at MICOM was requested to provide technical and manufacturing cost data to the Office of Under Secretary of Defense for Research and Engineering. On 28 September 1984, this millimeter wave data was the subject of discussion at the Defense Systems Acquisition Review Council (DSARC) review of the Multiple-Launch Rocket System-Terminally Guided Submunition (MLRS-TGSM), an international program that featured a millimeter wave homing seeker. This review led to the establishment of the M^3I Committee to make a more comprehensive industrial base analysis presented in Section VI. As the work of the M^3I Committee progressed, the need for a structured program became better crystallized, (Section VII) and a number of MIMIC conferences served to further focus the program and highlight the key challenges (Section VIII). One of the key factors in the success of the program was the integration of metrology and standards with technology development.

The globalization of defense activities in which the MLRS-TGW program was formulated, and the loss of U.S. industry in the international marketplace led to a searching re-examination of U.S. science policy and an attempt to formulate a new one (Section X, XII). The MIMIC program bears the imprint of the Global Environment in the period in which it was formulated and executed. The sense of urgency created by the searching re-examination of what was wrong with the industry, as well as other industry sectors, was doubtless a contributing factor in the success of the program, but there was also great concern about protecting the U.S. interest while still maintaining competitiveness in the global market. The uniqueness of the environment in which MIMIC emerged makes it a valuable model for study. Section XI provides a summary of the program, and Section XIII presents the elements that made it a success. Section XI provides a summary of the elements that made it successful and that also make MIMIC a valuable model for study.

II. EARLY BACKGROUND

Achieving compact, low cost, and highly reliable electronic circuit functions was an objective as well as that of the radio proximity fuze program conducted under the supervision of the Office of Scientific Research and Development with the Navy responsible for the development of fuzes for rotating projectiles, and the Army responsible for non-rotating projectiles such as bombs, missiles and mortars. All the fuzes were based on the same principle of the Doppler effect, but each application presented unique design challenges in environmental effects, safe and arming, antenna radiation patterns and power sources. The tiny assembly that included miniature vacuum tubes, resistors, capacitors, and inductors were required to fit existing projectiles using the same space as the mechanical fuzes, without changing the ballistic characteristics of the projectiles. The development and use of the proximity fuze has been presented in a number of papers. [4 through 9]

The proximity fuze program conducted during World War II by the Ordnance Development Division of the National Bureau of Standards (NBS) and continued after the war, provided motivation for compact, integrated electronic subsystems that could be manufactured at low cost. The successful application of printed circuit technology to the radio proximity fuze during the war led the NBS to prepare a comprehensive treatment of printed circuit technology in anticipation of the peacetime applications. The processes used for applying conductors to an insulating surface fell in six categories: (1) painting, (2) spraying, (3) chemical deposition, (4) vacuum processes, (5) die stamping, and (6) dusting. Through numerous innovations in the first five categories, it was possible not only to apply conducting paths between circuit elements on a planar surface, but through process variations, fabricate resistors, capacitors, inductors and antennas, as well as printing portions of the circuit on the miniature and subminiature vacuum tubes, the principal active circuit element before the arrival of the transistor. The benefit of printed circuits was reduction of circuit wiring to two dimensions through printed circuit technology that also allowed a reduction in the number of labor-intensive soldering operations even in the smallest radio sets. One indicator of the intensity of the innovative activity in printed circuit technology is the number of patents cited in the Brunetti-Curtis Paper. [10]

Project Tinkertoy, initiated in 1953, was an outgrowth of the wartime work on the radio proximity fuze that was conducted by NBS in collaboration with industry under the sponsorship of the Navy. The objective of the program was to achieve both miniaturization of electronic assemblies and automation of the manufacturing process. The basic module was composed of five ceramic wafers with resistors and capacitors mounted on each of the flat sides of the wafers with printed silver conductors connecting the circuit elements. The wafers with attached components were then stacked one above the other with the top wafer formed to provide a socket for a vacuum tube. Although transistors were coming into wider use at the time the projected was initiated, Tinkertoy was never adapted for the arrival of the transistor which led to the demise of the concept. Further information on the project can be found in References 11 through 13.

A modified version of Tinkertoy emerged in October 1957, shortly after the Russians launched Sputnik when the Surface Communication Division of the RCA demonstrated a pen-size radio to the U.S. Army Signal Corps. The modified version of Tinkertoy was christened the Micromodule Program and received strong support from the Signal Corps which led to the demonstration of helmet radios and miniature computers in 1960. The micromodule featured transistors and smaller ceramic wafers with the top most wafer configured to support a vacuum tube; however, that feature was never used since transistors were in widespread use. [14]

Although both the Tinkertoy and the Micromodule Program were in a sense successful, Tinkertoy was overtaken by the invention of the transistor, and the Micromodule Program was overtaken by the invention of the integrated circuit by Noyce and Kilby. According to Kilby's patent:

> "It is possible to achieve component densities of greater than 30 million per cubic foot compared with 500 thousand per cubit foot, which is the highest component density attained prior to this invention." [12]

To provide continuity in the technology of electronics components miniaturization for defense application, the Army Diamond Ordnance Fuze Laboratory (DOFL) was formed in 1953 with the transfer of the Ordnance Development Division of NBS to the Department of the Army under the Chief of Ordnance to continue the fuze work. In 1957, DOFL won the Micro-Miniaturization Award for the Application of photolithographic production of the transistor. [15] In 1962, DOFL was renamed the Harry Diamond Laboratories with a broader mission under the Army Materiel Command (AMC) that was created that year. The Signal Corps and its successor, the U.S. Army Electronics Command, also played a pivotal role in working with industry in the development of miniaturization and micro-miniaturization of electronics involving the development of the transistor, printed wiring technology, and integrated circuits over the period of 1946 to 1964 that established the foundation for the semiconductor industry. Some of the key players in this effort were Stanislaus F. Danko, Frank Brand, James Meindal, Bernard Reich, Milton Tobman, and Leon Shumann. [16] In 1965, a group was formed under Vladimir Gelnovatch to provide a focus for the appointed manager of the Army MIMIC program.

The Post-World War II work by NBS, Centralab of Globe Union, the Navy, Air Force, and the Army Signal Corps led to a number of innovations that were available for integration with the transistor when it arrived. [17] In 1962, DOFL was renamed Harry Diamond Laboratories with a broader mission under the AMC created that year. The concept of the field effect transistor that would provide one of the key active devices for the MIMIC program had its origins in the work of William Shockley. [18] Shockley could later point to the page of his laboratory notebook, dated 20 February 1940, at Bell Telephone Laboratories as the first record of the Schottky field effect transistor:

> The invention of Figure 4(b) was theoretically sound.
> It describes a device of the type now known as a
> Schottky – gate field effect transistor. [19]

The formulation of an Ad Hoc Group in the Defense Department Research and Development Board (RDB) gave recognition to the potential impact of transistors on military systems. This led to the formation of a Sub-panel on Semiconductor Devices under the RDB's Panel on Electron Tubes. In his paper on the invention of the integrated circuit, Jack Kilby gives credit to G. W. A. Dummer of the Royal Radar Establishment as the first to perceive the possibilities of circuit integration based on semiconductor technology in 1952, in an Electronics Components Conference:

> "With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out various layers." [17]

These words are suggestive of the monolithic approach on which MIMIC is based that implies that both the active and passive components including the transmission medium are fabricated on a common semi-insulating substrate. A second concept included in the term MICs is one in which a planar transmission medium capable of being printed on a dielectric substrate provides the integrating structure for discrete active and passive components attached to it. This is the hybrid approach to integration that is referred to as hybrid-MICs, or more commonly, MIMICs. The experience gained in the development of MICs, or hybrid-MICs, provided a foundation for maturing the monolithic technology or MIMIC. Harlan Howe has provided an excellent historical review of the technology. [20] The progress in MIMICs was built on advances in materials growth and characterization, active and passive device development, transmission line media, manufacturing process development, design modeling and simulation that began in the early 1950s, and was mature enough in the early 1980s to allow the formulation of the MIMIC program.

R. M. Barrett of the U.S. Air Force observed in the early 1950s that planar transmission media fabricated by low-cost printed circuit techniques could be extended to allow both passive and active circuit functions to be coupled together to provide a complete receiver. Barrett visualized the symmetrical flat transmission line as an evolution of the coaxial transmission line obtained by flattening both the inner and outer conductors into rectangular shapes and then removing the sidewalls of the outer conductor. [21] Barrett credits V. H. Rumsey and H. W. Jamieson with the first application of the symmetrical stripline as a power division network in World War II. Barrett was active in promoting the application of the stripline as a low-cost alternative to the heavy hybrid junctions and waveguide components in airborne radars and communication equipment, and also observed that:

> "It seems quite possible that the entire RF circuitry of a microwave receiver could be constructed by this method (printed circuit etching techniques)." [21]

There were other innovations that contributed to the unfolding of the technology in the 1950s. In a personal communication, Gelnovatch recalls these early years of research on transmission media, and the contributions of Ardeti of ITT, and George Gobeau at Signal Corps Engineering Laboratories (SCEL). According to Gelnovatch who worked with George Gobeau:

> "Gobeau did propagation experiments, one of them being launching waves into a dielectric coating over a ground plane without the aid of a center string transmission line. Later in the 1980s when researchers were investigating higher modes in microstrip, lo and behold they found that the first higher order TE mode (or was it the TM mode) was really the Gobeau mode." Gelnovatch also recalled that it was H. A. Wheeler who characterized microstrip. "He did a multi-dielectric analysis of the non- Transverse Electromagnetic Mode (TEM) mode in microstrip using his 'filling fraction' method to approximate TEM propagation. This gave researchers the first handhold on relating impedance, dielectric constant, and W/H ratios that allowed reliable design. Tables and charts of this work were published in the Microwave Journal Handbook in the late 1960s."

The microstrip line was introduced by Greg and Engleman to provide adaptability for wide-band communication power level components that demonstrated zero dispersion over a band of frequencies from 20 GHz to 10 GHz. [22]

In the late 1950s, a major challenge in making the region of the electromagnetic spectrum between 30 GHz and 300 GHz more broadly applicable beyond its early use in spectroscopy and materials research was achieving adequate levels of power. The launching of Sputnik in October 1957, provided an additional stimulus for research in electronics miniaturization sponsored by the Department of Defense (DoD), and one effect was to put the focus on millimeter wave technology. An early indication that a broader vision for millimeter waves was beginning to crystallize occurred at the Symposium on Millimeter Waves at the Polytechnic Institute of Brooklyn on 31 March, and 1 to 2 April 1959, but no solid state millimeter source appeared as a topic on the program.

The office of Naval Research, the Air Force Office of Scientific Research, and the U.S. Army Signal Research and Development Laboratory were co-sponsors of the event, and representatives from these agencies gave brief greetings with forecasts for millimeter waves. The two sessions devoted to millimeter wave power generation gave a clue that millimeter wave was emerging as a technology of importance for both military and civilian applications. Also in April 1959, an integrated circuit concept was announced at the Institute of Radio Engineers (IRE) show in which both active and passive devices are processed on one wafer of silicon and provided with interconnections between circuit functions.

There was also vigorous research in the 1950s and early 1960s, on providing the theoretical foundations and manufacturing methods for microwave semiconductor devices, particularly two-terminal devices. The 26 papers in "Selected Papers on Semiconductor Microwave Electronics" edited by Sumner N. Levine and Richard R. Kurzrok, concentrated on the use of the p-n junction to achieve amplification and frequency conversion of microwave frequencies. Included were 14 papers on parametric amplifiers, 4 papers on tunnel diodes, 4 on general theory of non-linear elements, 3 on fabrication, and 3 general survey papers. [23] One of the general survey papers was "Semiconductor Devices for Microwave Applications" by Milton Tenzer, U.S. Army Signal Research and Development Laboratory. The discovery of the phenomena on which the tunnel diode depends by Leo Esaki in 1957, the IMPATT diode or transit time diode in 1958 by Read, and the Gunn effect diode in 1963 by J. B. Gunn, provided the stimulus for developing the technology of two-terminal devices that could operate in the microwave and millimeter wave region. Esaki reported that it was very easy to make a Radio Frequency (RF) oscillator in the early days "without much effort" [24]. The transfer of electrons from a high-mobility conduction band to a low-mobility sub-band provided the physical basis for the differential negative resistance in the Gunn effect in gallium arsenide. Oscillators based on this effect were low noise. Progress was rapid in extending the frequency into the millimeter wave region with increasing power levels. Although the first IMPATT diode was not fabricated until 1964, by the late 1960s power output was increasing at the rate of 2 watts per year. [25] In January 1966, the *IEEE Transactions on Electron Devices* devoted a special issue to Gunn effect devices, avalanche transit time devices, and microwave radiation from indium antimonide. [26] The Gunn diode, IMPATT, the varactor, and the tunnel diode were the two terminal devices that provided the transmit-receive functions for early work in smart munitions development. The conflict over the invention of the integrated circuit was resolved and Jack S. Kilby and Robert N. Noyce shared honors for the achievement.

Hybrid microwave and millimeter wave integrated circuits achieved greater maturity with advances also made in the 1960s in miniature guided wave structures in both microwaves, millimeter waves and optics as the vehicle for integrating small and rugged circuit functions into subsystems. S. E. Miller's paper "Integrated Optics: An Introduction," was published [27]; the slot line characteristics were described by S. B. Cohn [28]; and the characteristics of the coplanar waveguide were presented by Wen. [29] Drawing on the work of Marcatelli, Knox, and Toulios saw the potential of the high permittivity dielectric image line offering the prospect for lower propagation loss for millimeter wave integrated circuits than the microstrip line. [30] The Symposium on Submillimeter Waves held at the Polytechnic Institute of Brooklyn on March 31, and April 1 to 2, 1970, provided an excellent review of the state-of-the-art in millimeter and submillimeter waves at the close of the decade of the 60s. [31] However, transmission line media received limited attention and the only semiconductor devices appearing on the program for power generation were the Gunn and IMPATT diodes. [32, 33]

At the symposium cited, Skolnik presented the useful characteristics and limitations of millimeter and submillimeter waves, and identified 47 potential applications in radar, communications, radiometry, and instrumentation. Skolnik noted that the relatively poor status of components was well documented, but even if the limitations of millimeter wave components were overcome, the limitation of small antenna apertures and high losses would remain. Although a microwave radar had been demonstrated in Germany in 1904, it was the maturing of the airplane in the 1930s that created a real need for microwave radar that provided the stimulus for extensive advancement in microwave technology. According to Skolnik, the economic benefits of millimeter waves for specific applications was yet to be examined. [34]

A. Hybrid MICs for Radar Applications

The first efforts to advance the art of MICs in silicon by Texas Instruments under the sponsorship of the Air Force Molecular Electronics for Radar Applications (MERA) program began in 1964, and by late 1968, 600 radar Transmit/Receive (TR) modules had been fabricated. Although the initial focus of MERA was on advancing the art of microwave integrated circuits, the program eventually led to the first demonstration of a solid-state array radar at x-band based on silicon processing technology. The T/R module was MIC technology built in alumina microstrip using thin film techniques and featured an S-band preamplifier, two-phase shift networks, 2 times 4 multipliers, a pulse amplifier, a T/R switch, a mixer, and a preamp. [20, 35] The MERA work was apparently the stimulus for a series of T/R module studies [36, 37, 38, 39], and intensive development of MIMIC technology. A decade of progress in millimeter and microwave integrated circuits was featured in three special issues of the IEEE MTT-S Transactions devoted to microwave integrated circuits over the decade from 1968 to 1978: July 1968, July 1971, and October 1978.

The special issue of the *IEEE Transactions*, Vol. MTT-16, No. 7, July 1968, edited by Sy Okwit, was a signal that the stage was being set for a revolution in microwave and millimeter wave technology. In the lead article, "Integrated Microwave Modules – A Prospectus" [40], William Webster observed:

> "There is also a premium on size, weight, and power in airborne applications. These factors are the main reasons for the intensive early interest on the part of the Air Force. By far, the biggest segment of the microwave business in the easily foreseeable future is radar."

Although research was in progress on millimeter wave integrated circuits at 94 GHz [41, 42], the technology was much less mature than the lower frequency bands. The insight that this technology would make smart weapons feasible emerged with the recognition that discrete Gunn and IMPATT oscillators could provide the basis for solid state transceivers that could be packaged in a 6-inch diameter missile. The demonstration of molecular beam epitaxy by Cho and Arthur at Bell Telephone Laboratories in 1969 [43], and U.S. Patent 362257 *Semiconductor Device with Superlattice Region*, issued to Esaki, Ludeke, and Tsu set the stage for much research in the 1970s [44] and provided the foundation for advancing three-terminal devices such as MESFET and HEMTS.

B. The Emergence of the GaAs MESFET and Monolithic GaAs Integrated Circuits

The superior properties that GaAs offered as an alternative semi-insulating substrate with suitable dielectric properties for forming microstrip transmission lines between circuit functions was soon recognized and became the leading candidate material. In 1966, Mead reported the desirable features of a GaAs Field Effect Transistor (FET) using a Schottky barrier gate. [45] In 1967, Hooper and Lehrer reported the characteristics of an epitaxial GaAs field-effect transistor. [46] In 1968, Mehal and Wacker fabricated Schottky barrier diodes, Gunn oscillators, varactor diodes, and tunnel diodes in planar form in semi-insulating GaAs using the epitaxial selective growth method and the mesa etching method. The application of the two Schottky barrier diodes to form a balanced mixer in conjunction with the Gunn local oscillator provided the basis for a RF receiver front end at 94 GHz. [42] By the early 1970s, the promise of the GaAs FET as a low-noise microwave transistor capable of extending the useful frequency range by more than a factor of two over existing silicon transistors for variety of circuit functions was widely recognized. In 1976, Pengelly and Turner reported the first broadband FET amplifier. [47] In his 1976 report on recent and current work in microwave FETS, Charles A. Liechti, included a bibliography of 250 references. [48] In 1978, DiLorenzo reported that over 250 papers had been published on the GaAs since 1970 [49]. In 1978, U.S. Patent 4,163,237, *High Mobility Multilayered Hetrojunction Devices Employing Modulated Doping* was issued to Raymond Dingle, Arthur C. Cassard, and Horst L. Stormer of Bell Telephone Laboratory. [50] In 1979, DiLorenzo and Wisseman reported that over 350 papers on the GaAs MESFET had been published since 1973, and gave the first comprehensive state-of-the-art review of the GaAs MESFET as a power amplifier. [51]

C. Development of MICs and MMICs by Army Laboratories

1. Ballistic Research Laboratories (BRL)

The work of the Millimeter Wave Team of the Army BRL at Aberdeen Proving Ground, MD was an integral part of the development of millimeter wave technology. This team under the leadership of Richard McGee began, about 1960, a wide ranging program of research not only in phenomenology of both active radar and passive radiometric systems, but the development of components and instrumentation that provided the technological foundation for millimeter wave seeker development. This in-house research led to the development of laboratory demonstration models of the first all-solid-state radars operating at 35, 45, 140, and 240 GHz. By 1969, the feasibility of tracking a target in a complex background with a radiometer featuring a scanning antenna was also demonstrated. This was followed by a guidance radiometer demonstration at 35 GHz that provided the foundation for the MICOM Terminally Guided Submunition (TGSM) design. Among the BRL pioneers in the development of millimeter wave radiometry were Victor W. Richards, Kenneth A. Richer, and Richard A. McGee. [52] In conjunction with a periodic analysis of the state-of-the-art in component and device technology, missile guidance concepts were developed and analyzed for application to direct fire close combat, including millimeter command and beamrider, air-to-ground, air defense, and fire support. To accomplish this research, specialized instrumentation had to be developed that required collaboration with the Fort Monmouth Laboratories.

The phenomenology research included target scattering, multipath effects, backscatter from ground clutter, atmospheric attenuation, attenuation and backscatter from rainfalls. Carefully designed experiments established quantitative relationships between the rain characteristics (rainfall rates, drop size distribution) and the attenuation and backscatter from the rain at 9.375, 35, 70, 94, 140, and 225 GHz over a wide range of rainfall rates. From this research through the end of the 1960s, Richer concluded:

"From the broad series of propagation measurements made to date, however, a general picture begins to emerge. One should be able to operate short range (possible 10 or more km) radars in the 35, 94, 140, and 225 GHz regions except for heavy rainfall and fog conditions at the two higher frequencies. Short range (1 to 2 km) radiometric systems should be feasible at 35 and 94 GHz; possibly only relatively cloudless days at 94 GHz. However, the extremely high resolution and potentially small size systems at millimeter wave lengths are attractive even for such relatively short ranges of operation. Further, millimeter wave techniques are extremely valuable for measurement of the environment itself." [53]

This research by Richer and his group on propagation effects established the broad boundaries on what was achievable in the millimeter region for missile guidance. [53,54,55,56] This early work in "passive" and "active" radiometry by the Army, Air Force, and Sperry led to sensing options that were part of the first source selection for millimeter wave seekers held at Aberdeen Proving Ground in 1972. The first generation 35 GHz millimeter wave seeker that emerged from this process is shown in Figure 1.

From the results of the propagation research and the risk in component and device development above 100 GHz, plans for guidance subsystem development above 100 GHz at MICOM were dropped. This decision was also responsive to a request from the Electronics Technology and Devices Laboratory (ET&DL) that MICOM needs for ET&DL work be prioritized.

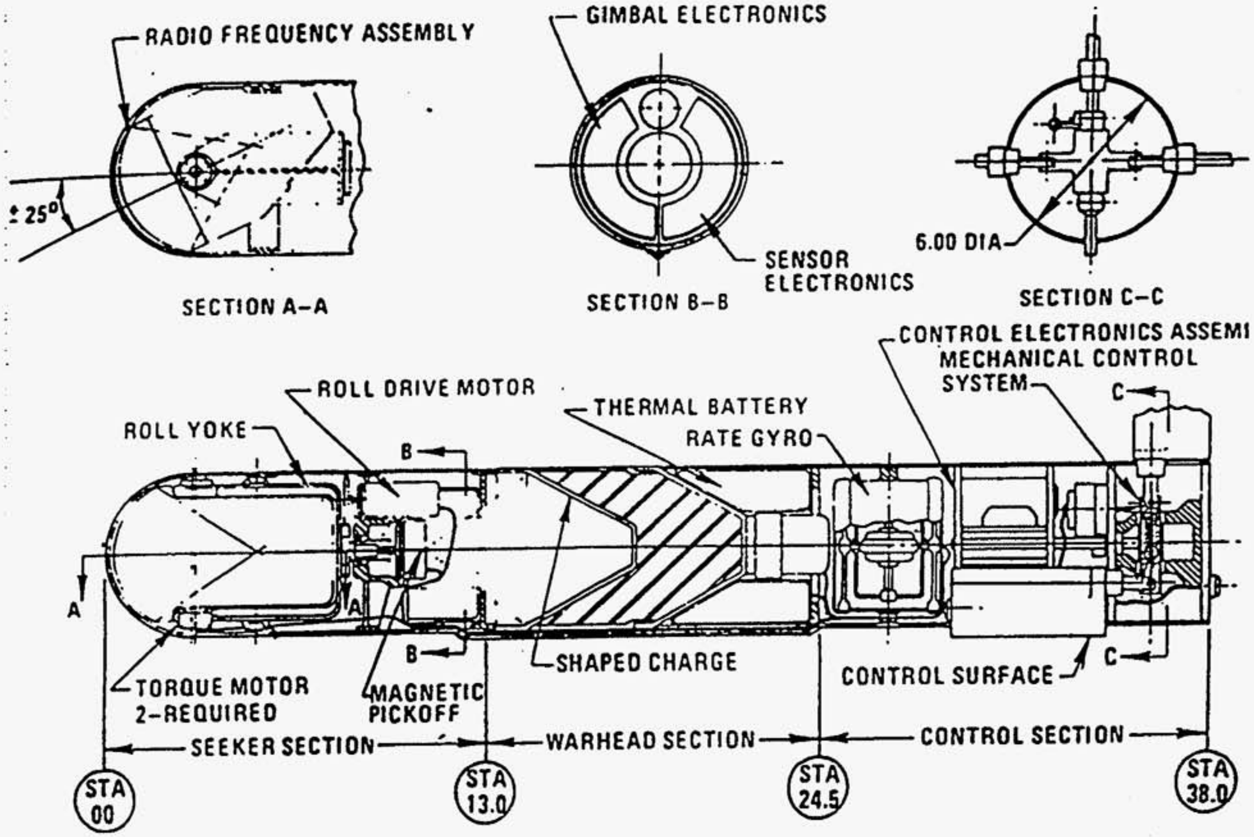

Figure 1. First Generation Millimeter Wave Seeker (Courtesy BRL)

2. Fort Monmouth Laboratories

The U.S. Army Signal Corps was on the forefront of major technical innovations from the date of its founding on 21 June 1860, by Albert James Myer, the first signal officer, and this tradition was continued in the Signal Corps Engineering Laboratories at Fort Monmouth, NJ that played a vital role in winning World War II. In the post-World War II period, the laboratories led an effort in miniaturization and micro-miniaturization of Army communications - electronics. In a sense, it was the Signal Corps Engineering Laboratories that launched the nation into the missiles and space age in the early post-World War II period. William Stroud of the Laboratories led the development of a scanning system for the Vanguard satellite. Signal Corps scientists using a SCR-271 long-range radar bounced radar signals off the moon on 10 January 1946. The announcement of the "Dick Tracy" *Transistor Wrist Radio* by the U.S. Army Signal Corps Laboratories in 1953, not only attracted wide-spread public interest, but alerted the defense community to the high potential of the new invention for a variety of applications. The Army encouraged the inventors to file a patent application and explore the commercial applications - perhaps a signal that the concept of "dual-use" technology was taking shape. The Laboratories not only pursued a search for transistor applications, but maintained a program of fundamental research to achieve a better understanding of the physics of materials and devices and develop the manufacturing process technology for the devices. In 1958 and 1959, the Signal Corps Engineering Laboratories made a major payload contribution to the Vanguard satellite program, and on 18 December 1959, in collaboration with the Air Force, launched the first communication satellite under Project SCORE (Signal Communication via Orbiting Relay Equipment).[57]

In 1965, a group was formed under Vladimir Gelnovatch in the Electronics Component Laboratory to provide a focus for the development of hybrid microwave integrated circuits. The program of research in this group included a broad range of microwave circuit techniques, both distributed and lumped to provide the foundation for integration of the advances in solid state microwave devices. This included the investigation and ranking of several transmission lines including microstrip suspended substrate line, slot line, and coplanar waveguide. Materials technology for substrates, conductors, and dielectrics was a key part of this effort, and provided the foundation for development of design methodology that took into account the need to achieve a balance between performance, yield, cost, and reliability. One illustration of technology was demonstrated through the computer-aided design of wide-band integrated microwave transistor amplifiers on high dielectric substrates. [58] Strong emphasis was placed on efforts to employ digital computer technique to automate the design process, and one program was developed that optimized 24 variables in 383 seconds running time. [59]

By the time the Electronic Technology and Devices Laboratory was established in 1971, the foundation for the design of hybrid integrated microwave circuits had been established at the lower microwave, and the performance of lumped circuit elements was found to give performance as good as distributed elements up to 6Ghz. A principal challenge was to achieve integration at the higher frequencies where active devices were available, but the technology for integration was not. [60] In the meantime, the availability of two-terminal sources of microwave and millimeter power led to the conception of simple transceivers that made use of these devices that could be packaged in 6-inch diameter missiles. ET&DL had supported this application with exploratory development funds for Gunn and IMPATT diodes. Closer communication evolved between ET&DL and the Laboratory at MICOM that gave a sharper focus to the application of MIC and MIMIC to smart weapons applications.

At the close of the 1970s, ED&DL had plans to invest approximately 6 million dollars overall in microwave technology, and about 3 million dollars in millimeter wave technology. The program had a thrust that provided for "Low-cost practical millimeter wave devices (35 to 600 Ghz) and nano second pulsers for target location and identification systems capable of all weather operation through battlefield ECM." [61] The solid-state devices program apportioned an average funding of 4 million per year toward low cost millimeter wave components for high resolution radar; missiles and projectile terminal homing; wideband SIGINT receivers; secure communications; all-weather capability; and penetration of battlefield obscurants. [62] The ET&TL was not only exploiting opportunities in MIC technology, but also focusing on monolithic technology based in gallium arsenide with the Field Effect Transistor as the active element at the higher millimeter wave frequencies. A strong in-house program was complemented by a diversified research program in industry. [63, 64]

As the need for a DoD-wide program in millimeter wave technology began to crystallize in the early 1980s, ET&TL was in a strong position to influence the structure of the program, particularly at the higher millimeter wave frequencies, since its wise investments in research and technology development over the prior 15 years was now ready for transition into applications in communications, radar, smart weapons, and countermeasures and counter-countermeasures. The pace of activity intensified following the formulation of the M^3I Committee by Under Secretary of Defense James Wade in 1984 as the first step in initiating a national program. ET&DL was represented on the committee by Vladimir Gelnovatch, Hans Hieslmair, Lothar Wandiger, and James Kesperis. By 1987, ET&DL and industry had achieved a W-band transceiver in MIMIC technology that set the stage for a MIMIC transceiver at that wave band. [65] The complementary features of MIMIC and VHSIC were provided by Thornton in Reference [144].

In October 1992, the Army Research Laboratory (ARL) was activated and ET&DL became an element of the laboratory. The management of MIMIC program for the Army continued in ARL through program completion in 1995.

III. THE BASELINE MILLIMETER WAVE SEEKER

The work of the Millimeter Wave Team at the Army Ballistic Research Laboratory in phenomenology, radiometric sensing, and solid-state radar development led naturally to the formulation of missile seeker concepts utilizing this technology. However, the high cost of millimeter wave components in the late 1960s and 1970s, led system developers to consider the use of the components for dual functions in a millimeter radar and radiometer integrated in one instrument to achieve improved reliability and performance. Such an instrument has been described by Foiani and Pearce that featured a Frequency Modulated-Continuous Wave (FM-CW) radar combined at 3.2 mm with a Dicke-type radiometer. [66] This concept provided the basis for the first millimeter wave seeker referred to as the baseline seeker. However, as higher frequency operation was achieved, it was found that the radiometric mode was of limited value above about 40 GHz, and was dropped after experience was gained at 94 GHz.

The availability of two-terminal solid-state sources of microwave power in 1970s (Gunn and IMPATT diodes), made it possible to conceive a transmitter-receiver unit that could be packaged as part of a millimeter wave missile seeker in a 6-inch airframe. The favorable results of a joint Army-Air Force evaluation of passive microwave radiometry in 1971, led the Ballistics Research Laboratory to issue a technical requirement for fabricating three millimeter wave/seekers capable of operating at 35 GHz in both the passive and active mode. MICOM provided funding and technical guidance for the program that led to a contract with Sperry Microwave. An early version of the first generation seeker is shown in Figure 2. The Sperry Microwave design featured a transmitter-receiver unit, with a conically-scanned antenna, target acquisition and tracking processor, and a two-axis gimbal that allowed the seeker to search, acquire, and track targets and provide steering signals to cause the submunition to impact the target. [67] Sperry fabricated three engineering prototypes, the first of which was configured for captive flight-testing in the Airborne Instrumented Millimeter Measurement System, at Redstone Arsenal, AL. The other two seekers were configured for a 6-inch diameter TGSM airframe, and ultimately one of these was converted to 94 GHz with the same circuit configuration as the 35 GHz seeker.

The seeker was capable of search in the active mode with a cone angle of 8.7 degrees, and track in both the active and passive mode. The basic concept featured dual-mode operation with the active mode for target acquisition and track to the terminal phase, then switchover to the passive or radiometric mode to obtain more stable centroid tracking. After the submunition is ejected from the launch vehicle, the active mode is initiated with FM-CW radar mode until the ground is acquired. An area search of the ground is then initiated in the active mode until a target is located, at which time target tracking begins providing signals to guide the submunition into the target. At some pre-selected terminal range, angle tracking in the active mode is switched to angle tracking in the passive mode to provide a more stable tracking centroid as the submunition closes on the target. [56] Massed battle tanks and armored personnel carriers were the intended targets of the submunition that could be attacked in partially obscured conditions unfavorable to optical and infrared sensors.

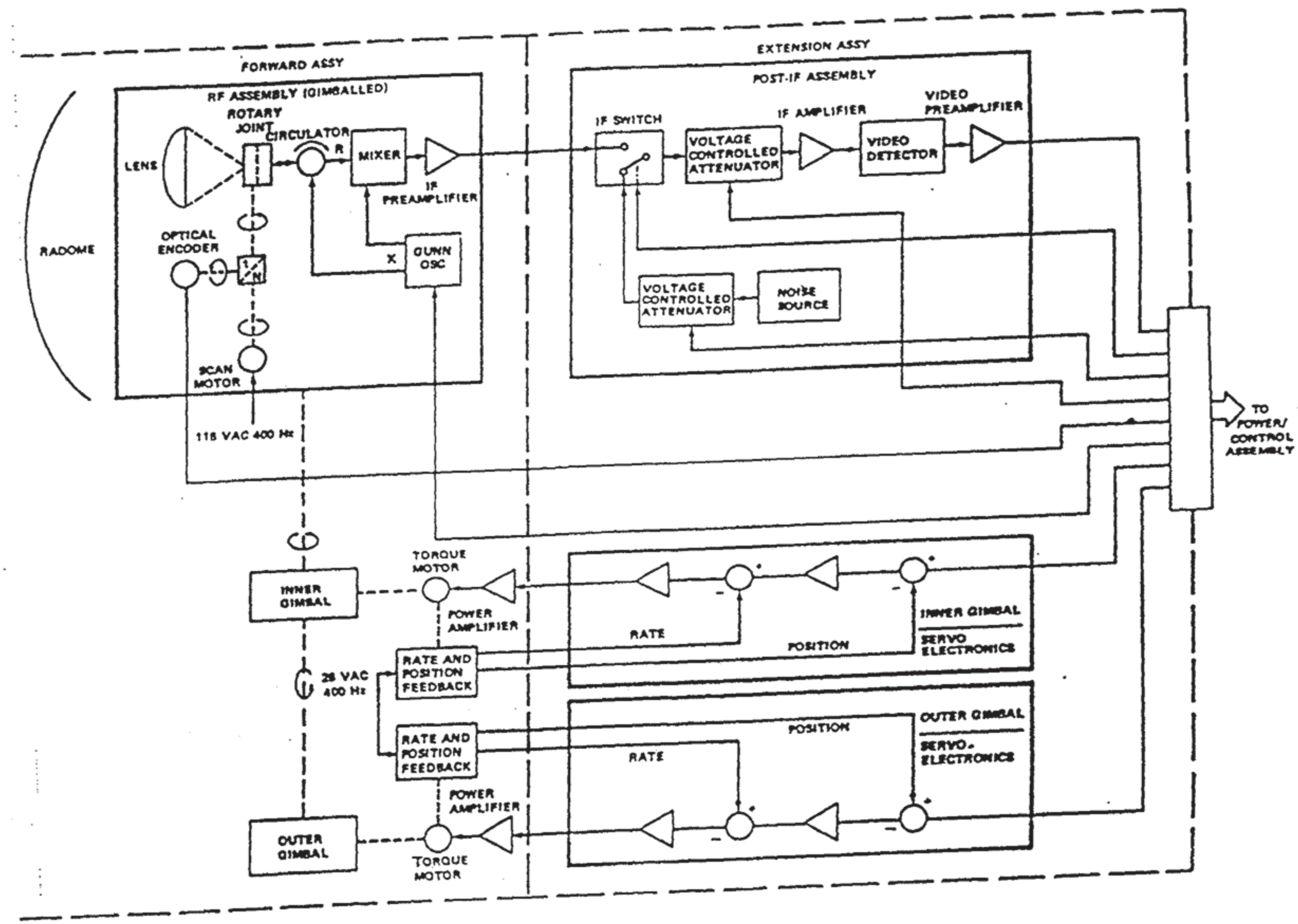

Figure 2. Block Diagram of Microwave Radiometric Seeker Subsystem [68]

Comparative evaluation of 35 GHz and 94 GHz seekers was performed at Redstone Arsenal in 1974 to 1975. [68] Under Air Force sponsorship, they were also evaluated in both tower and captive tests at Eglin Air Force Base. The prototype seekers were capable of operating in: (1) the active FM-CW mode, (2) the active noise illumination mode, or (3) the passive mode. The stabilization and control circuitry to provide integration with a missile airframe was not part of the delivered prototype seekers. Figure 2 shows the prototype seeker configured for testing at Redstone Arsenal. [68] Propagation effects were not considered in comparing the performance of the seekers in the two-millimeter wave bands, and the limited availability of radar target cross-section data in the two bands did not allow a complete comparative analysis at the time.

Two performance measures sought in the evaluation of the two-millimeter wave band were the detection range and the reliable tracking range in the active seeker modes. Figure 3 provides a comparison of the two seeker subsystems. The available power at 94 GHz was only 40 percent of that at 35 GHz, but the reduction in antenna beam with 94 GHz reduced the illuminated clutter area thus offering the potential for offsetting the lower power and higher losses. Although component losses in the two bands were not assessed at the time, it was recognized that losses would be substantially higher at 94 GHz, and the technology was much less mature. The results of this comparative seeker evaluation provided a stimulus for the ET&DL to focus on maturing millimeter wave technology at 94 GHz. Plans were in place to undertake MM&T projects on the seeker following the comparative evaluation of 35 Ghz and 94 Ghz seekers. [69, 70]

Characteristic	Symbol	MRSS-35	MRSS-94
Transmitted Power	P_t	50 mW	20 mW
Antenna Aperture	D	12.5 cm	12.5 cm
Noise Figure	NF	7.5 dB	9.0 dB
Receiver Aperture Efficiency	η	0.7	0.7
Wavelength	λ	8.6 mm	3.2 mm
Predetection Bandwidth	B	500 MHz	300 MHz
Tracking Loop Bandwidth	b	5 Hz	5 Hz
Conical Scan Fraquency	C_f	100 Hz	100 Hz
Center Frequency	F_c	35.0 GHz	94.0 GHz

Figure 3. Characteristics of the Microwave Radiometric Seeker Subsystem (MRSS) [68]

IV. MANUFACTURING METHODS AND TECHNOLOGY PROGRAMS

The baseline seeker developed by Sperry Microwave provided the design on which the first manufacturing process development conducted on a millimeter wave seeker was conducted. Sperry was able to draw on extensive developmental experience in conducting a two-phase MM&T project on the Assault Breaker Phase II Drop Test Seeker (the baseline seeker). Under Phase I, the procedure was to start with the baseline seeker design and establish the criteria for comparing manufacturing processes, assembly techniques, inspection procedures, configuration, and test procedures. [71] From this, actual costs of the baseline design were obtained and the cost drivers identified. Alternate approaches were then developed to reduce the impact of the cost drivers in the following areas: material substitution, configuration change, tolerance studies, fabrication techniques, fixtures, procedures, and tests. From this process, Sperry concluded that a cost-effective approach could be developed that would allow a production rate of 800 transceiver units per month with current (1982) technology at a cost of 2,300 dollars per unit (Fig. 4). This process flow summary for Phase I is shown in Figure 5. The production cost analysis of the baseline seeker showed that 80 percent of the RF Front End Section was contained in major component development.

Type of Realization	Unit Production Cost Estimate	Relative Volume	Production Availability
Discrete Component	$14,000	26 in^3	1978
Semi-Integrated	$ 6.500	9 in^3	1979
Fully Integrated	$ 2,300	6 in^3	1984
Monolithic	$ 900	1 in^3	1986-88

Figure 4. W-Band RF Front End Evolution for an FMCW System [71]

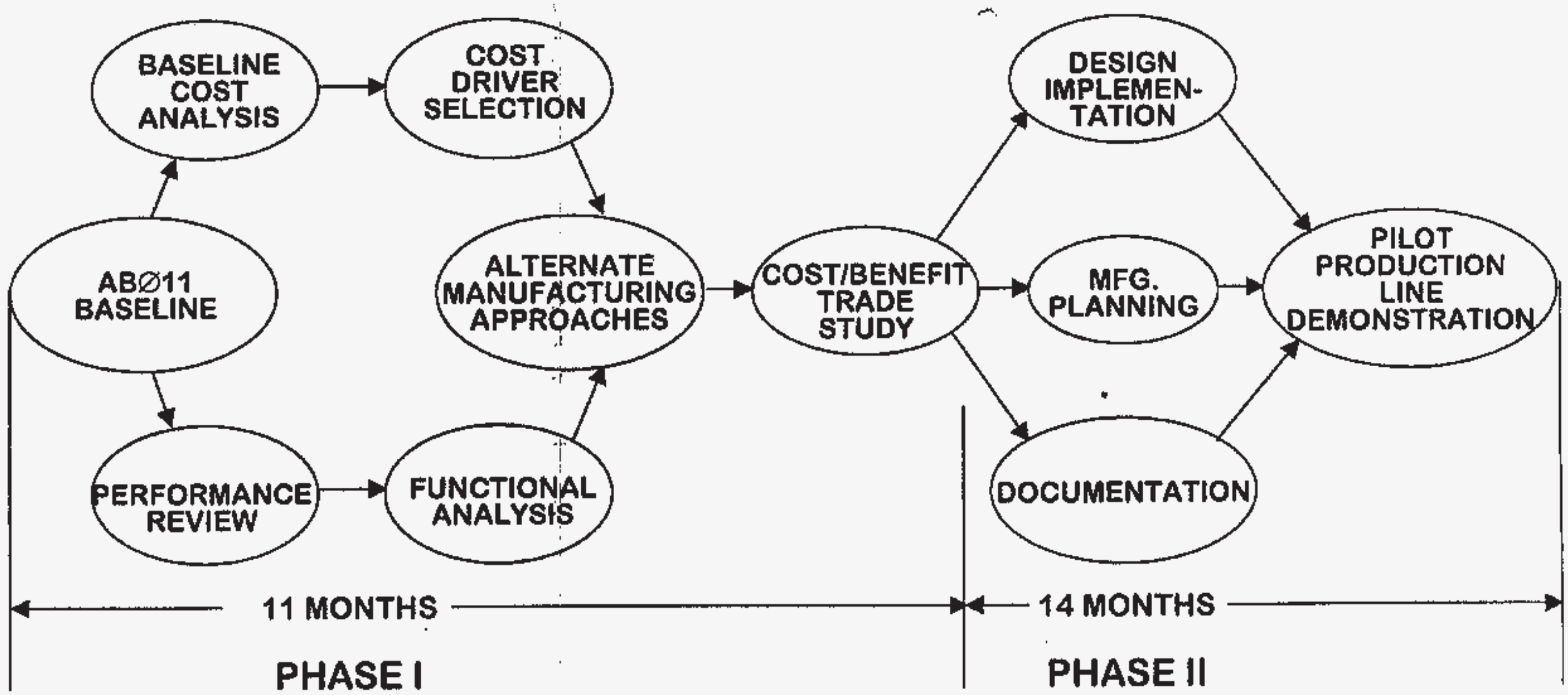

Figure 5. Producibility Engineering and Planning Flow Diagram for the Assault Breaker Phase II Drop Test Millimeter Seeker [72]

Under Phase II of the MM&T project, an alternative configuration of the seeker front end was developed that was referred to as the Producibility Engineering Planning Configuration (PEP'd). [72] In this configuration (Fig. 6) the parts count was 37 percent less than in the Baseline configuration. This was accomplished by eliminating the interconnecting waveguide assemblies allowing ease of assembly and interchangeability of the RF source, isolator, mixer-IF-amplifier, and duplexer. The circuit diagram of the RF front end and antenna assembly is shown in Figure 7. Both the radome and parabolic reflector in the baseline configuration were machined from REXOLITE, a non-moldable plastic. In the PEP'd configuration, these parts were injection-molded from NORYL.

Five millimeter seeker heads were produced in the Pilot Production Line phase of the project, and an industry, Government demonstration was held in Clearwater, Florida on 25-26 January 1983. [72] This phase of the program was a valuable learning experience, since the change from the Baseline Configuration to the Planning Configuration led to an entirely new technical data package; substantial product development took place during the manufacturing cycle. It was determined early in Phase I of the program that the RF components and the antenna assembly represented 79.7 percent of the unit production cost of the Front End Section. The cost of the same components in the PEP'd configuration showed that the same components represented 60 percent of the unit production cost, or a 19.7 percent reduction. [72] This was attributed to the "fully integrated" RF component design approach that led to the significant parts count reduction. (The term "fully integrated" means "millimeter integrated circuits" or hybrids.)

Sperry concluded that the greatest impact on unit production cost of the RF front end could be achieved by the introduction of monolithic millimeter and microwave integrated circuits, but for Sperry this would involve an IR&D investment of 8 to 10 million dollars over a 5- to 8-year program [72], woefully inadequate to pay for new capital facilities, research on device physics, MIMIC design tools, improvements in materials quality, and manufacturing process development. The Sperry conclusions led naturally to the question: "What is the magnitude and content of the IR&D industrial base and the DoD funded technology base in industry?" The answer to this question will be discussed in the following two sections.

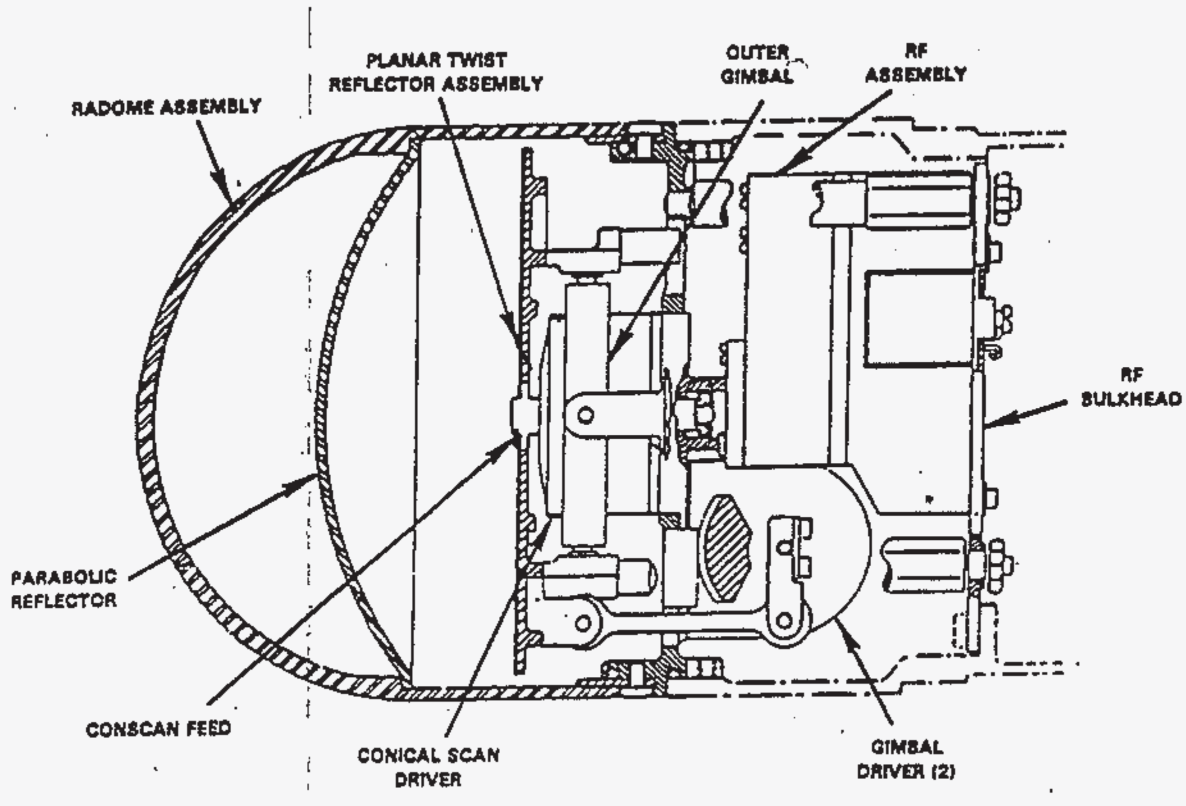

Figure 6. Millimeter Wave Front End for the Producibility Engineering Planning Configuration [72]

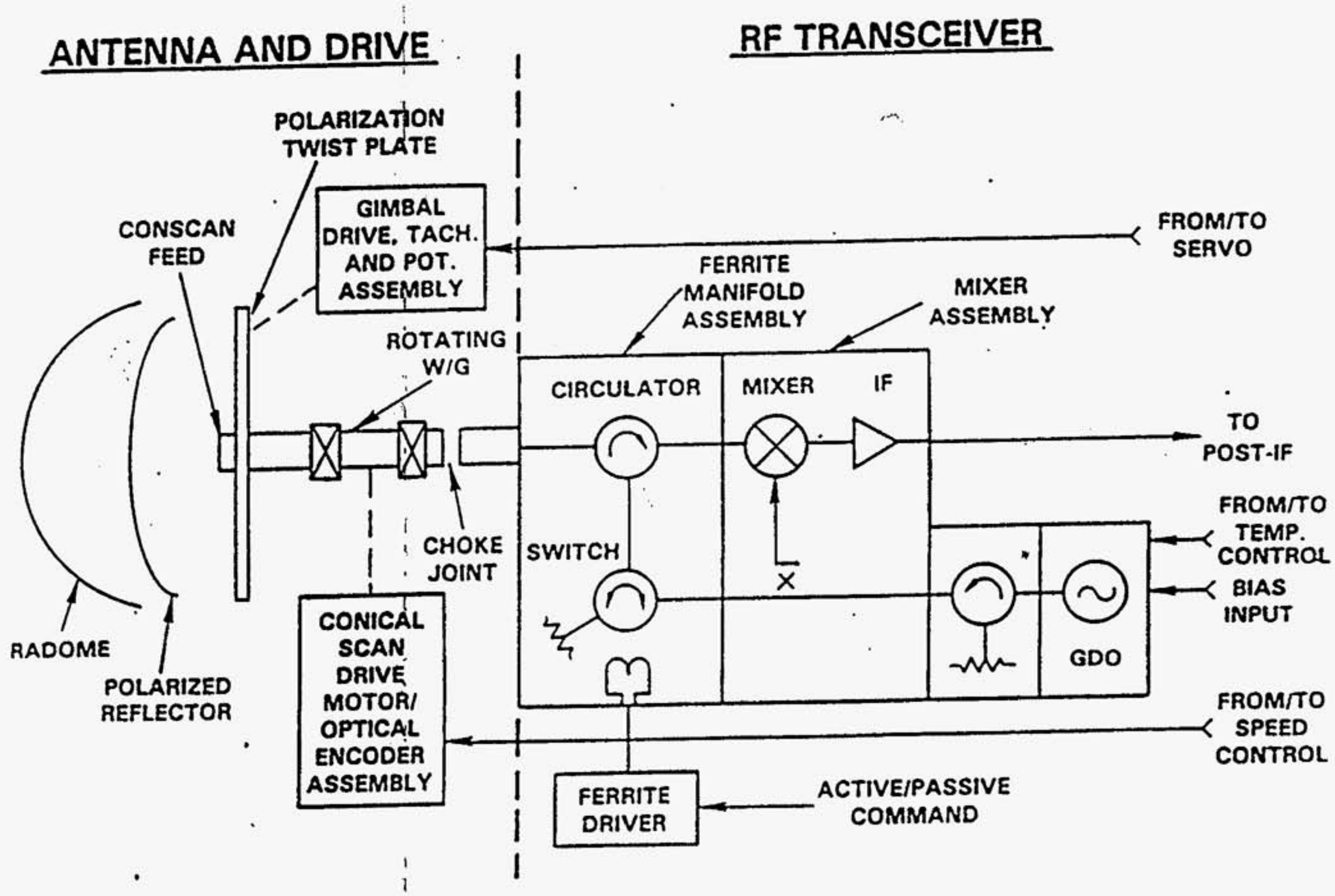

Figure 7. Manufacturing Methods and Technology Components, Millimeter Seeker Front End [72]

V. THE MONOLITHIC MILLIMETER AND MICROWAVE INITIATIVE (M^3I) COMMITTEE

In August 1984, in preparation for the DSARC on MLRS-TGW the following month, the Office of Under Secretary of Defense for Research and Engineering requested cost and technical data on the maturity of millimeter wave technology from the Advanced Sensors Directorate, MICOM. In response, the results of the MM&T project on Millimeter Wave Seekers conducted by Sperry was submitted along with the quick-look IR&D analysis and the follow-up state-of-the-art review by Deo and Toulious. A proposed DoD program on MIMIC was also submitted (Appendix C). As a result, concern was expressed in the DSARC review on 28 September 1984, about the absence of a mature technical base on which to establish the program. As a follow-up action, the Assistant Secretary of Defense for Acquisition Management asked the Product Engineering Service Office (PESO) to look into the state-of-the-art of millimeter wave components. Cornelius "Neil" Sullivan in PESO was tasked to contact the Office of Under Secretary of Defense for Research and Advanced Technology, ODUSD (R&AT), to obtain their cooperation in organizing a program in millimeter wave technology. Dr. Robert J. Heaston, Staff Specialist for Weapons Technology in ODUSD (R&AT) was selected to work with him. On 9 January 1985, Dr. Heaston prepared a cover brief for ODUSD (R&AT) to USDRE requesting the formation of a DoD committee to recommend a millimeter wave initiative. On 1 February 1985, USDRE James Wade signed the memorandum to the services and DARPA on "OSD Microwave/Millimeter Wave Monolithic Technology Initiative." [73] The M^3I Committee was thus established with R. J. Heaston and C. L. Sullivan as co-chairmen of the committee. The membership of the committee is shown in Figure 8. At the kickoff meeting held on 5 March 1985, in Rosslyn, VA, Sonny Maynard gave a presentation on "GaAs MMIC Initiative." [74] Following the meeting at Georgia Tech on 18-19 March 1989, the committee made onsite visits to 19 corporations beginning in late March 1985. [75] Nicholas Mangus and Thomas Barley served as MICOM representatives on the committee. The committee continued to request data of MICOM on the requirements of MIMIC to support the Army thrust in smart weapons. Figures 9 through 11 were part of the briefing material furnished to the committee in response to these requests. [76] The principal task of the M^3I Committee was to establish the current state of the technology (1985) as a prerequisite to formulating the outlines of a plan. Following the industry site visits the committee concluded:

1. Few millimeter monolithic devices have been made to date;
2. Gallium Arsenide is subject to variability in quality;
3. Bringing the chips from laboratory to production is a major hurdle requiring great expense and engineering effort;
4. Rapid on-wafer testing of chips has yet to be achieved;
5. Packaging of monolithic chips has received little attention;
6. There is no good measure of yields; other materials such as indium phosphide and aluminum gallium arsenide need investigation;
7. New high-speed, high-frequency devices such as High Electron Mobility Transistor (HEMT) will require extensive work.

Efforts were made during the site visits to obtain answers to a series of questions concerning each firm's level of effort, quality of the staff, Government programs, current and projected market, and categories of device technology. The Committee's assessment of the MIMIC manufacturing technology risk is shown in Figure 12. On 14 May 1985, the M^3I Committee briefed the Deputy Under Secretary of Defense for R&AT and recommended a program of over 500 million dollars that was forwarded to the Defense Resources Board by Dr. Wade. The Defense Resources Board endorsed the program, but reduced the funds to 135 million. Mr. E. D. (Sonny) Maynard, Jr., the Director of the VHSIC program, was appointed to manage the MIMIC program, and briefed the program to USDRE on 10 June 1985 [77]. The management structure recommended by the committee for the program is shown in Figure 13. The M^3I Committee made it clear in its report the primary motivation in establishing the program:

> "The initial driver for M^3I occurred in September 1984 with the Multiple Launch Rocket System – Terminally Guided Warhead DSARC, where the future success of the program was questioned because of the lack of a sufficient technical base in the area of low-cost millimeter wave integrated circuits." [75]

The gallium arsenide markets in 1984, including both digital and the analog MIMIC technology, are shown in Figure 14 with a projection of the market for 1990. The large growth projected for commercial computes has not materialized.

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CORNELIUS SULLIVAN, AM

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VLADIMIR G. GELNOVATCH, ERADCOM
HANS HIESLMAIR, ERADCOM
LOTHAR WANDINGER, ERADCOM
JAMES KESPERIS, ERADCOM
NICK MANGUS, MICOM
TOM BARLEY, MICOM
HARRY WILLING, MICOM
WILLIAM RITCHIE, AMMCOM/ARDC
KEITH LYDING, AMCCOM/ARDC
NORMAN GOLDFARB, AMCCOM/ARDC

<u>NAVY</u>

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JIM CAUFFMAN, NAVELEX
RON WADE, NAVELEX
DREW GLISTA, NAVAIR
GEORGE CUDD, NAVAIR
PETE LUPINO, NAVAIR
JOE ZELINSKI, NAVAIR
G.M. BORSUK, NRL
BARRY SPEIRMAN, NRL
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<u>AEROSPACE CORP</u>

C.C. LEE
DONALD ROMEO

PALISADES INSTITUTE FOR RESEARCH SERVICES INC.

<u>NATIONAL BUREAU OF STANDARDS</u>

BRIAN BELANGER

Figure 8. DoD Monolithic Millimeter and Microwave Integrated Circuits Committee [75]

- **ARMY SMART MUNITIONS WORK IS AT 35GHz AND ABOVE**
- **THE PRINCIPAL THRUST OF MIMIC THEREFORE MUST BE AT 35GHz AND ABOVE**
- **THE TECHNOLOGY IS GENERALLY LESS MATURE AT THE HIGHER FREQUENCIES**
- **AFFORDABILITY AND PRODUCIBILITY ARE KEY DRIVERS FOR SMART MUNITIONS**
- **INDUSTRY ALLOCATES LITTLE FUNDING TO PRODUCIBILITY UNDER IR&D**
- **GENERIC CHIP SETS, COMPUTER-AIDED DESIGN TOOLS, RF SHIELDING AND PACKAGING, AND FLEXIBLE AUTOMATED PRODUCTION TESTING ARE NEEDED EFFORTS**

Figure 9. A Microwave and Millimeter Monolithic Integrated Circuit Program for Smart Munitions [76]

TWO-TERMINAL DEVICES

- CURRENT ARMY SMART MUNITIONS EFFORT IS BASED ON TWO-TERMINAL DEVICES
- TWO TERMINAL DEVICES LESS COMPATIBLE WITH MONOLITHIC PROCESSING
- THERMAL DESIGN IS A MAJOR TECHNICAL CHALLENGE, PARTICULARLY AT W-BAND
- MATERIAL PROPERTIES HAVE A STRONG INFLUENCE ON YIELD AND PERFORMANCE
- THE ONLY TECHNOLOGY AVAILABLE FOR POWER GENERATION AT W-BAND

THREE-TERMINAL DEVICES

- BASIC DEVICE FUNCTIONS HIGHLY COMPATIBLE WITH MONOLITHIC PROCESS TECHNOLOGY
- THERMAL DESIGN IS A MAJOR TECHNOLOGY CHALLENGE
- ELECTRON BEAM LITHOGRAPHY IS ESSENTIAL FOR EXTENDING TECHNOLOGY ABOVE 35 GHz
- HAS RECEIVED MORE INTENSIVE DEVELOPMENT OVER THE PAST DECADE THAN TWO-TERMINAL TECHNOLOGY

Figure 10. Circuit Functions for Millimeter Integrated Circuits [76]

- MATERIAL GROWTH AND CHARACTERIZATION MUST BE GREATLY IMPROVED AND EFFECTS OF MATERIAL PROPERTIES ON DEVICE PERFORMANCE ESTABLISHED.
- THE DEFINITION OF GENERIC CHIP SETS AND SUBSYSTEM BLOCKS THAT MEET ARMY NEEDS IN SMART MUNITIONS MUST BE MADE TO CONTROL DESIGN COST.
- DEVICE AND CIRCUIT MODELS FOR ANALYSIS AND SYNTHESIS OF MONOLITHIC CIRCUITS IN COMPUTER-AIDED DESIGN PROGRAMS MUST BE ESTABLISHED AT THE SHORTER MILLIMETER WAVELENGTHS.
- TECHNIQUES FOR ON-CHIP RF TESTING MUST BE DEVELOPED AND STANDARDS FOR MEASUREMENTS AND INSTRUMENTATION ESTABLISHED.
- A SEARCH FOR OPPORTUNITIES TO COMBINE MILLIMETER FUNCTIONS AND DIGITAL SIGNAL PROCESSING ON ONE CHIP MUST BE MADE.
- PACKAGING AND SHIELDING, A MAJOR COST ELEMENT OF THE TECHNOLOGY, NEEDS FURTHER DEVELOPMENT.

Figure 11. MIMIC Technology Challenges for Smart Munitions [76]

		2-20 GHZ-NAVE ELECT. WARFARE	22/44 GHZ-AF SATELL. COM MILSTAR	35 GHZ-ARMY SMART MUNI-TIONS/SADARM	94 GHZ-ARMY TERMINAL HOMING
TRANSMIT	POWER SOURCE	M	M	M	H
	COMBINER	L	M	M	M
	MICROSTRIP, PLANAR WAVEGUIDE	L	M	M	M
RECEIVE	LOW NOISE	M	M-H	M-H	H
	IF AMP	L	M	M	M
	MIXER	L	M	M	M
CONTROL	LIMITER	L	L	M	H
	PHASE SHIFTER	M	M	M	H
	RF SWITCH	L	L-M	L	H
ANTENNA	RADOME WINDOW	L	L	L	H
	CIRCULATOR	M	M	M	H
	MULTIPLEXER	L	M	L	M

L = 1 – 3 YEAR HORIZON
M = 3 – 5 YEAR HORIZON
H = 5 – 10 YEAR HORIZON

Figure 12. MIMIC Manufacturing Technology Risk [75]

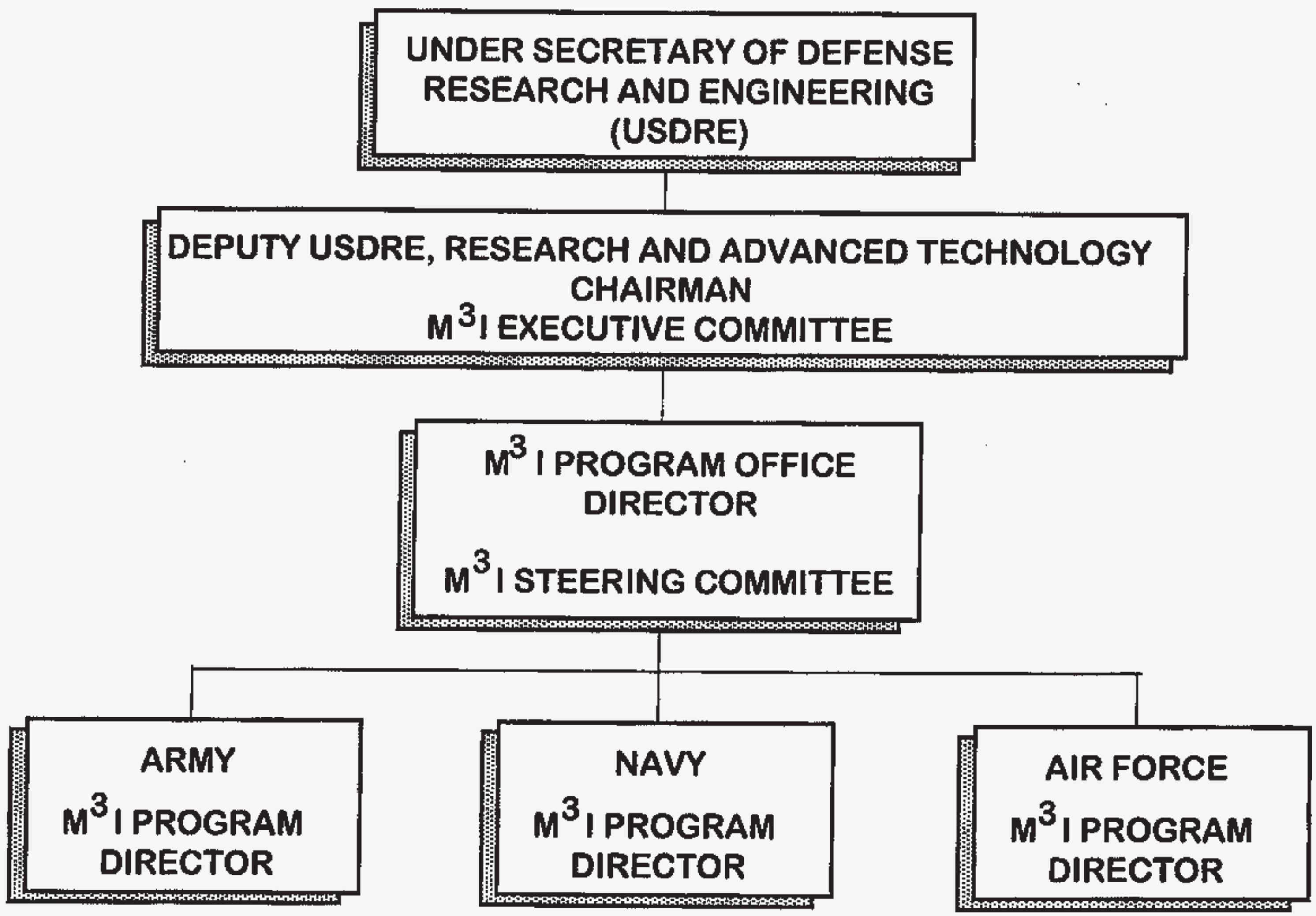


Figure 13. MIMIC Management Structure Proposed by the DoD M^3I Committee [75]

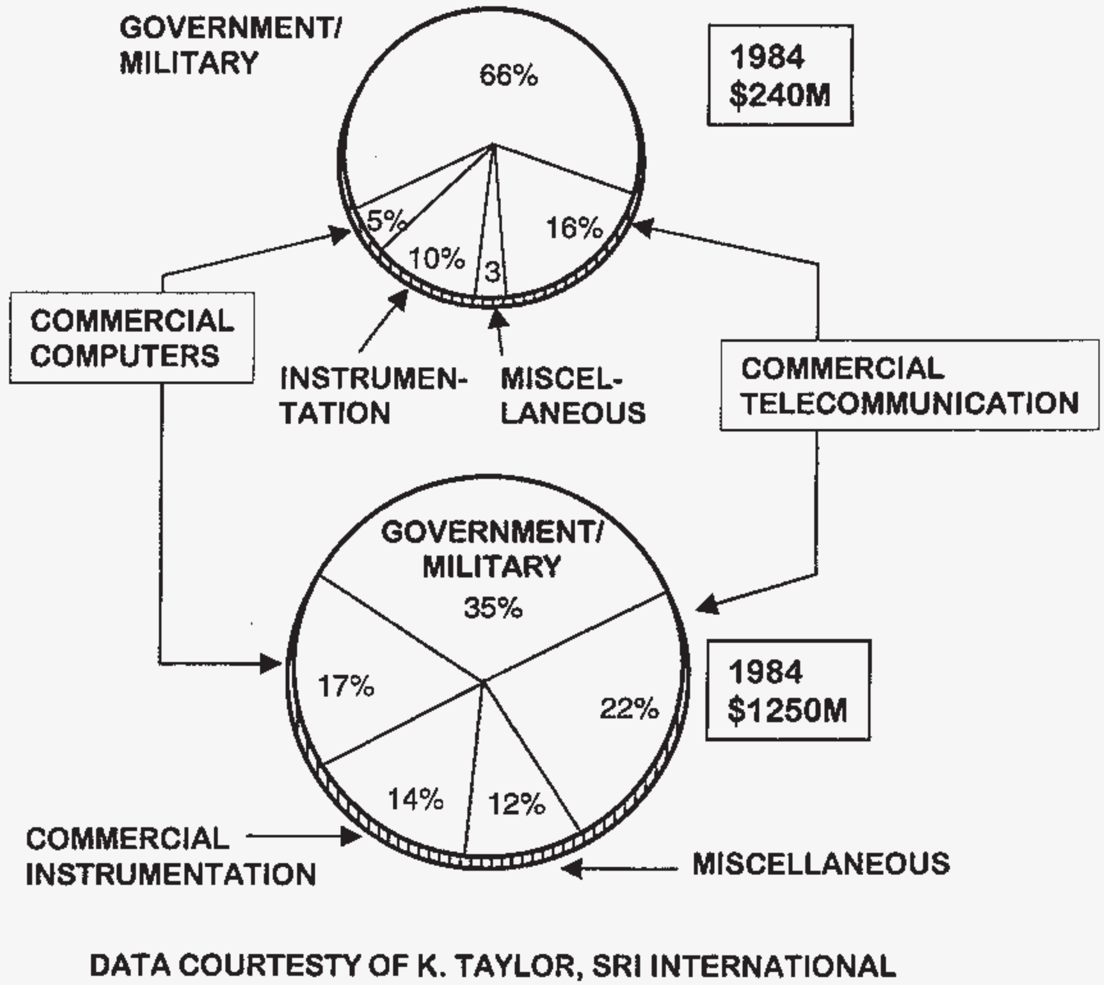


Figure 14. 1984-1990 Market Segments for GaAs Device Application [77]

VI. INDUSTRIAL BASE ANALYSIS

In the early 1980s, the outline of a national initiative began to crystallize from the numerous state-of-the-art reviews of millimeter monolithic gallium arsenide integrated circuits that appeared in both domestic and foreign publications. [78–88] The first IEEE Gallium Arsenide Monolithic Circuits Symposium was held at Lake Tahoe, NV in 1979, with 340 attending; attendance increased to 423 in 1981. The best papers from the 1981 meeting were selected for a special issue of the IEEE Transactions on Microwave Theory, July 1982, Vol. MTT-30, No. 7. The Society of Electron Devices also published Special Issues on Monolithic Microwave ICs in January 1983 (Vol. ED-30, No. 1), and December 1983 (Vol. ED-30, No. 12) with the IEEE MTT Society. In the foreword to the January 1983 issue, Gelnovatch observed that "the microwave and millimeter wave technical community stands on the doorstep of technological breakthrough [89]."Attendance at the 1983 and 1984 Symposia had increased by 40 percent per year to a number nearly double that of the 1981 meeting. By 1985, attendance had risen to 934 with an increase in attendance of 19 percent over the previous year. E. D. Maynard, Jr., announced the DoD MIMIC program at the 1985 meeting of the Government Microcircuit Application Conference, and gave the invited talk "DoD Microwave and Millimeter Wave Integrated Circuits Program" at the 1986 meeting of the GaAs Monolithic Circuits Program in Baltimore, MD on 4-5 June. He also gave the keynote talk "DoD Microwave and Millimeter Wave Program" at the Conference on Producibillity of Millimeter and Microwave Integrated Circuite, 5-6 November 1985, at Redstone Arsenal, AL. [90]

As a small part of this activity, between 1981 and the date of the DSARC for MLRS-TGW in September 1984, MICOM put together a substantial database on millimeter integrated circuit technology. As a follow-up to the completion of the manufacturing methods and technology program by Sperry Microwave on millimeter wave seekers, an industry-wide quick look IR&D analysis was conducted in 1984 at MICOM to identify firms by name, level of effort, and the content of the research. The results showed there were 40 companies working in the field of millimeter integrated circuits (both hybrid and monolithic) with practically no work that could be classified as manufacturing process development. Only 5 firms had levels of effort well above the other 35. There were approximately 375 man-years of IR&D efforts DoD-wide. As a follow-up to this analysis, a task to conduct an industry-wide survey of the technology was also prepared at MICOM to focus on a more detailed technical analysis. This task was executed as an amendment to a solicitation issued by ITT Research Institute, 30 July 1984, by Dr. Naresh C. Deo of the Millitech Corporation and Dr. Peter Toulios of Epsilon Lamda Electronics. [91-93]

The state-of-the-art analysis performed by these authors included: (1) the characteristics of circuit functions for monolithic realization, (2) the design process for MIMIC, (3) the transmission line structures suitable for planar monolithic fabrication, and (4) the major technological issues and problems. The authors also clarified the distinction between "millimeter integrated circuits" (MICs or hybrids) and "millimeter monolithic integrated circuits" (MMICs or MIMICs). The authors concluded with a summary of the most significant accomplishments that led to the present state-of-the-art (1985) with the potential for further advances.

The first generation of millimeter wave components, circuits, and systems were derived from scaling in wavelength from the well-established microwave technology. However, this required extremely tight tolerances, bulky structures difficult to package with high losses. In between this generation of technology and the monolithic integration of both active and passive circuit elements in a single substrate, Deo and Toulios found various approaches to achieving some degree of "integration" that are characterized as "millimeter integrated circuits" or MICs (hybrids). Both technologies were initially included in developing the criteria for the MIMIC program, but subsequently, MICs or hybrids were dropped in light of the overwhelming advantages of MMICs or MIMICs in cost, size, weight, volume, and reliability.

Four transmission line structures were identified as having potential for planar monolithic integration: the microstrip line, slot line, coplanar waveguide, and coplanar stripline (Figs. 15 and 16). From the analysis Deo and Toulious concluded there was no single transmission line medium that was ideal [92]. An examination of both two-terminal and three-terminal devices (Fig. 17) for four-circuit functions, showed that conceptually both classes of devices could be applied in the four-circuit functions, but in practice, there were severe limitations. The device geometries of two-terminal devices were not readily adaptable to monolithic integration although planar fabrication of Gunn devices had been demonstrated in 1968. Deo and Toulious highlighted the potential of two three-terminal devices: the Hetrojunction Bipolar Transistor (HBT), and the HEMT that would both be featured prominently in the MIMIC program. The most serious voids in MIMICs at the time of the analysis was in the area of power generation, particularly above 35 GHz, an issue of great importance to the smart weapons community. In an examination of the design rules imposed by monolithic integration, the authors found a number of constraints that represented a departure from the design rules for hybrid integrated circuit technology, as shown in Figure 18. An assessment of the several methods of growing the bulk starting material, the manufacturing processing steps in gallium arsenide, and epitaxial methods of growth was also part of the study.

The concern of the smart weapons community at the time of the analyses was whether or not active devices from the MIMIC program could be made to provide adequate power at 94 GHz. The two-terminal active devices (Gunn diodes and IMPATTS) in addition to not being readily adaptable to monolithic processing, had other limitations, but the use of e-beam lithography in achieving gate lengths of less than .5 microns for MESFETS had been a factor in achieving operation above 35 GHz with three-terminal devices. Deo and Toulious recognized the most critical challenge was the development of new active three-terminal device structures:

> "To meet the needs of a growing millimeter wave market, however, a new generation of transistors must be developed with superior high frequency characteristics, beyond the capability of current GaAs MESFETS." [93]

At the beginning of the formulation of the MIMIC program in 1985, the Army had a total of $2.3 million allocated for the technology in 6.1, 6.2, and MM&T; the Navy had a total of $7.1 million also in these same categories. The Air Force had by far the largest program with a total of $19.4 million in 6.1, 6.2, MM&T, and 6.3A. [94] The industrial base analysis of IR&D programs performed at Redstone Arsenal the prior year showed that there were approximately 40 companies working in the field, but almost no work in the area of manufacturing process development. Also, in contrast to these programs in analog technology, the Strategic Defense Initiative had $22 million in funding for digital gallium arsenide technology to take advantage of the radiation hardness of this material for space applications. In 1985, the principal application of the digital technology was military, but the military application was projected to shrink as a fraction of the total as the growth of digital gallium arsenide grew in the commercial computer market – a projection that never materialized. The digital program was not part of MIMIC (Fig. 14).

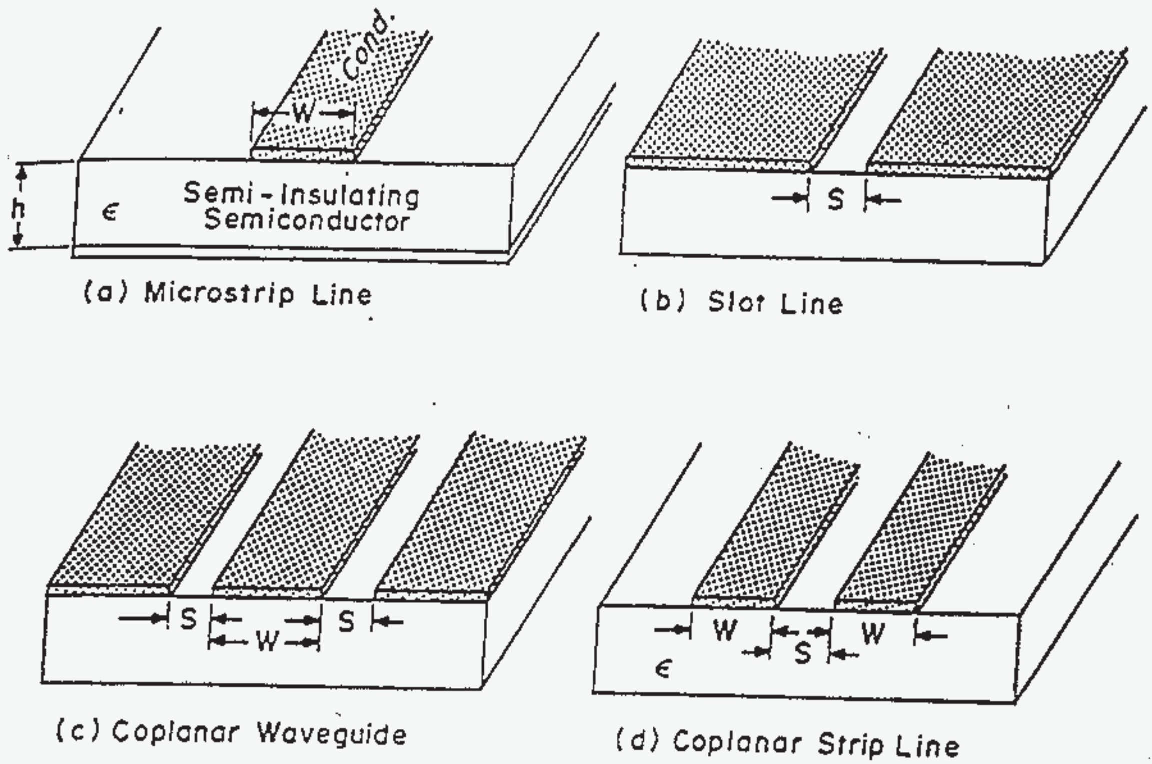


Figure 15. Transmission Line Structures for Monolithic Integrated Circuit Realization [91, 93]

	MICROSTRIP LINE	COPLANAR WAVEGUIDE	COPLANAR STRIP LINE	SLOT LINE
ATTENUATION	LOW	MEDIUM	MEDIUM	HIGH
DISPERSION	LOW	MEDIUM	MEDIUM	HIGH
IMPEDANCE RANGE,	10-100	25-125*	40-250*	HIGH
CONNECT SHUNT ELEMENTS	DIFFICULT	EASY	EASY	EASY
CONNECT SERIES ELEMENTS	EASY	EASY	EASY	DIFFICULT

* INFINITELY THICK SUBSTRATE.

Figure 16. Relative Properties of Various Transmission Lines [91, 93]

CIRCUIT FUNCTION	TWO-TERMINAL DEVICE	THREE-TERMINAL DEVICE
POWER GENERATION	TED (GUNN FAMILY), IMPATT DEVICES	MESFET, MODFET, HJBT, HEMT
AMPLIFICATION	GUNN DEVICES, DISTRIBUTED GAIN ELEMENT	MESFET, HEMT HJBT, MODFET,
MIXER/DETECTOR	SCHOTTKY BARRIER DIODE, JOSEPHSON JUNCTION DEVICE	MESFET
CONTROL FUNCTION	PIN, NIP STRUCTURE	MESFET, DUAL-GATE STRUCTURE
TUNING DEVICE	VARACTOR	FET

Figure 17. Devices for Monolithic Circuits and Their Applications [91, 93]

- Space taken by the passive elements in the circuit must be kept to a minimum
- The range of element values permitted is limited by the planar format.
- The circuit performance characteristics must be tolerant of the expected variation in device parameters due to the lack of any tuning capability to compensate for device parameter variations.
- Circuit complexity and chip partitioning are determined by yield objectives, what can and cannot be implemented monolithically, problems in biasing, and isolation requirements.

Figure 18. General Constraints Imposed on the Design Process for Monolithic Millimeter and Microwave Integrated Circuits [91, 93]

Other state-of-the-art reviews, published on the eve of the beginning of the MIMIC program, identified gaps in the technology and recommended specific courses of action for DoD. For example, A. Christou [84] identified needs in materials growth and characterization, FET process technology, lithography, ohmic contacts, Schottky gate formation, passive element processing, device modeling, and computer-aided design tools. Sleger [85] summarized the GaAs monolithic analog components manufacturing puzzle (Figs. 19 and 20) from the 1985 perspective that included 13 pieces of the puzzle, and concluded that DoD needed a strategy for success in MIMIC manufacturing and warned that if a domestic manufacturing base for MIMIC did not evolve within the next 5 years, the threat of foreign competition would be very real. In another paper, Sleger [80] presented a broad overview of applications of GaAs to Government systems, that included the results of a survey that displayed the system type versus the chip description, IC development, IC application, and potential chip buy. The Army, Navy, and Air Force were included in the survey. Sleger included both analog and digital GaAs in the analysis, and presented a funding summary for DoD and NASA in gallium arsenide monolithics, principally 6.2, for the 10-year period from 1973 to 1983 (Fig. 21).

David K. Ferry and 14 other top experts from industry, academia, and Government produced an excellent benchmark in the publication of the book Gallium Arsenide Technology that was published the same year the MIMIC program was announced. [95] The book included topics in the three application areas of gallium arsenide: digital, analog, and microwave photonics. The first demonstration of the HEMT device was in 1980, and the pseudomorphic HEMT was introduced the year the book was published. The authors of Chapter 4 (Tu, Hendel, and Dingle) took note of the rapid growth in papers on selectively doped hetrostructure transistors over this 5-year period. The growth of world-wide sales of molecular beam spitaxy systems over this same period grew from 13 systems in 1980, to 86 systems in 1986. [95] Clearly, David K. Ferry's optimistic observation in the Preface was well-founded:

> "Gallium Arsenide is the material of the future. This statement has been the logo for workers in the Field for over thirty years now. One may readily ask whether or not we will ever see large scale usage of gallium arsenide circuits. There have been long and bitter discussions between its advocates and is antagonists, yet, I feel that we can reasonably answer in the affirmative."

But, a later statement that "GaAs is today (1985) a firmly established technology" is a bit too strong. It would take the 7-year MIMIC program to make this true for analog gallium arsenide technology. In 1986, Gelnovatch called for a "Microwave VHSIC Program." [96]

PUZZLE PIECES	1985 STATUS
Semi-Insulating substrate quality and availability	-- Available in pilot line quantity -- 3" wafers need flatness improvements -- Dislocation density may require improvement. -- Industry depends on foreign sources
Processing Equipment (Focus on 0.5 to 1.0 micron definition over long gate width runs)	-- Mostly available from silicon industry -- Could require special equipment for short run innovative manufacturing -- E-beam not high volume oriented -- Processing still in evolutionary stage
Device and Circuit Models (1-100 GHz)	-- Formidable for active devices -- Large signal models limited -- Limited accuracy above 10 GHz -- In development above 20 GHz -- No general techniques for circuit design
Process Models	-- Limited for silicon -- Emerging for GaAs - no standard process
Computer Aided Design (1-100 GHz)	-- Limited to COMPACE, SPICE, CADEC -- Non-linear circuit design non-existent -- Limited microwave circuit elements -- Iterative procedure takes months (cost barrier) -- Unavailable above 20 GHz -- Considered a research frontier for MMIC
Computer Aided Engineering and Manufacturing (1-100 GHz)	-- Embrionic to non-existent -- Analog (RF) compiler may become available in 1985
Custom Design (1-100 Ghz)	-- Many (in response to DOD funding) Yields below 1% on 2" wafers Very high performance -- Cost barrier
Standard Designs (1-100 GHz)	-- Commercially driven - low cost -- Many use distributed amplifier concepts -- Most foreign activity here -- Cost and performance Impact for DOD?

Figure 19. GaAs Monolithic Component Manufacturing Puzzle: 1985 Perspective [85]

PUZZLE PIECES	1985 STATUS
Second Generation Technologies (Example: MODFET)	-- Research and development -- MODFET a candidate for generic low noise amplifier -- Market niche not determined
Short Run Concepts for Volume Generation	-- Being developed for silicon -- Ready by 1988? -- A key to affordability for GaAs
Human Resources	-- Business perception; Increased DOD funding in FY '86 to FY '90 may be counter productive to manufacturing
Packaging	-- Limited to narrowband designs -- Unavailable for wideband designs in off-the-shelf quantity -- In development above 20 GHz--critical cost barrier
Assembly	-- Limited to MIC experience -- Undeveloped for MMICs with 4 millimeter substrates -- Critical cost barrier
DC and RF Testing	-- Available: 2-18GHz wafer/package -- Limited: Above 20 GHz -- Cost barrier
Quality Outlook	-- Transition to quality outlook beginning in DOD pilot lines and component houses
Business Outlook	-- Technologist driven -- systems cost savings unknown -- Components required for DOD systems pull -- Strong commercial market emerging with questionable impact on DOD needs
Reliability, Radiation Tolerance Operation in Harsh Environments	-- Reliability, radiation tolerance data very limited -- Design for reliability, radiation tolerance non-existent -- Operation over military temperature range not demonstrated

Figure 20. GaAs Monolithic Component Manufacturing Puzzle: 1985 Perspective [85]

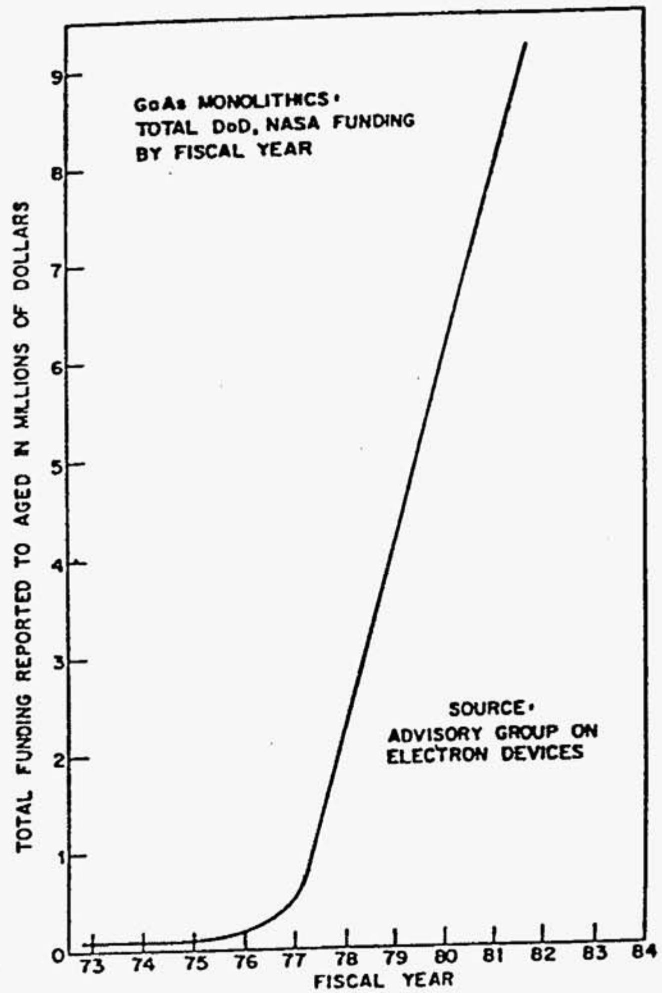


Figure 21. DoD, NASA Investment in GaAs Monolithics Component Principally 6.2 Exploratory [85]

The 84 carefully selected seminal papers in the 1985 IEEE book Monolithic Microwave Integrated Circuits seemed to provide the framework for the DoD MIMIC program announced by E.D. Maynard that year. [97] The potential benefits and limitations of both the monolithic and hybrid technology had been explored, and new directions for research were defined to overcome the limitations in the monolithic technology. The key cost drivers in each step of the gallium arsenide process from starting material to finished chip had been identified, thus providing the focus for much of the work executed under the MIMIC program. The growing patent literature in MESFETS the year the book was published underscored the importance of the MESFET as the key active device in MIMIC technology. Both civilian and military applications were foreseen (direct broadcast receivers, and phased array radars), and work was in progress on MIMIC devices in the 94 Ghz region of great interest to the smart weapons community. The progress in CAD for HMICs had established the springboard for CAD for MIMIC, and new test, measurement and diagnostic techniques were emerging to meet the challenge for MIMIC. Clearly, the scope of the effort identified in the 84 seminal papers was beyond the capability of individual organizations. It was up to DoD to serve as catalyst in releasing the creative energies in a focused effort to achieve national objectives.

The vigorous activity in MIMIC during the course of Phase I was reflected in the publication of Monolithic Microwave Integrated Circuits in 1989 that spanned the process from beginning to end in a format suitable for a two-semester college course as well as the practicing engineer. [98]

VII. THE NEED FOR A STRUCTURED PROGRAM

As noted, it was the MLRS-TGW program that drove the decision by the Under Secretary of Defense for Research and Engineering to establish the structured MIMIC initiative, and MICOM provided part of the supporting data leading to that decision. The first effort to highlight the need for such an initiative was made when the SPIE Conference on Integrated Optics and Millimeter and Microwave Integrated Circuits was organized and held on 16-19 November 1981, in the Von Braun Civic Center, Huntsville, AL. [99] Potential applications of the technology had been identified and individual MM&T plans had been prepared and submitted; however, the realization grew that the technology could not be advanced through a collection of uncoordinated MM&T projects. Major investments were required that were beyond the capabilities of individual companies, and a program structure was required that would allow the application of concurrent engineering. The DoD had initiated the Very High Speed Integrated Circuit (VHSIC) program a little over a year before in March 1980, so there was little enthusiasm for another major initiative at the time. Also, MIMIC was viewed as a specialized niche technology that did not deserve the same level of attention as a broad generic technology such as VHSIC; MIMIC was too much in the shadow of VHSIC at the time. However, one of the conclusions of the conference was that MIMIC was mature enough to sustain a structured program, but integrated optics was not.

Several events converged to create a climate favorable to the formulation of a national program in monolithic millimeter and microwave gallium arsenide technology. As noted, all three services, DARPA, and the Strategic Defense Initiative Organization, had analog millimeter wave monolithic gallium arsenide programs as part of programs in millimeter wave technology, but it was the perception in Congress that these were uncoordinated. As a result, the services were asked to explain the duplication in the technology. (The result of this examination at Redstone Arsenal was that the 1498s were, in many cases, unfunded, or the term "millimeter wave" was misused in the title as a catchy phrase for use in budget documents.) In addition, the Committee on Critical Materials after reviewing MM&T projects completed and planned at MICOM on 9 December 1985, observed in their report:

> "The combined effort that exists in the United States, including that in the Army and other military organizations, industry and universities is not sufficient to present the ultimate dominance by the Japanese as suppliers of III-V compounds, materials, devices, and circuits." [100]

Also, the data emerging from the MM&T programs was leading to the inevitable conclusion that achieving competitiveness on a national level could not be achieved through the summation of uncoordinated individual projects in 6.1, 6.2, MMT. For example, in the MM&T study on the Assault Breaker Drop Test Millimeter Seeker discussed earlier, Sperry concluded that in the 1983-84 period, it would be possible to achieve a "fully integrated" RF front end production cost of 2,300 dollars at a production rate of 800 per month for a total of 50,000 units; but to achieve a monolithic front-end for a cost of 900 dollars would require an expenditure of 8 to 10 million over a 5- to 8-year period. Clearly, this estimate for one firm and one project was far below the investment needed to achieve competitiveness on a national level. [71, 72]

(Incidentally, the term "fully integrated" in the report does not mean monolithic, but refers to "millimeter integrated circuits", or MICs, meaning hybrids.)

Clearly, a structured program was needed to achieve some economy of scale in the research and development process, as well as the manufacturing process development, and a model for accomplishing this was provided by the VHSIC. The MIMIC team approach brought together the systems houses, foundries, specialty firms skilled in software tool development, device physics, modeling and simulation, on-chip testing, and others. As a follow-up to the paper presented at the SPIE Conference on Integrated Optics and Millimeter and Microwave Integrated Circuits, 16-19 November 1981 (SPIE Volume 317), an Army-wide proposal, "A Structured Program in Microwave and Millimeter Circuit Technology" (Appendix B), was prepared and submitted to the Army which reflected this structured approach. [101] Also, a revised version for DoD: "Improving the Availability, Affordability and Producibility of Microwave and Millimeter Integrated Circuit Technology" (Appendix C) was submitted to DDR&E in August 1984, in response to a request from the USDRE. [102]

The need for a structured program was clearly delineated in the planning directives and memoranda issued by DDR&E. For example, the memorandum prepared by Dr. Robert Heaston and signed by James Wade on 1 February 1985, to the Assistant Secretaries of the military departments and DARPA contained the following:

> "It is generally agreed that no single guidance and control, electronic warfare, communications, or radar program can afford to adequately advance the technology that needs to be supported. Too many gaps remain unfunded if we continue to support a series of disconnected individual programs. Consequently, critical technology needs, generic chip designs, required testing capabilities, and mass production techniques need to be identified and funded as a coordinated DoD-wide program." [103]

In Criteria for DoD Program in Microwave and Millimeter Integrated Circuits, dated 19 March 1985, is the following:

> "The program should not just be "more of the same" of what industry is doing under the IR&D program, but provide the basis for the Government to be a smart buyer of the technology as well as strengthening the industry itself." [104]

The criteria also made producibility goals rather than performance goals the major thrust of the program, and provided a strong role for the DoD in-house laboratories. Both hybrid and monolithic technologies were to be included in the program according to the criteria, but hybrid technology was subsequently dropped.

VIII. 1985-1986 MIMIC PLANNING CONFERENCES, HIGHLIGHTS, CHALLENGES

The U.S. Army Technology and Devices Laboratory served as host for the U.S. Army Gallium Arsenide Workshop on 24 through 26 February, which included: (1) Industry Capability Baseline Review, (2) TRADOC Requirements, (3) Army System Managers Requirements (1990-2010), and (4) SDI/DARPA Inputs. Also, on the agenda were workshops by the four key specialty areas: Smart Weapons, Electronic Warfare, Radar, and Communications. [105]

Potential programs to meet service requirements was the theme of the workshop held on 18-19 March 1985, by the M31 Committee at Georgia Tech Research Institute with participants from the three services. [106] As a follow-up to the earlier industrial base analyses, members of the Committee visited 19 corporations heavily involved in MIMIC technology. A summary of the results of these visits is contained in Reference 107.

On 5-6 November 1985, the Missile Research, Development, and Engineering Center served as host for the 1985 Producibility of Microwave and Millimeter Wave Integrated Circuits Conference. [108] Dr. E.D. (Sonny) Maynard, Director of the VHSIC Program office and the MIMIC Program Office gave an outline of the structure of the MIMIC program and observed that the MIMIC program would provide the "eyes and ears" of systems that have "brains" provided by VHSIC, with similar benefits provided by both technologies. The program structure of MIMIC according to Maynard would be similar to that of VHSIC. The conference program included seven sessions: (1) Overview, (2) Materials, (3) Reliability Physics and Environmental Effects, (4) Production Testing, (5) Process Technology, (6) Applications, and (7) Roundtable Discussion. The Overview session included "DoD Needs for Measurement Standards," and "State of the Art Review of Microwave and Millimeter Wave Monolithic Integrated Circuits" and an "Overview of the AMC Smart Munitions Center."

A key theme of this conference was the wide gap between the growth of the microwave and millimeter wave industry and declining funding for the NBS to develop the metrology to support the industry. In 1984, the IEEE MTT-S Society of Microwave Theory and Techniques formed the Committee to Promote National Measurements Standards (PNMS). The PNMS Committee conducted a detailed study of NBS and several other national measurement laboratories with the help of the International Scientific Radio Union (URSI). The conclusion was the NBS had lost its world leadership position. Plans began immediately after the conclusion of the conference to put together a program for a two-day conference on measurement standards for miniaturized systems the following year to highlight this problem in the same week as the second Conference on the Producibility of Millimeter and Microwave Integrated Circuits. [109] On 29 January 1986, a meeting of the DoD Calibration Coordination Group (CCG), the NBS, and the DoD Laboratories was held at Redstone Arsenal to plan the agenda for the conference in 1986.

The follow-up to the 1985 conference on Producibility of Millimeter and Microwave Integrated Circuits was held on 4-5 November 1986, at the Redstone Arsenal Post Theater [109], and on 6-7 November the Conference on Millimeter and Microwave Measurement Standards for Miniaturized Systems was held in the same location. [110] The latter meeting provided a leadership role for the NBS (to become later the National Institute of Standards and Technology) in the MIMIC program that was a major factor in the success of MIMIC.

IX. MIMIC ADVANCES SMART MUNITIONS

The Multi-Option Fuze for Artillery (MOFA), the Search and Destroy Armor (SADARM), and Multiple Launch Rocket System-Terminally Guided Warhead (MLRS-TGW) were all relatively small-diameter munitions with potential for production in large numbers, and therefore attractive candidates for MIMIC insertion. The first use of proximity fuzes in combat was in World War II, and the principal change in the technology following World War II was the replacement of miniature vacuum tubes with transistors. The undesirable proximity patterns for these fuzes that operated below the microwave band required a new design for each munition. Hittite Microwave was a member of the Raytheon-Texas Instruments MIMIC team that successfully integrated all the microwave functions required by MOFA on a single chip that included a voltage controlled oscillator, amplifier, circulator, and mixer. Although no hardware was required in phase I, Hittite provided transceivers for evaluation by Armaments Research, Development, and Engineering Center (ARDEC) in prototype fuzes. Hittite delivered transceivers to ARDEC for use in 60 fuzes designed and fabricated in-house as part of the 6.3A MOFA program. Hittite was not funded in Phase II MIMIC, but continued to work to reduce the unit production lost when PM Crusader decided to fund the Phase II effort. Hittite continued to work under a contract modification to the existing Raytheon/Texas Instruments BAA. Hittite fabricated, packaged, and tested over 7500 transceivers to verify yield and performance, and demonstrated that the $10.00 cost goal could be met. [111]

The MIMIC technology offered the potential for higher precision in a transceiver at microwave frequencies and programmability that could provide detonation signals for a variety of options including contact burst, delayed burst, or proximity burst, at heights that could be varied over a wide range. The research trail that led to MOFA began in basic research in 1968-1970, and moved through all phases of acquisition to production as XM 773 MOFA. MIMIC was coupled to MOFA from the beginning of Phase 0, and in February 1995, a panel of academic and industrial leaders declared the MIMIC MOFA to be a world-class design. [112]

The SADARM is the first indirect fire, fire-and-forget munition capable of attacking enemy armor columns. The munition is configured for launching as an artillery payload with growth potential for transportation by a carrier rocket to the target area. After arriving in the target area, a parachute unfolds from the submunition and slows the descent of the submunition into the target area. During descent, a dual-mode infrared-millimeter sensor executes a circular scan. Upon detection, the error signals generated by the circular scan provide the commands for submunition to move in the direction of the target for impact. The sensor system features an infrared sensor capable of producing a full image of the target, and both active and passive sensing in the millimeter region.

The millimeter wave technology in the early generation of SADARM featured hybrid technology. MIMIC technology was identified as a technology that could improve performance and reduce size and cost. The original goal of putting all the functions of the millimeter wave transceiver on one chip was not achieved. An early perception was that higher frequency operation could improve aimpoint selection, countermeasures immunity, and receiver function to provide an extended range and a larger footprint, but this was not adopted.

The concept has been proven in over 130,000 tests, including both captive and live fire tests. The SADARM has been in production in small quantities, and the team at Picatinny Arsenal, Dover, NJ, has initiated a Product Improvement Program and a Cost Reduction Plan. [113]

The MLRS-TGW program was originally sponsored by the U.S., the United Kingdom, France, and Germany through a joint venture contractor MDTT, Inc, composed of Martin Marietta (U.S.), Diehl Gmbh (Germany), Thomson-CSF (France), and Thorn-EMI (United Kingdom). The objective of the program was to provide an indirect fire, fire-and-forget, all-weather precision guided submunition against armor that featured a millimeter wave seeker to detect, lock-on, track, and guide the warhead into the target. The baseline transceiver for the millimeter seeker consisted of two subassemblies; the transmitter developed by TRW and the receiver developed by Thomson-CSF, who was also responsible for integrating the subassemblies. The millimeter wave seeker was identified as one of the potential risk factors in the Concept Demonstration Phase, but it was concluded that the component risk was at an acceptable level to allow the program to enter the System Demonstration Phase in 1989. The plans for this part of the program provided for 44 TGSMs to be fabricated for a series of tests that included end-to-end delivery of the submunitions to the target area by the MLRS rocket, as well as drop tests of the submunition from high-speed aircraft against an array of targets. In 1990, the TGSM was down-selected as a contender for the Deep Battle mission. [114]

Among the problem areas that made the millimeter wave seeker a risk factor were: (1) The metal waveguide structure made packaging difficult; (2) High peak power was required to overcome the high circuit losses at high millimeter wave frequencies; and (3) Poor frequency stability was the result of open-loop stabilization. MIMIC offered a solution to these three problems through (1) the integration of many functions on a few chips to reduce size, (2) the use of a monolithic direct frequency synthesizer to improve stability, and (3) the use of a low-noise HEMT amplifier to reduce the noise figure of the receiver, and thus reducing the IMPATT transmitter power requirements. However, the MIMIC program was not part of the international program. The coupling of MIMIC with MLRS-TGW was accomplished outside the framework of the international program through a MICOM Manufacturing Technology (MANTECH) program initiated during the System Demonstration Phase. The Manufacturing Technology Division, MICOM, developed the insertion strategy and managed the program that achieved a number of major milestones in MIMIC technology.

The MANTECH transceiver developed by TRW met or exceeded the MLRS-TGW specifications, including (1) The first W-band power amplifier to replace the Gunn diode assembly, and (2) The first low-noise amplifier at W-band. Although the U.S. withdrew from the international program in 1992, the excellent results with the MANTECH transceiver has led to the decision by the Army to integrate it into some of the residual hardware from the international program. [115]

Since the original three smart munitions candidates were selected for MIMIC insertion, other candidates have emerged: AMRAM, PATRIOT, LONGBOW, and the BAT P31 program. The latter system will be able to capitalize on the advancements made in MIMIC transceiver technology since the MLRS-TGW MIMIC transceiver was developed. The MIMIC program provided the stimulus for several follow-on MANTECH programs that will be reviewed in a separate publication [115].

X. THE GLOBAL ENVIRONMENT

A. Introduction

The MIMIC program was undertaken at a time when there were serious concerns about the erosion of U.S. leadership in technology. The globalization of the Defense industrial base had led to a major dependence on foreign sources for materials and components for defense. In the civilian sector, by 1984 major industries and products including automobiles and color television sets had lost 50 percent or more of their market since 1960, as shown in Figure 22. According to A. Blanton Godfrey and Peter J. Kolesar:

> "The broad picture of the sudden decline in international competitiveness of U.S. manufacturing is no less startling: a 1986 overall trade deficit of $170 billion, $59 billion of that with Japan alone, with $30 billion in that most American of industries - - automobiles. And that $30 billion is with "voluntary" export restrictions by the Japanese." [116]

In 1982, the Microelectronics and Computer Technology Corporation was formed in response to the Japanese Fifth Generation Computer Project. To strengthen U.S. Competitiveness in the semiconductor industry, Congress passed the Chip Protection Act of 1984, and the National Cooperative Research Act of 1984, to modify antitrust restrictions and provide a less threatening framework for forming joint ventures, and as a result, the Semiconductor Manufacturing Technology (SEMATECH) consortium was formed in 1987 by 14 leading major semiconductor manufacturing companies. [117] To explore the opportunities for improving U.S. competitiveness by shortening the product development cycle, DARPA conducted a Workshop on Concurrent Engineering in 1987, and the following year DARPA launched a Government-Industry-Academia consortium on concurrent engineering. The same year, the 1988 Omnibus Trade and Competitiveness Act transformed the NBS into the National Institute of Standards and Technology (NIST) with new responsibilities. Under the legislation, NIST was charged with the responsibility to transfer advanced manufacturing technology developed at NIST to industry through regional extension centers. [118] The following year, NIST served as host for the first annual MIMIC Conference at Gaithersburg, Maryland; a timely move since the MIMIC program provided a major challenge in manufacturing technology. The legislation also provided $100 million per year for five years to the SEMATECH consortium.

AUTOMOBILES	**FOOD PROCESSORS**
CAMERAS	**MICROWAVE OVENS**
STEREO EQUIPMENT	**ATHLETIC EQUIPMENT**
MEDICAL EQUIPMENT	**COMPUTER CHIPS**
COLOR TELEVISION SETS	**INDUSTRIAL ROBOTS**
HAND TOOLS	**ELECTRON MICROSCOPES**
RADIAL TIRES	**MACHINE TOOLS**
ELECTRIC MOTORS	**OPTICAL**

Figure 22. American Industries Named Products that Lost 50 Percent or More of Their Share of World Markets Between 1960 and 1984 [116]

B. U.S. Participation in an International Missile Program

It was an international program in which the U.S. was a participant that focused attention on the affordability of millimeter wave seekers and the potential of MIMIC as a solution. In 1983, the multinational MLRS-TGW program was established under a Memorandum Of Agreement (MOA) signed by the U.S., France, Germany, and the United Kingdom. A Joint Venture was formed with four national contractors: Martin Marietta Corporation (U.S.), Diehl GmbH (Germany), Thompson CSF (France) and THORN EMI, Ltd, (United Kingdom), and the internationally staffed MDTT, Inc. that performed the management function. The project management office for the program was located at Redstone Arsenal, Alabama.

As the MIMIC program approached the end of Phase I, the DoD evaluated the MLRS-TGW and two other target-sensing submunitions in response to direction by Congress, and the submunition for MLRS was eliminated in favor of an alternative selected in 1991. However, U.S. participation in the program continued under reprogrammed DoD funds approved by Congress in addition to 1992 appropriated funds to complete the development phase then in progress. In April 1992, the U.S. General Accounting Office (GAO) reported on a review of the provisions of the MOU to determine how U.S. interests were protected (Fig. 23 and 24). [119]

The GAO found that the U.S. had the highest cost share, but the lower quality work share. In addition, GAO concluded MOU provisions on data rights and termination could prove costly, and third country transfer provisions might not adequately protect U.S. interest. The GAO interpretation of the MOU was that if a country introduced a new technology during the development phase of the TGW, this could require the release of the technology to the other partner nations, and a key technology developed under a separate program affected by this interpretation was the MIMIC Program. The DoD nonconcurred with the conclusion that third country transfer provision would not adequately protect U.S. interests. The DoD also nonconcurred with the conclusion that design and manufacturing technology would have to be transferred to the other partner nations if MIMIC was introduced in the program. [106]

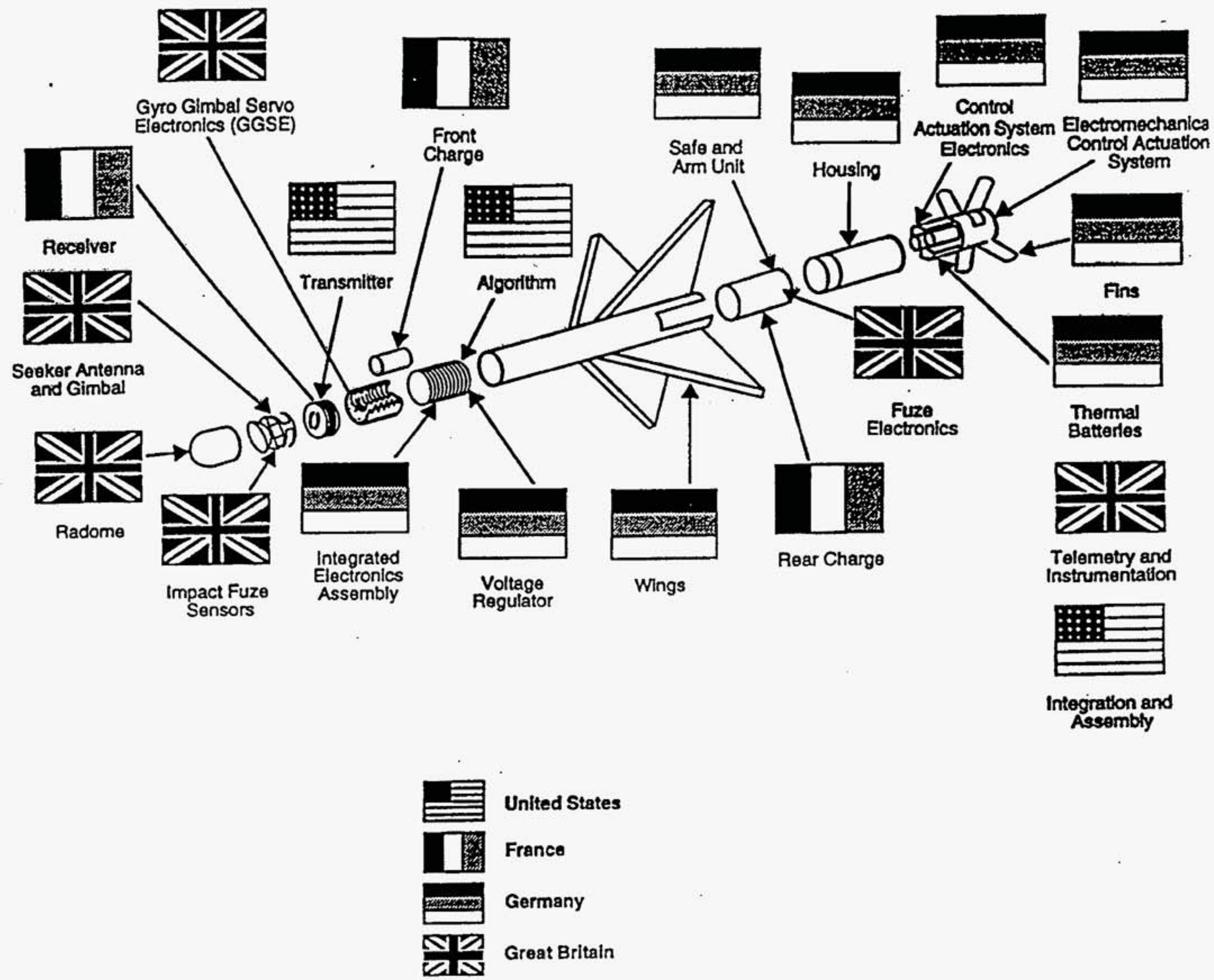


Figure 23. MLRS Terminally Guided Submunition [119]

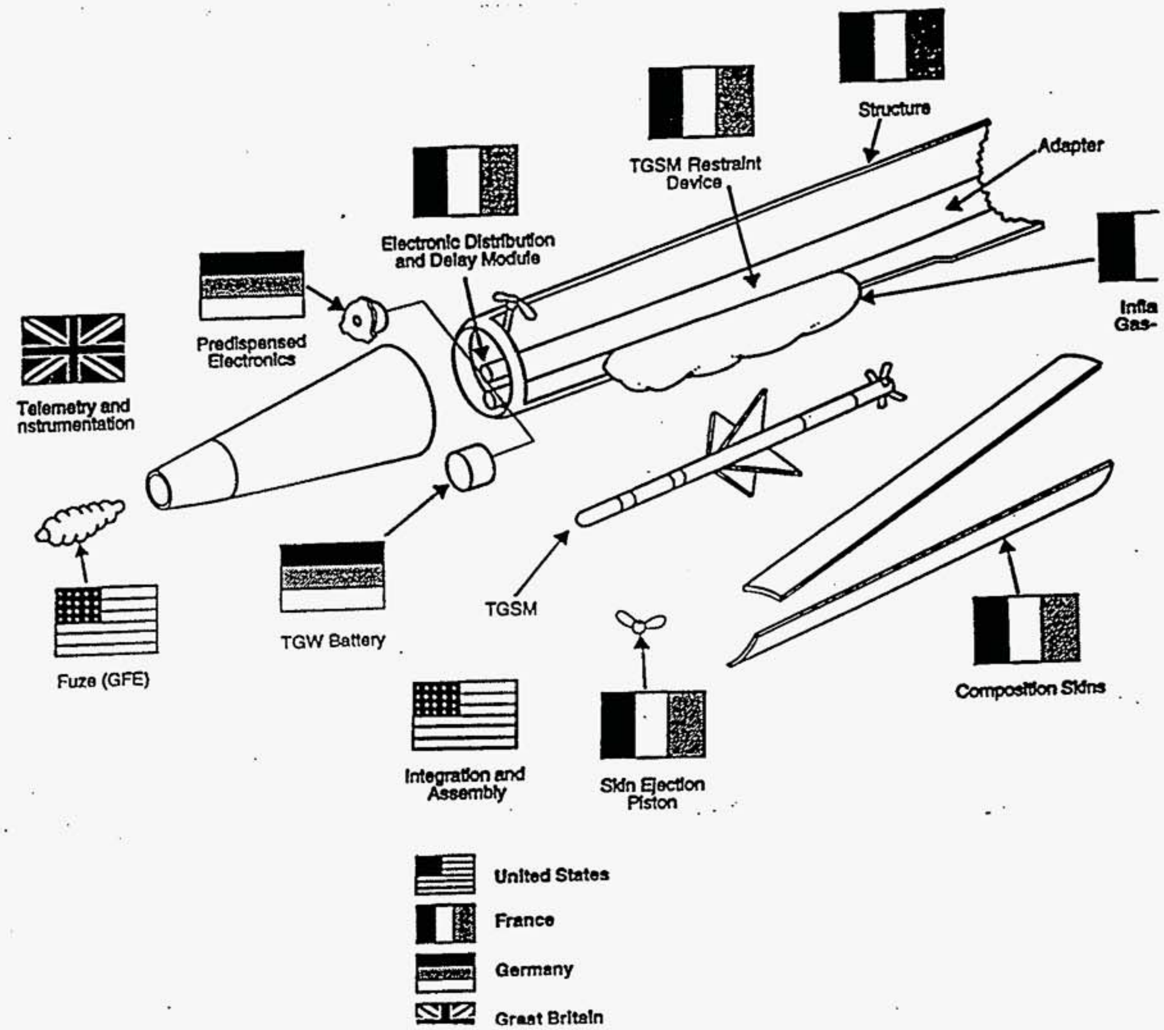


Figure 24. MLRS Terminally Guided Warhead [119]

C. Export Control Issues for VHSIC and MIMIC

During the course of the VHSIC program, the Defense Science Board Task Force devoted extensive thought to the issue of balancing the requirement for national security against the need to allow open communication among researchers in VHSIC technology to permit advancements to take place outside the arena of military weapons. Three possible control mechanisms were examined in relationship to the technology: (1) The DoD Security Classification Systems, (2) The Arms Export Control Act, and (3) The Export Administration Act. Military unique brassboard, software, and integrated circuits properly belonged under the DoD security classification guidelines. However, the dual-use nature of some of the technology having substantial application outside military systems suggested classifying it according to technology that could be inferred from finished products, and technology that could not be inferred from finished products. For the first category, the Export Administration Act was considered the appropriate control, but the second category, along with keystone fabrication equipment, design and test generation software, and remote design services were recommended for interim control under the Arms Export Control Act (International Traffic in Arms) until the Export Administration Act could be upgraded. [120]

D. Relations with JAPAN

In 1987, as the MIMIC program was getting underway, the Office of Japan Affairs was established by the National Research Council to develop improved working relationships between the scientific and technical communities of the two countries and to achieve a better understanding of Japanese science and technology.

In one study, the committee on Japan identified 12 types of U.S.-Japan alliances that could be grouped under four headings: (1) Research and Development, (2) Product Development, (3) Manufacturing, and (4) Sales and Development. For the 30 years between 1950 and 1980, the committee found that the number of alliances were few in number and restricted to the category of research and development in the form of licensing agreements for the sale of U.S. Patents to Japan. With the removal of legal and regulatory constraints, the number of alliances increased markedly as the MIMIC program was being formulated. By the time the MIMIC program was under way, a number of agreements were signed in the area of semiconductor equipment, but the number of agreements peaked before Phase I MIMIC was completed. A conclusion of the study of US-Japan strategic alliances in the semiconductor industry by the committee on Japan was that the flow of technology was one way from the U.S. to Japan. [121]

E. Defense Science Board Studies

The 1987 Defense Science Board Task Force on Semiconductor Dependency concluded that it was difficult to determine the extent that U.S. defense systems were dependent on foreign semiconductors, but the evidence indicated that for the newest systems about to be deployed, up to several tens of percent were either entirely made, or packaged and tested abroad. The Task Force found that the leadership in commercial volume production was being lost by the U.S. semiconductor industry, and the movement of manufacturing off-shore tends to pull the "upstream" industries that support the manufacturing base along with it. The Task Force was clearly alarmed that the trend would ultimately undermine the U.S. leadership in such "downstream" industries such as computers and telecommunications that depend on a healthy semiconductor industry. The conclusion was that although the Defense Department was a customer for only a few percent of the semiconductor market, DoD was strongly dependent on a healthy semiconductor industry, and that health was maintained by high-volume commercial production. The logic of the Task Force's thought process regarding the threat is summarized in Figure 25. The threat was particularly alarming for gallium arsenide technologies for which the commercial market was limited and the Defense Department was the principal customer:

> "In nonsilicon products, such as compound semiconductor optoelectronics and fast digital technologies and particularly in optoelectronic circuits, the U.S. also trails Japan. The US currently maintains a lead in linear compound semiconductor IC technology, largely because of military interest in fast and radiation-hard circuits for satellite and radar applications." [122]

This appears to refer to the DARPA digital gallium arsenide efforts that were not part of the MIMIC program. Any lead the U.S. might have had here was of small comfort since the Task Force had concluded that the health of the semiconductor industry was dependent on high-volume commercial markets - - not small-volume defense markets which was the condition at the time of the Defense Science Board study. Much of the processing equipment for manufacturing could be applied to either silicon or compound semiconductor production, but Japan was making larger investments in the development of semiconductor manufacturing equipment than the U.S. The status and trends of semiconductor technology in Japan and the U.S. is shown in Figure 26 and trends in manufacturing productivity in the U.S., Japan, and West Germany is given in Figure 27.

In the 1988 Defense Science Board Summer Study on The Defense Industrial and Technology Base, the Board found that "If our nation is to ensure its security for the coming decade and beyond, it must adopt a strategy which links military strategy with a policy to ensure the availability of the industrial and technological resources on which operational plans rely." [123] The Board was clearly concerned that the loss of leadership in semiconductors would ultimately lead to a loss of leadership in computers.

The Defense Science Board was also asked to take a "quick relook" at the 1986 summer study on Use of Commercial Components in Military Equipment. The Board stated in their 1989 report that although there was overwhelming support for the idea, there had been little increase in the use of commercial parts in military equipment. The Board felt impelled to offer a specific course of action embodied in four thrusts: (1) a component demonstration program using microcircuits as case studies, (2) a subsystem demonstration program using computers, both hardware and software as case studies, (3) a pilot acquisition system demonstration program, and (4) establishment of new organizations to support the shift to commercial goods and practices. [124]

THE PERCEIVED THREAT TO U.S. LEADERSHIP BY THE DEFENSE SCIENCE BOARD TASK FORCE ON SEMICONDUCTOR DEPENDENCY [12]

- U.S. MILITARY FORCED DEPEND HEAVILY ON TECHNICAL SUPERIORITY TO WIN.
- ELECTRONICS IS THE TECHNOLOGY THAT CAN BE LEVERAGED MOST HIGHLY.
- SEMICONDUCTORS ARE THE KEY TO LEADERSHIP IN ELECTRONICS.
- COMPETITIVE, HIGH-VOLUME PRODUCTION IS THE KEY TO LEADERSHIP IN SEMICONDUCTORS.
- HIGH-VOLUME PRODUCTION IS SUPPORTED BY THE COMMERCIAL MARKET.

Figure 25. The Perceived Threat to US Leadership by the Defense Science Board Task Force on Semiconductor Dependency [122]

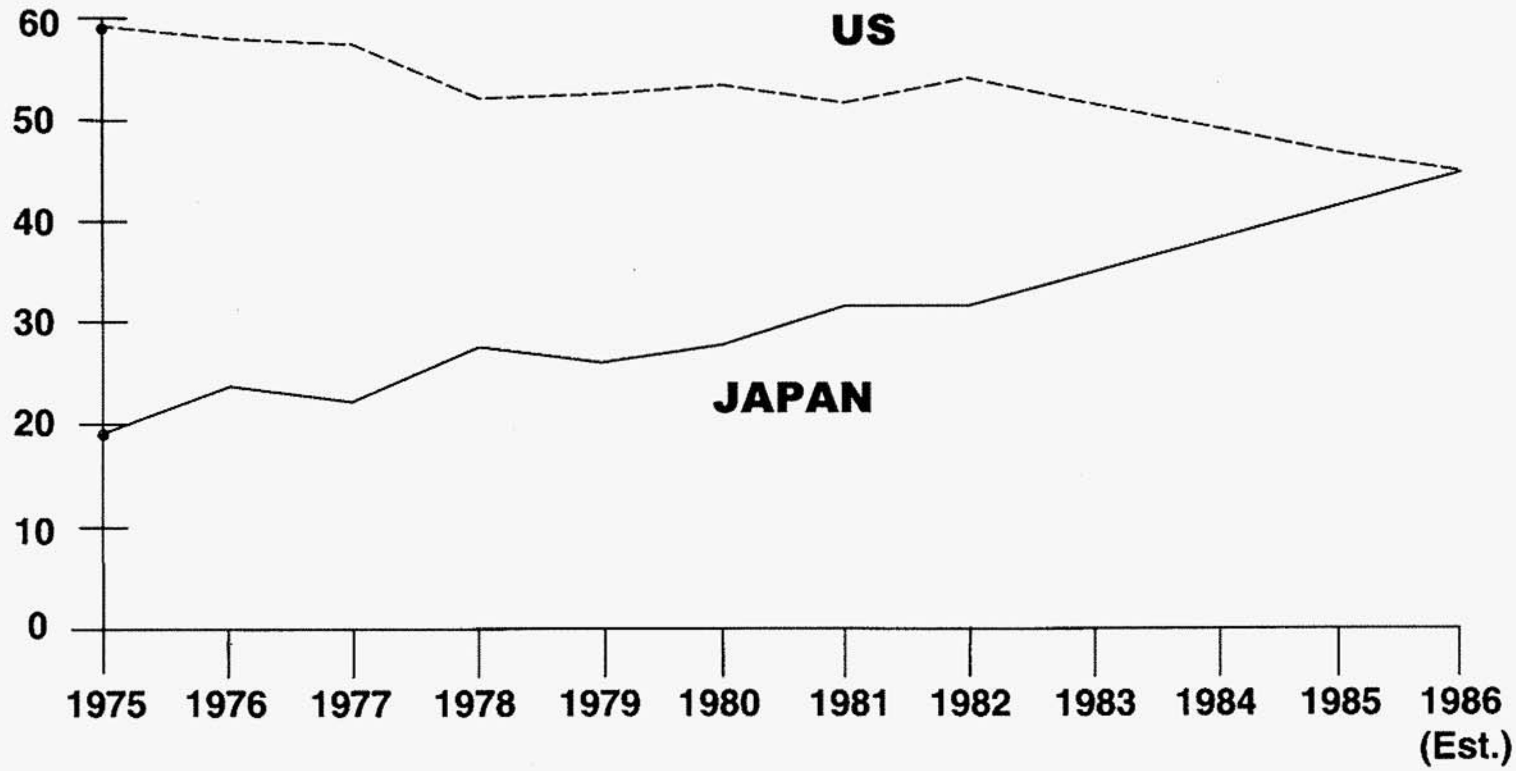
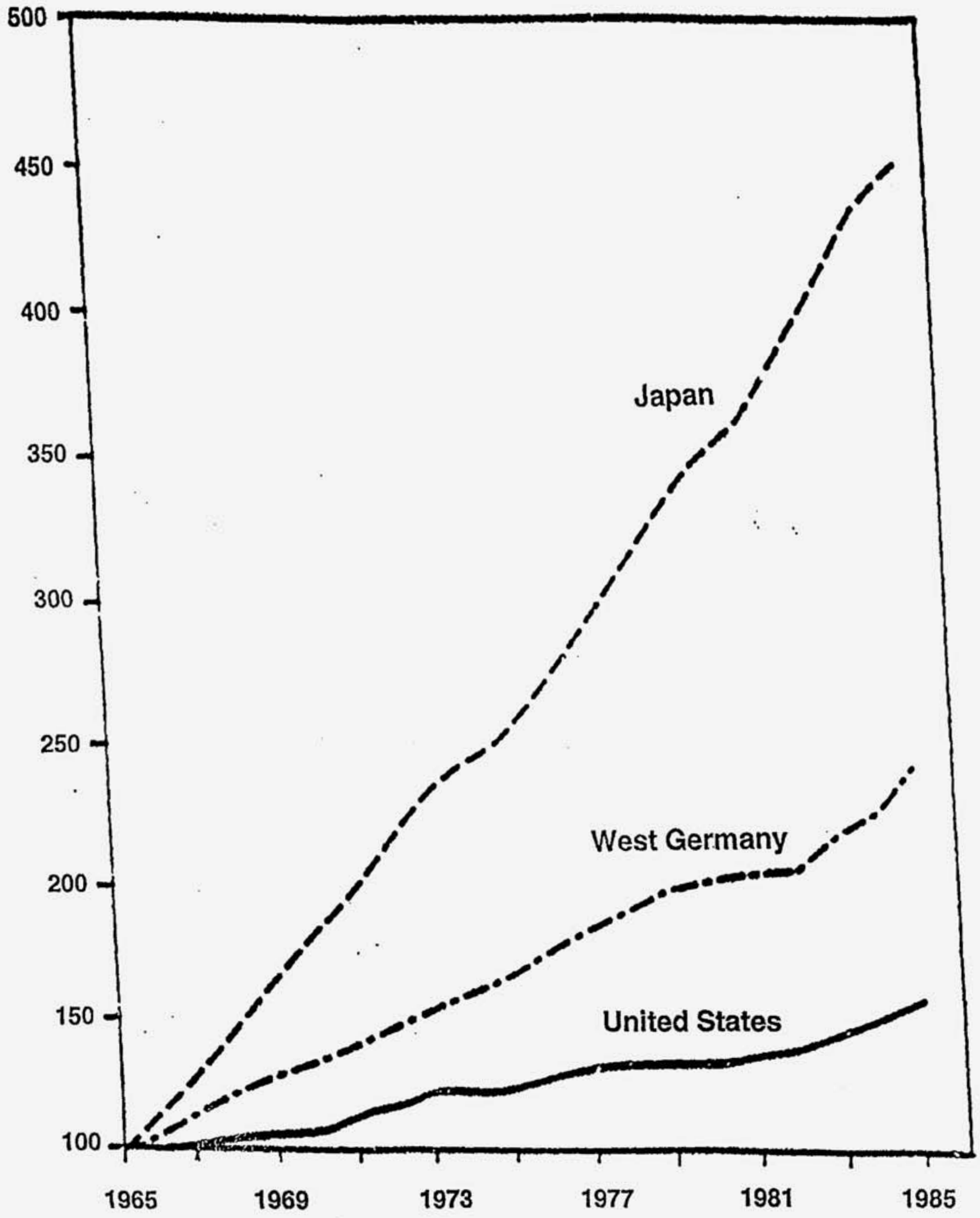


Figure 26. Status and Trands of Semiconductor Technology in Japan and the U.S. [122]



Source: U.S. Dept of Labor Bureau of Labor Statistics Office of Productivity and Technology: 1985

Figure 27. Manufacturing Productivity, 1965-85 [122]

F. Actions Bolstering Defense Industrial Competitiveness

In recognition of the absence of any coordination mechanisms between defense planning and private sector industrial planning, the Under Secretary of Defense for Acquisition, in July 1988, recommended an action plan to the Secretary of Defense that included six strategic thrusts: (1) forging the right relationship with industry, (2) establishing industrial strategic plans, (3) improving the acquisition system, (4) developing manufacturing capabilities concurrent with the development of weapon systems, (5) strengthening the skill base required to meet tomorrow's defense needs, and (6) improving the policy process. Specific actions taken by the Under Secretary of Defense for Acquisition was establishing the DoD Defense Manufacturing Board, modeled after the Defense Science Board, and by working with the National Academy of Sciences, arranged to have a nondefense counterpart organization called the Manufacturing Strategy Committee. The recommendations acknowledged the low status of manufacturing in general:

> "The attitude in the United States toward manufacturing and manufacturing technology is somewhat negative. American universities have little to offer in these fields. Even within the manufacturing firm, research and design engineers are perceived to have more prestige than manufacturing engineers. One result is that the manufacturing function does not compete effectively for high-quality personnel. (Conversely, the Japanese have a high regard for manufacturing and are totally committee to innovation in both process and product). These attitudes (and resultant rewards systems) toward manufacturing careers often prevent the best people from beginning or sustaining careers in manufacturing." [125]

The same year (1988) the Under Secretary of Defense for Acquisition made his recommendation, DARPA established the Concurrent Engineering Center at West Virginia University to provide a national resource devoted to designing, developing, and promoting concurrent engineering technologies.

In 1989, the Institute for Defense Analysis (IDA) reported the results of a study for the Assistant Secretary of Defense for Production and Logistics to determine the benefits of concurrent engineering in providing products of improved quality at lower cost in shortened product cycle. The IDA team reviewed the results of the 1987 DARPA workshop on Concurrent Engineering and conducted two workshops on this subject in 1988 to define concurrent engineering, and describe how companies were applying concurrent engineering techniques. Six companies were selected for detailed case studies with results summarized in Figure 28. Although pitfalls were found in the process, IDA concluded that a successful strategy could be based on concurrent engineering and made seven recommendations to the Secretary of Defense for implementing such a strategy. [126]

As a follow-on to the IDA study, the Defense Science Board Task Force focused on the areas of Integrated Product and Process Development (IPPD) and dual use in manufacturing in the 1993 report Engineering in the Manufacturing Process under the chairmanship of Dr. Kent Brown and Mr. Noel Longuemare. [127] The task force was organized into three subgroups to consider:

> (1) requirements for early consideration on manufacturing processes in the S&T environment, (2) the uses of advanced modeling and simulation in the IPPD phase, and (3) opportunities for increased use of best commercial products, practices and capabilities [124]. The key recommendation was that DoD institute a process that "focuses from the outset of development on improving the manufacturing process, that uses new tools in modeling and simulation, that takes advantages of commercial products, processes, and capabilities. The new process steps needed to implement integrated product- process development in the S&T phase is shown in Figure 29 and the benefits in Figure 30. As a result of the Board's recommendation, the Secretary of Defense issued a memo, 10 May 1995: "I am directing a fundamental change in the way the Department acquires goods and services. The concepts of IPPD and IPTs shall be applied throughout the acquisition process to the maximum extent possible." [128] The work of the Defense Science Board was continued with the publication of a report of Defense Manufacturing Enterprise Strategy. [129]

The Defense Science Board Task Force on Defense Manufacturing Enterprise strategy identified government policies that impeded lean manufacturing, and recommended changes leading to world-class production, including strategies to break the cost-volume relationships. The task force also recommended actions to reorient the acquisition workforce to these new manufacturing policies practices and procedures. The task force found that "what to do" was well documented, but the barriers that prevented the implementations of prior recommendations were (1) performance-driven program definition, (2) cost-based contracting, (3) expensive and sluggish design, and (4) risk aversion procurement. [129]

The task force found that the principal reason the prior recommendations on manufacturing, acquisition, and industrial management had no impact was the lack of a process. The recommendations were therefore focused on "how to" implement change, rather than "what to do" in the entire enterprise. Special emphasis was placed on the term "enterprise" that was defined as having three meanings: a business organization, a systematic purposeful activity, and readiness to engage in daring action, initiative.

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% savings on bid for reactor and Missile Projects	Significant savings (reduction from 45 weeks to 8 hours) in one phase of high-speed vehicle preliminary designs; 18 months saving of TAV-88 design	Setup reduced 58%, rework cost reduced 29% and non-conformance reduced by 38%; weld defects performance unit decreased by 70%; 68% fewer changes on reactor; 68% fewer drawing changes on TAV-88
Boeing Ballistics Systems Division	Reduced labor rates by $28/hour; savings 30%below bid	Part and materials lead-time reduced by 30%; one part of design analysis reduced by over 90%	Floor inspection ratio decreased by over 2/3; material shortages reduced from 12% to 0; 99% defect-free operation
AT&T	Cost of repair for new circuit pack production cut at least 40%	Total process time reduced 46% of baseline for SESS	Defects reduces by 30% to 87%
Deere & Company	30% actual savings in development cost for construction equipment	60% savings in development time.	Number of inspections reduced by 2/3
Hewlett-Packard Co. Instrument Division	Manufacturing costs reduced by 42%	Reduced development cycle time by 35%	Product field failure rate reduced 60%. Scrap and rework reduced by 75%.
IBM	Product direct assembly by labor hours reduced 45%	Significant reduction in PMT design cycle; 40% reduction in electronic design cycle.	Fewer engineering changes. Guaranteed producibility and testability.

Figure 28. Cost Schedule and Quality Benefits of Concurrent Engineering [126]

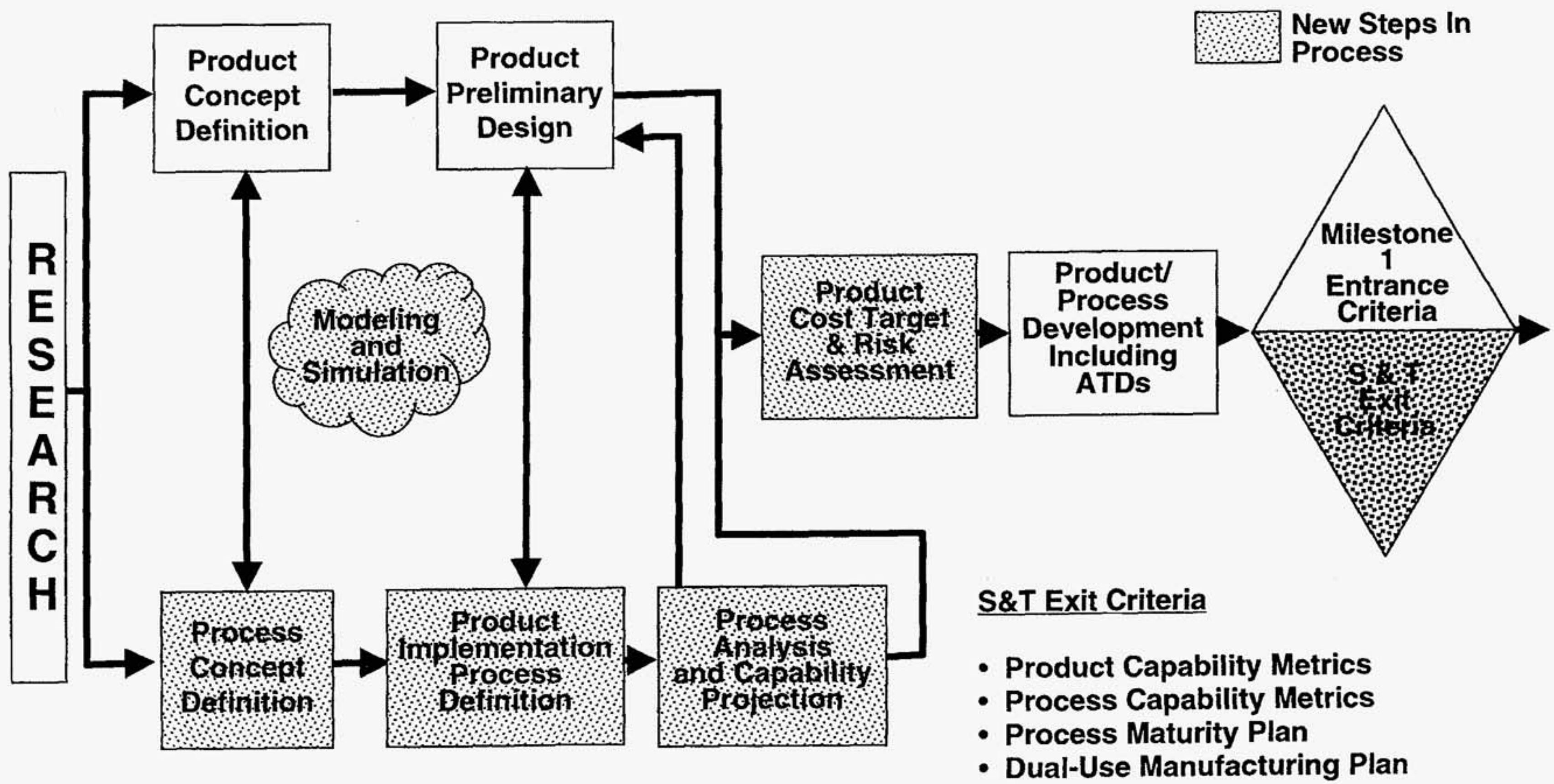


Figure 29. Recommended Approach – IPPD in the S&T Phase [127]

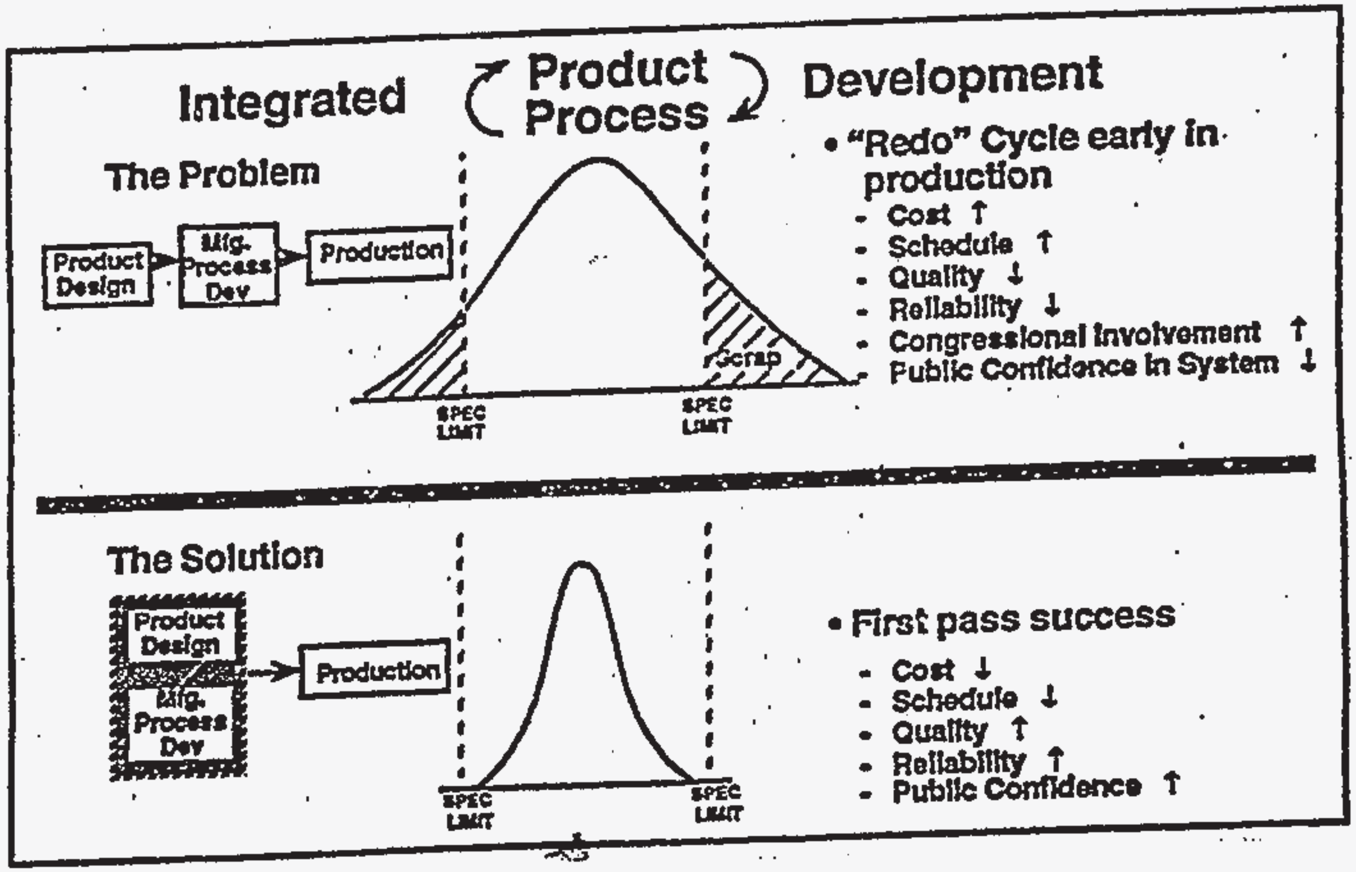


Figure 30. Integrated Product and Process Development [127]

XI. THE MIMIC PROGRAM

A. Outline of the MIMIC Program

The overall program structure of MIMIC featured four phases shown in Figure 31. A 1-year definition or study phase, a materials and technology development phase of 36 months followed by a second phase of 36 months that featured a higher level of integration than Phase 1, and capitalized on the lessons learned from Phase 1. Phase 3 was conducted in parallel with Phases 1 and 2, and provided supporting research in automated testing, device and circuit modeling to improve the computer-aided design process and materials research. The centralized management of the VHSIC program is shown in Figures 32 and 33. The MIMIC program drew heavily on the lessons learned from the VHSIC program, but had a similar centralized management structure shown in Figure 34.

Forty-eight contractors in 16 teams participated in the Phase 0, which was a study phase only to identify the specific problems to be overcome, and recommended approaches to overcome these problems. To achieve this required that existing design and fabrication processes and materials be characterized as the basis for recommending improvements. Part of the Phase 0 study was to identify supporting research tasks for Phase 3 conducted in parallel with Phases 1 and 2. To provide the framework for the study phase, generic systems were identified in the Phase 0 BAA in the following categories by service: Radar, Electronic Warfare, communications, and Smart Weapons. The Phase 0 efforts were completed in February 1988.

Four contractor teams were selected to participate in Phase 1 that was initiated in March 1988, with the objective of exercising and building upon the current state-of-the-art in MIMIC technology (Figs. 35 through 38). Each team member provided expertise in one or more areas of MIMIC product development: material growth, wafer processing, testing, device and circuit modeling, computer-aided designs, and manufacturing, packaging and systems integration. A key to reducing the cost of MIMIC chips was to minimize the cut-and-try processes in designing, fabricating, and testing MIMIC chips by putting computer-aided design on a more scientific basis, beginning with the initial design and the development of software tools that provided realistic models on performance. The projected products for this phase were not only approximately 80 MIMIC chips for the variety of application identified in the Phase 0, but 23 types of functional modules using these chips, and 16 brassboards demonstrating systems using these modules. The Phase 2 represented an effort analogous to Phase 1, but with a strong emphasis on advancing the state-of-the-art and increasing the complexity of the functions that could be fabricated on a single chip. Special emphasis was placed on the development and characterization of hetrojunction devices that are formed between semiconductor materials of different compositions and bandgaps such as GaAs/AlGaAs and InGaAs/ImP, in contrast to MESFETS that have junctions formed from similar materials. The most notable examples of such hetrojunction devices are the HEMT and the HBT. The GaAs HEMT represented an advancement in the state-of-the-art of the GaAs MESFET that provided low noise, high gain, and high power over the entire millimeter wave band. The advantages offered by the HBT for millimeter and microwave applications are as power amplifier oscillators and mixers. Both of these devices were compatible with the MIMIC processing technology and were particularly important for smart weapons applications of MIMIC that required the higher millimeter wave frequencies.

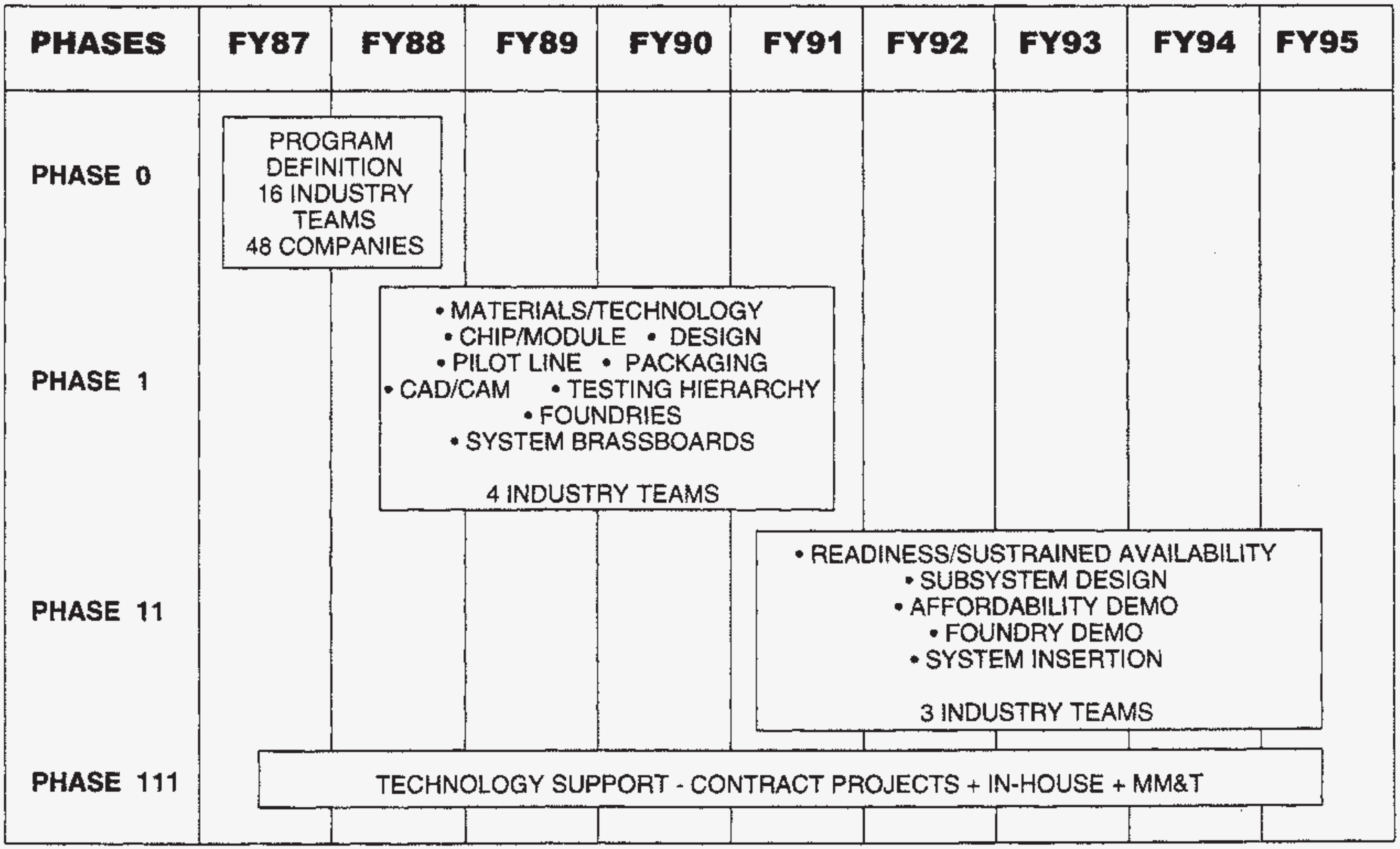


Figure 31. Roadmap of the MIMIC Program [135]

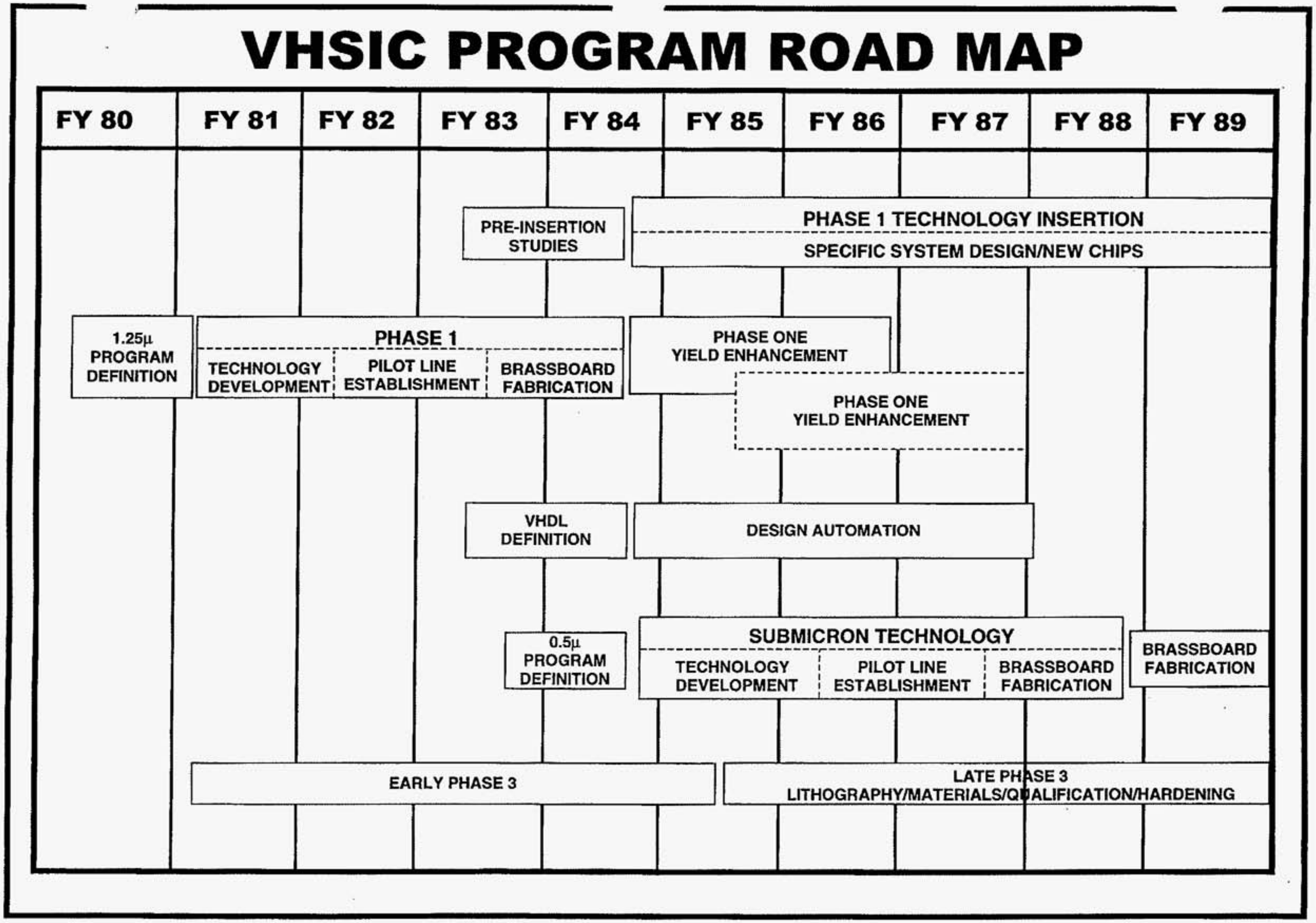


Figure 32. VHSIC Program Road Map [120]

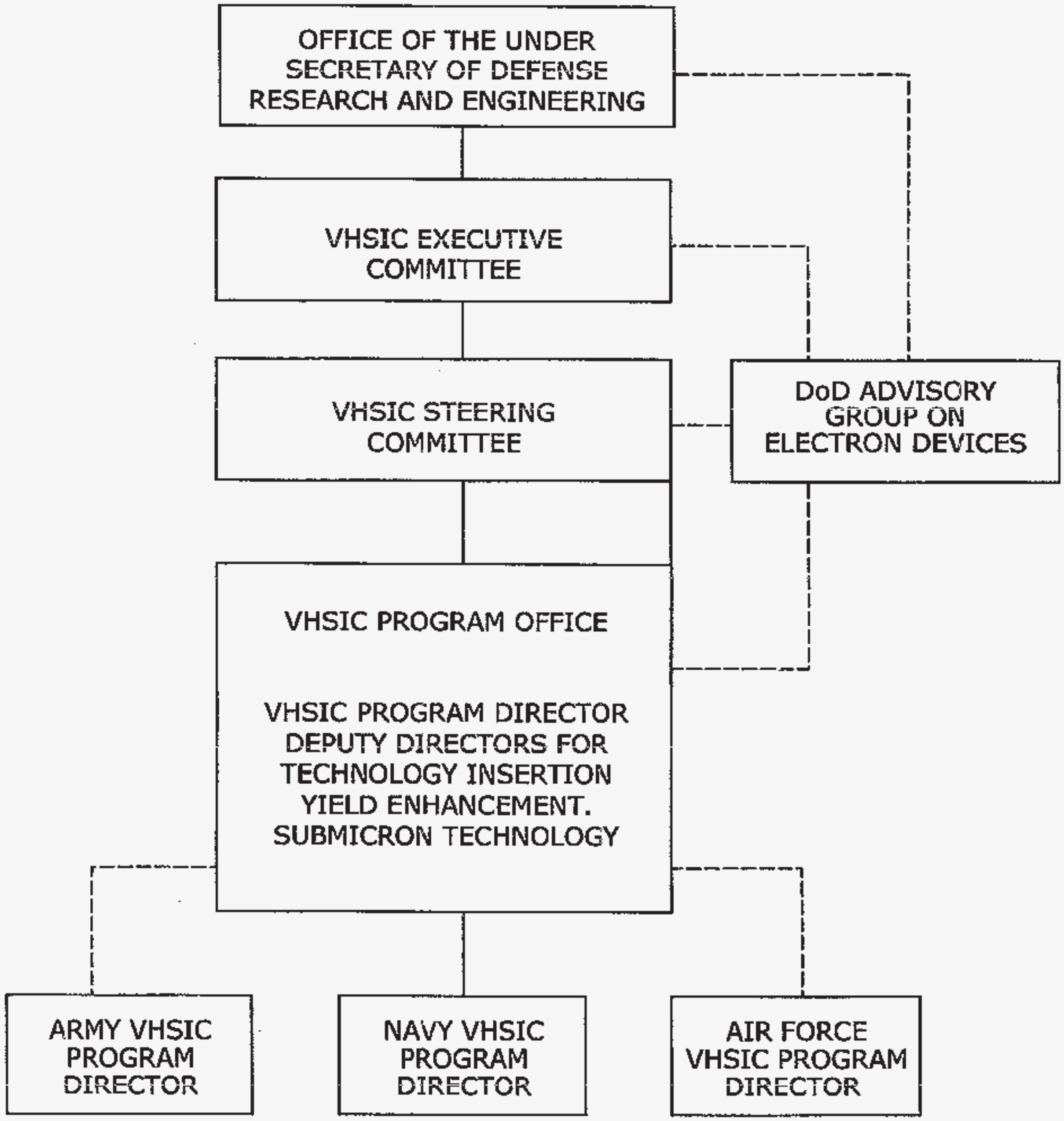


Figure 33. DoD VHSIC Program Office Structure [120]

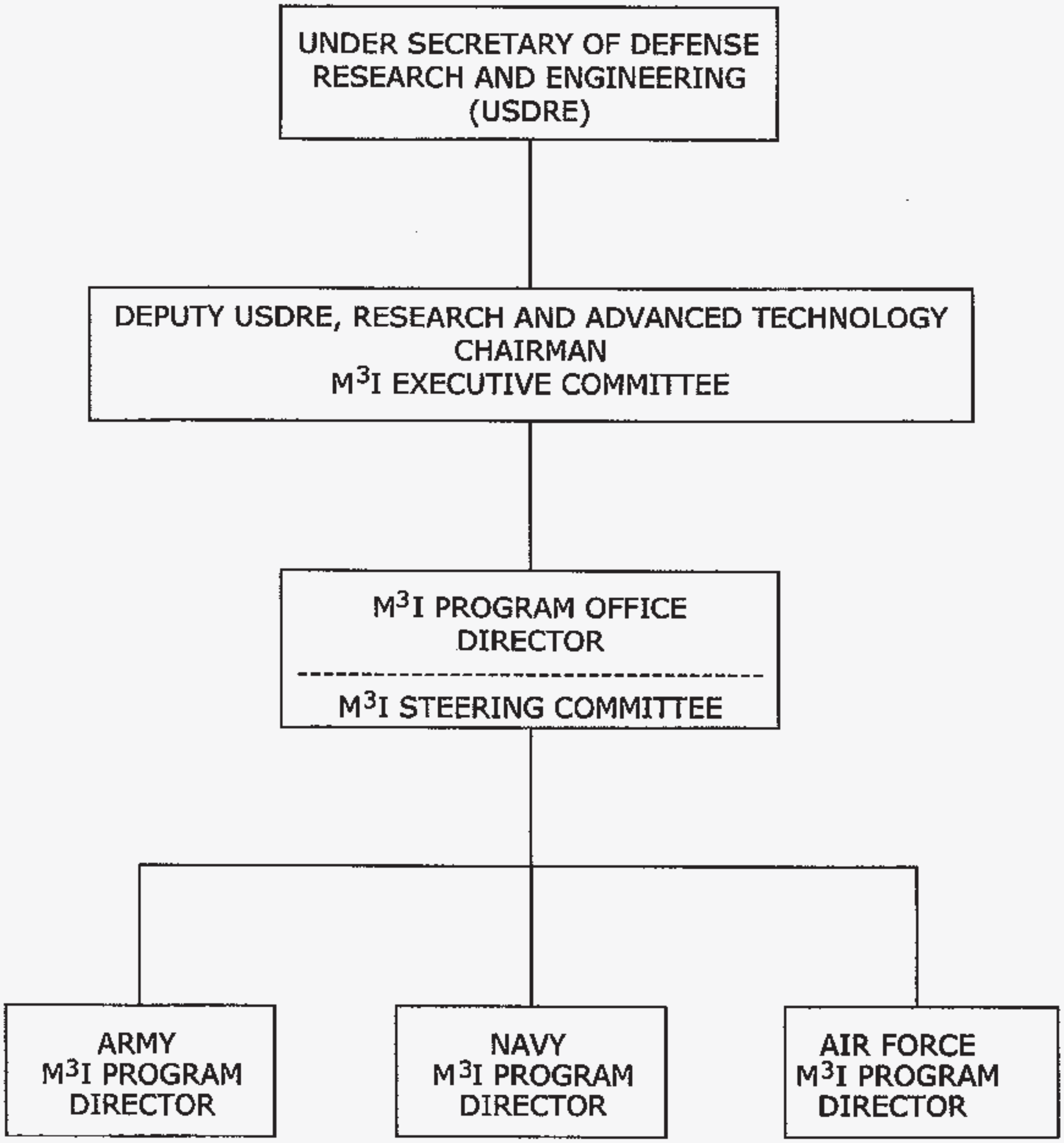


Figure 34. DoD M^3I Program Office Structure [107]

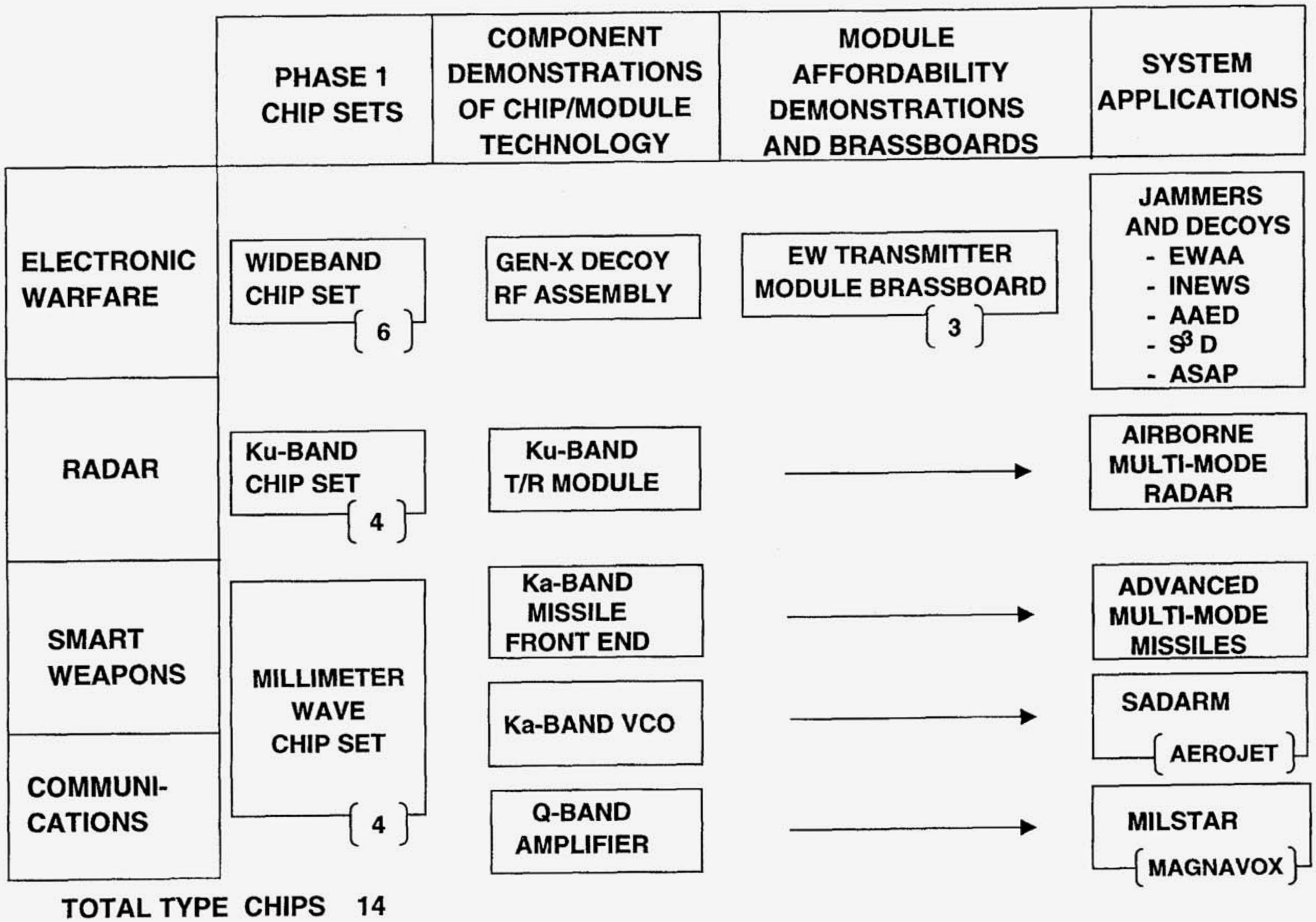


Figure 35. Raytheon/TI Team's Hardware Demonstration [130]

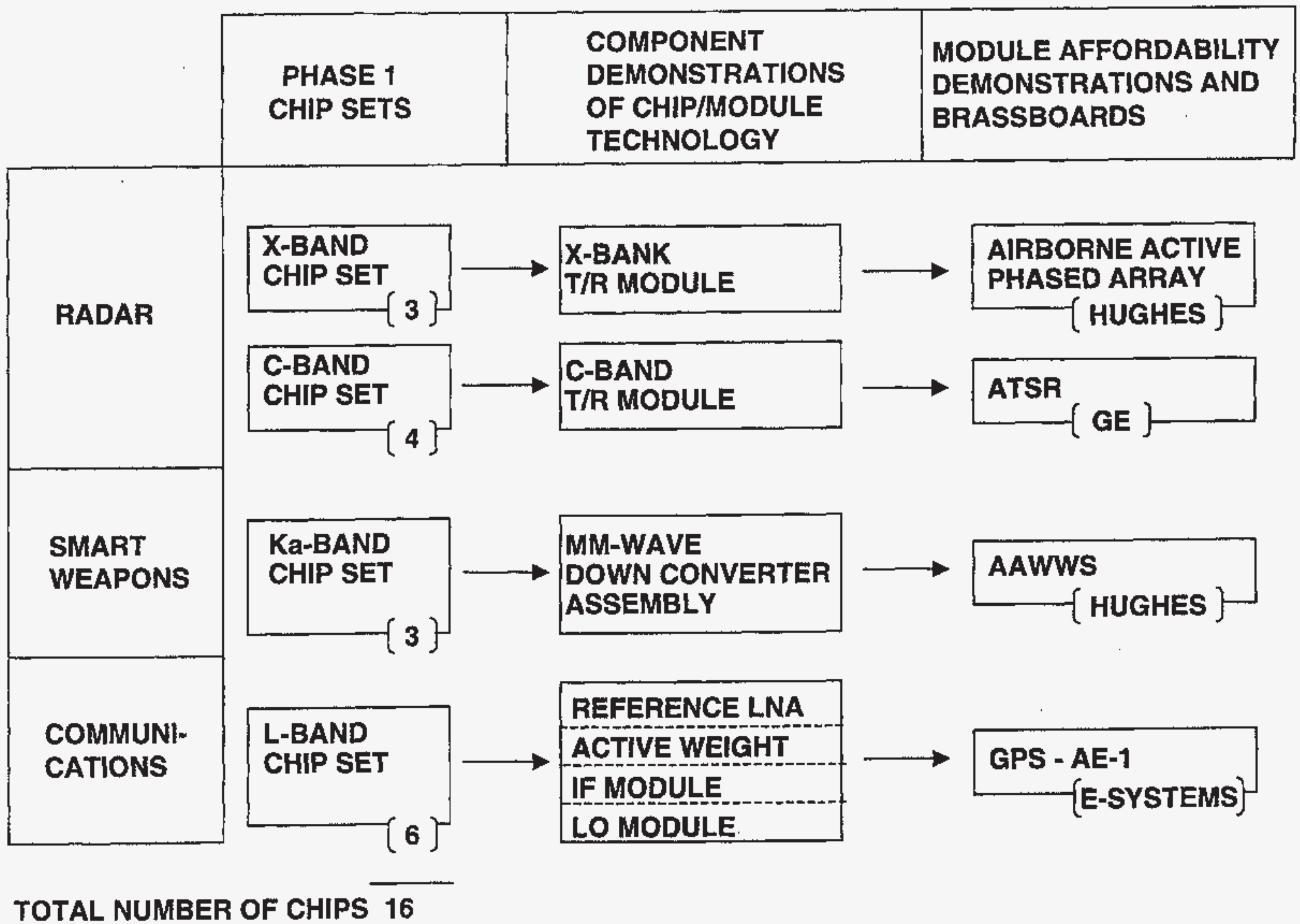


Figure 36. Hughes Team's Hardware Demonstration [130]

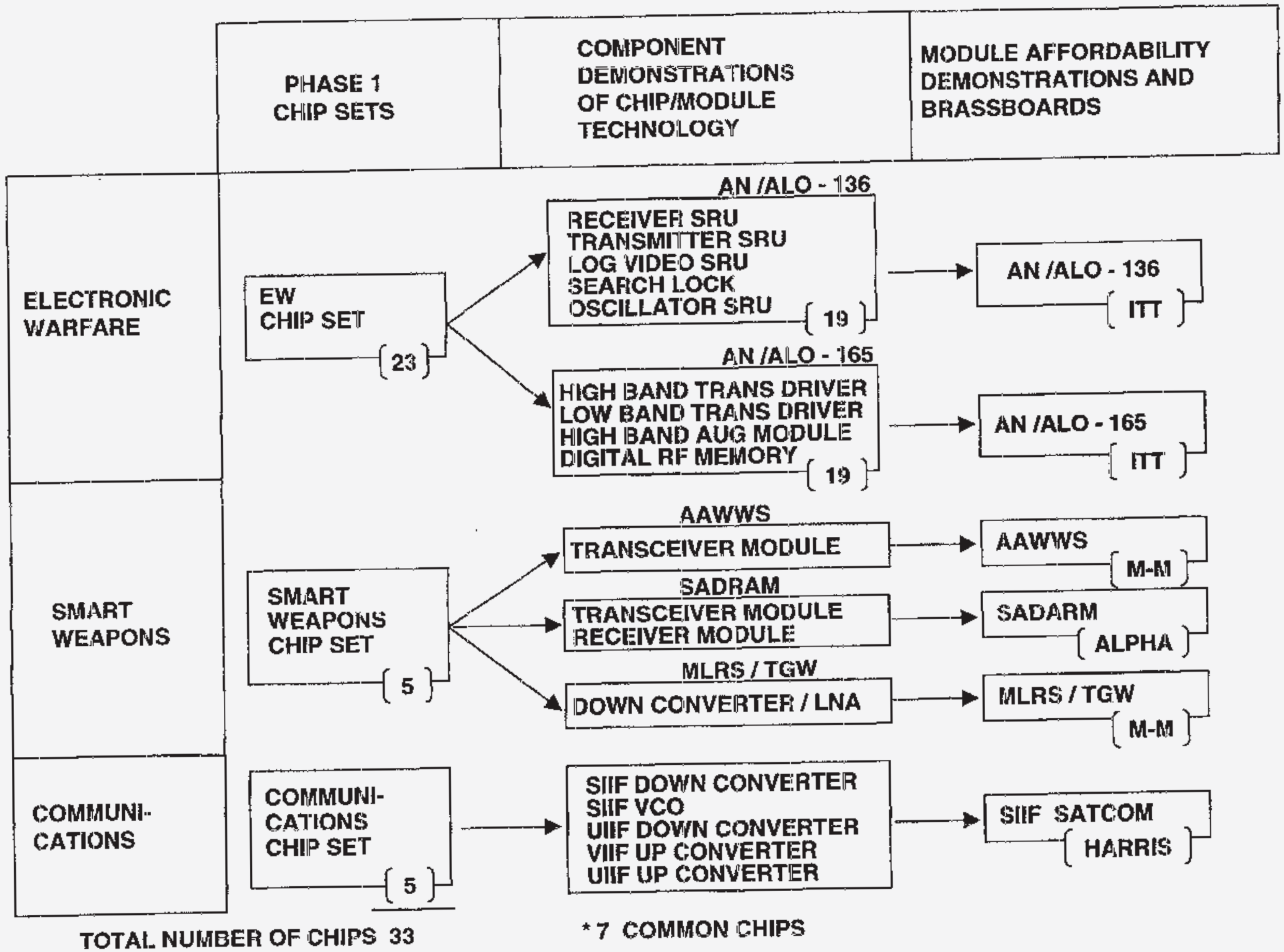


Figure 37. ITT Martin Marietta Team's Hardware Demonstration [130]