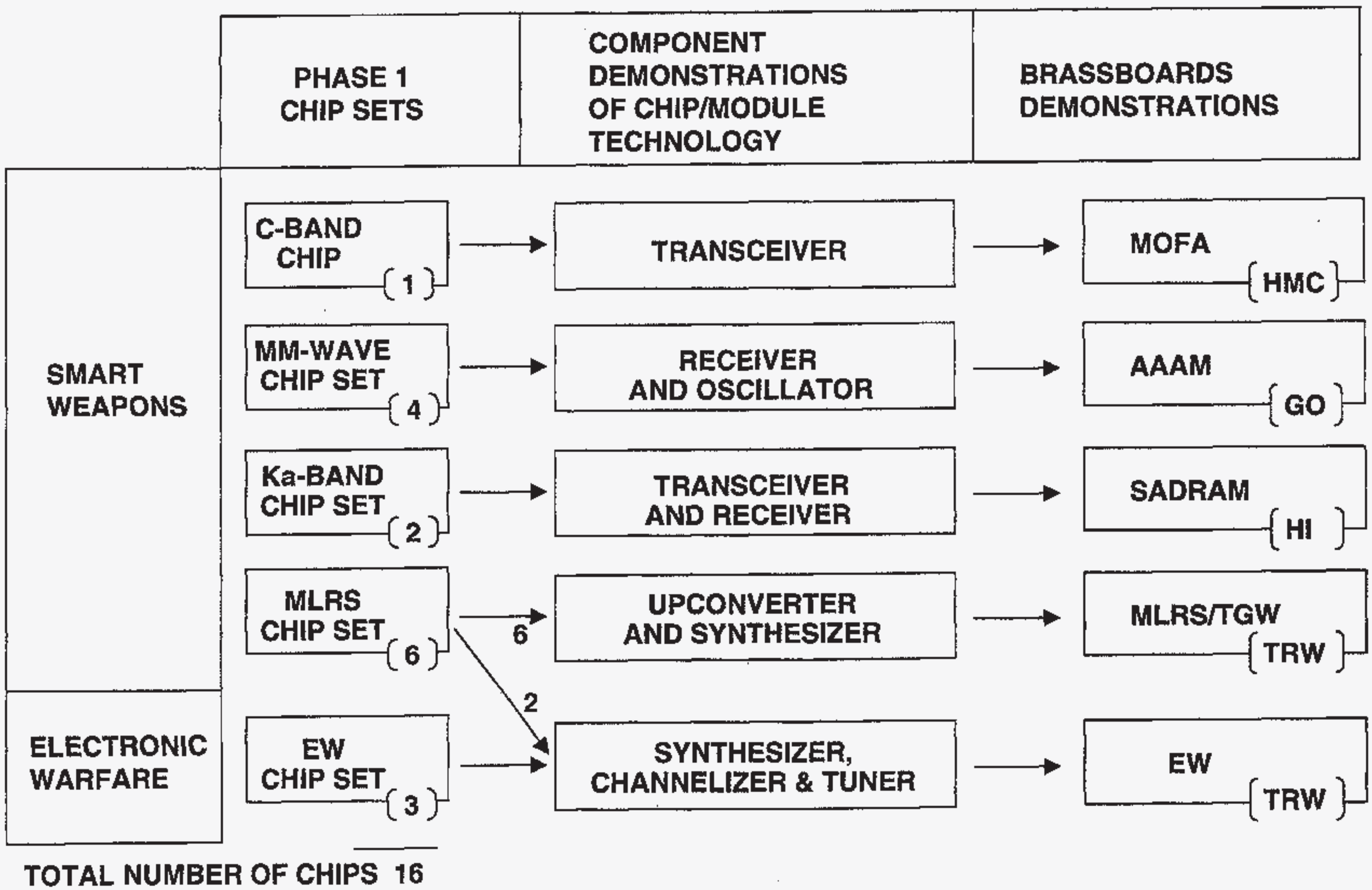

Figure 38. TRW Team's Hardware Demonstration [130]

Phase 3 was conducted in parallel with Phases 1 and 2 and provided the supporting research in device and circuit modeling to improve the computer-aided design process, novel circuit concepts, materials processing, fabrication processes, integration and packaging and metrology and testing. The early involvement of the NBS ensured that the latter category would receive strong efforts by both Government and industry. More than a third of the Phase 3 efforts were on automated testing that included: Optical diagnostics for characterizing wafer quality (AT&T); techniques for on-wafer testing of MIMIC chips (Ball Aerospace); and wafer testing (M/A-COM). Complementing the task funded by Phase 3 (DARPA) were tasks funded by the NBS and the NBS-Industrial Consortium. The success of the MIMIC program can be attributed in a large measure to the participation of NBS in the early phases of program formulation.

Both Mr. E. D. Maynard, Jr., and Mr. Eliot Cohen and the services provided extensive reporting in the open literature on the objectives, plans, progress, and benefits over the life of the program. [130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144] Mr. E. D. Maynard provided the reason for MIMIC, program structure, program objectives, and expected payoff at the 1986 IEEE Microwave and Millimeter Wave Monolithic Circuits Symposium. [131] Mr. Maynard observed that DoD applications for MIMIC were dominant, and expected to remain dominant.

At the end of Phase 0, Cohen announced that the first development phase of MIMIC was scheduled to start April 1988, with the objective of meeting first close-in system needs, and then providing an adequate longer term MIMIC component capability for the 1990s and the early 21st century. [120] Cohen also underscored the role of the Government in-house laboratories in carrying out supporting research, test, and evaluation, as well as program planning, proposal evaluation, and contract monitoring.

On 20 May 1988, 4 contractor teams consisting of 26 companies were awarded 225 million in contracts with admonition by Cohen that there was a constant necessity to share information. By December 1989, of the planned 79 Phase I chip types, 12 had been fabricated and demonstrated within the first 6 months of the program. [130] Mr. Cohen outlined four key tasks the contractors had to achieve in order to meet program objectives: (1) robust processing capabilities, (2) highly automated wafer testing, (3) comprehensive computer-aided design, and (4) modem production discipline. [130] Even before Phase I was completed, MIMIC was already finding application in DoD systems. At the completion of Phase 1, Cohen summarized the progress in smart weapons, electronic warfare, radar and communications. During this phase, both Raytheon and Texas instruments were producing .5 to 4 GHz IF amplifiers for the Navy/Air force HARM missile. MIMIC technology was under development at the end of Phase I for AMRAM, LONGBOW and MLRS-TGW. For electronic warfare applications, wideband MIMIC power amplifiers had been developed with efficiencies about twice those achieved previously, and packages made from metal matrix composites with the promise of lowering packaging costs to as little as $5.10 for a Phase I demonstration in the Generic Decoy (GEN-X). GEN-X was already in use in Desert Shield. The ITT/Martin MIMIC Phase I Team developed improved hardware for the Army AN/ALQ-13 6 helicopter jammer and the Navy's AN/ALGORITHMS-163 tactical fighter jammer. Over 23 chip types had been developed for 12 modules to upgrade these systems. The primary MIMIC chip type to be used in the Counter Battery Radar was being produced by General Electric (GE), Hughes Aircraft Co., Harris Microwave, AT&T, and

MA-COM. The Hughes/GE Team was also developing chips, modules and a brassboard demonstration for airborne phased array radars. For Global Positioning Systems, Hughes Aircraft Company, with team members E-Systems, were developing the next generation antenna electronics that was projected to reduce parts cost by 50 percent, package size by 79 percent, and weight by 65 percent.

Although the principal responsibility for executing the program was with the contractor teams, Mr. Cohen highlighted the role of the DoD in-house laboratories in working with the contractor teams. [137] At the 1998 IEEE Microwave and Millimeter Wave Monolithic Circuits Symposium, Mr. Cohen also summarized the contractor findings and recommendations in materials, chip design approaches, CAD/CAT/CAM, Packaging, and Test. [134]

At the close of the program, Cohen focused on the challenges of developing MIMIC chips and multi-chip module assemblies for application in electronically scanned arrays. Cohen identified eight key factors compacting recurring costs. At the module and multi-chip assembly, Cohen found that the key to reducing costs for both the recurring and non-recurring costs was improved computer-aided design capability combined with low-cost assembly and test methods. The need for more research in packaging materials was highlighted, and a number of candidate materials were discussed. After concluding that the T/R module made up approximately 50 percent of the overall active electronically scanned array cost, sub-array manufacturing cost, and array integration about 10 percent, Cohen concluded that potentially the greatest opportunity for savings was improved computer-aided design capabilities that would sharply reduce the MCA design cycle time and improve "first pass" design success.

In 1995, Eliot Cohen summarized the accomplishments in the final year: (1) a solid infrastructure for microwave and millimeter wave monolithic integrated circuits had been accomplished, (2) two substrate vendors were profitable and selling material world-wide, (3) two computer-aided design vendors were profitable and dominated the world market for CAD, (4) more than six MIMIC program participants were providing foundry services world wide. In the area of materials, gallium arsenide boule size had missed from 3 to 4 inches and wafer characteristic and uniformity had greatly improved. During Phase 2 of the program, the maturing of new manufacturing processes had allowed the development of devices that reduced feature size from .5 to .1 micron for the MESFET, as well as the HEMT and HBT. The improvements in commercially available test stations for both on-wafer testing and module testing allowed significant reduction in a major cost in the MIMIC process.

B. Productivity of the MIMIC Program

The unique cultural setting in which the MIMIC program was planned and executed had a catalytic effect that made the program itself a mechanism for effecting cultural change. The productivity of the program as a result of these changes can be traced to: (1) the unique program architecture, (2) the elevation of process development in importance in the product development life cycle, (3) the execution of a top level strategic planning process that drew on good ideas from all sectors of the economy, and (4) the recognition that the health of the American semiconductor industry was an essential factor in meeting future defense needs. The influence of these factors can be traced in the large volume of intellectual products including journal articles, books and patents that can only be briefly mentioned here.

The productivity of the MIMIC program is reflected in several seminal volumes published by IEEE: Modulation Doped Field Effect Transistors: Principles Design and Technology, Edited by Heinrich Daembke, was conceived as an extension or supplement to the IEEE Press book Low Noise Microwave Transistors and Amplifiers, Edited by H. Fukui. A second volume, Modulation - Doped Field Effect Transistors:

Applications and Circuits provide a survey of the application of MODFETS in analogy and digital circuits with approximately 100 papers organized into three parts: MODFETS in analog systems, MODFETS in digital circuits, and Optoelectronic applications. The new device has been given several names by different research institutions that were contributors to its development. High Electron Mobility Transistor (HEMT); Two-Dimension Electron-Gas Field Effect Transistor (TEGFET); Selectively Doped Hetro-FET (SDHT); and Hetro-Field-Effect Transistor (HFET). A third IEEE Volume: Modulation - Doped Field Effect Transistors: Principles, Design and Technology also contains approximately 100 papers organized in 15 sections in the following four parts: Introduction, GaAs MODFETS, Numerical Simulation of MODFETS; and Impact of New Materials and Structures. In addition, a large number of books in the Artech House Library contain MIMIC as a topic.

Patents also provide another measurement of the productivity of the MIMIC program. Although a direct correlation between the growth in MIMIC related patents (Fig. 39), and growth in MESFET patents (Fig. 40) and HEMTS (Fig. 41) and the DoD MIMIC program cannot be established, it is clear that the program provided a stimulus for this growth. The data for Figures 39 and 40 was produced from searching the CLAIMS/US Patents database. CLAIMS/U.S. Patents database provides access to over 2.9 million U.S. issued patentns by the U.S. Patent and Trademark office since 1950. The CLAIMS patent databases covers all areas of technology patentable in the U.S.. All the terms below were searched in the basic index fields. The basic index fields searches title, abstract, exemplary claims, text of claims or other claims. The MIMIC-related patents includes the term MIMIC (Microwave and millimeter Monolithic Integrated Circuits) with supporting search terms "gallium arsenide," "monolithic microwave integrated circuits," "millimeter wave integrated circuits," "Schottky-barrier-diode," or "Gunn-diode." The MESFET-related patents include those in which the terms MESFET (Metal-Semiconductor Field Effect Transistor) with supporting search terms of "gallium arsenide" "schottky-barrier." The MESFET can be fabricated in monolithic form with other passive circuits elements, or in discrete form as a single device, so the chart would include both. The HEMT related patents includes those for which the term HEMT (High Electron Mobility Transistor) or analogous terms: Two-Dimensional Gas Field Effect Transistor (TEGFET), Modulation Doped Field Effect Transistor (MODFET), Selectively-Doped Hetro-FET, SDHT, Heterostructure Field Effect Transistor, High Multilayer Heterojunction Transistor, HIGFET, or Hetro-Field Effect Transistor (HFET) with supporting search terms "GaAs" "GaAs/ARGaAs" "pseudomorphic Heterostructure Electron Mobility," "H-FET" or "PHEMT." In GaAs/AlGaAs "molecular beam epitaxyll," "metal organic-chemical vapor deposition." The HEMT or MODFET represents an extension of the capabilities of the MESFET as a result of its superior electron transport properties.

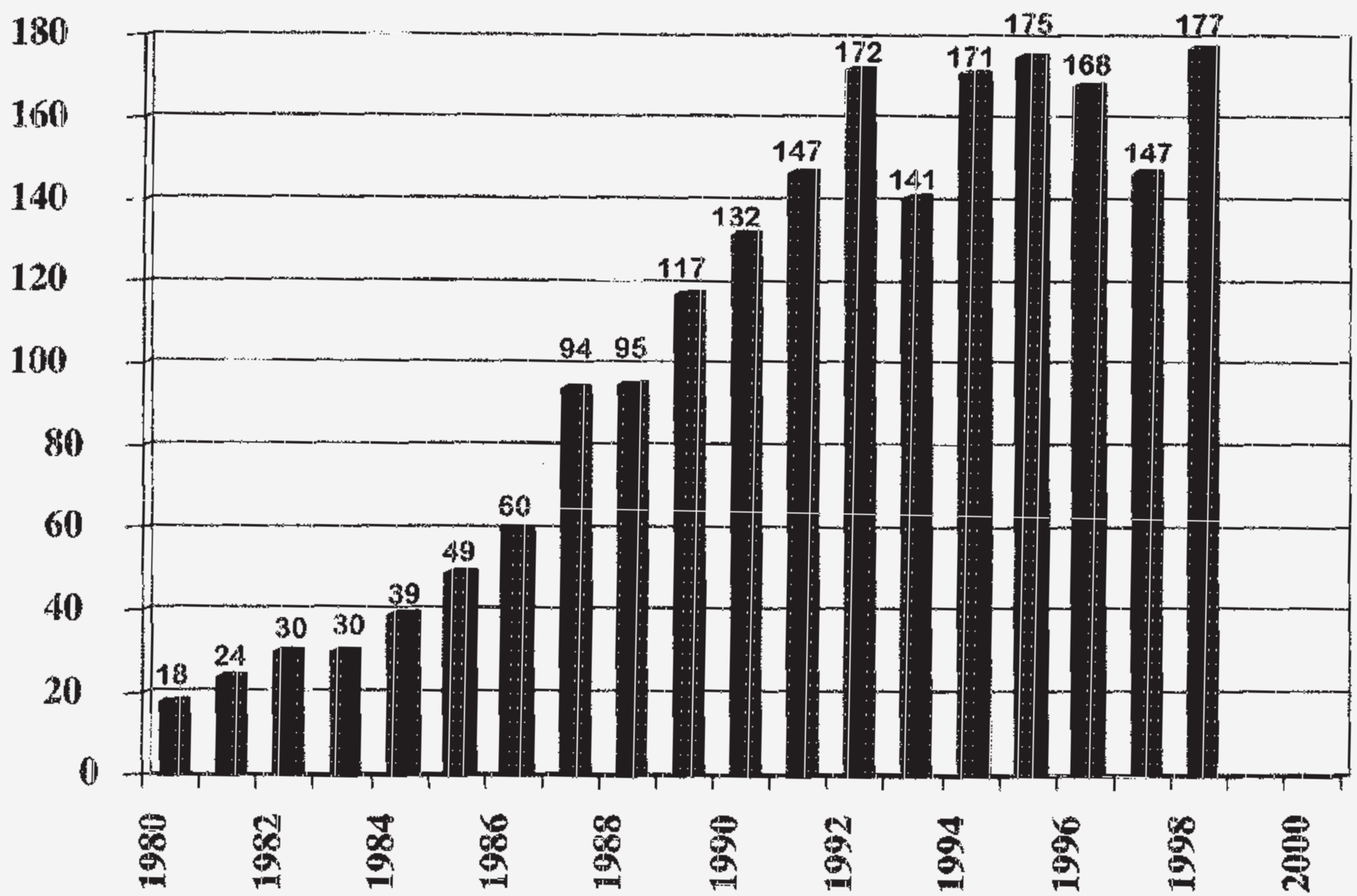

Figure 39. MIMIC Related Patents

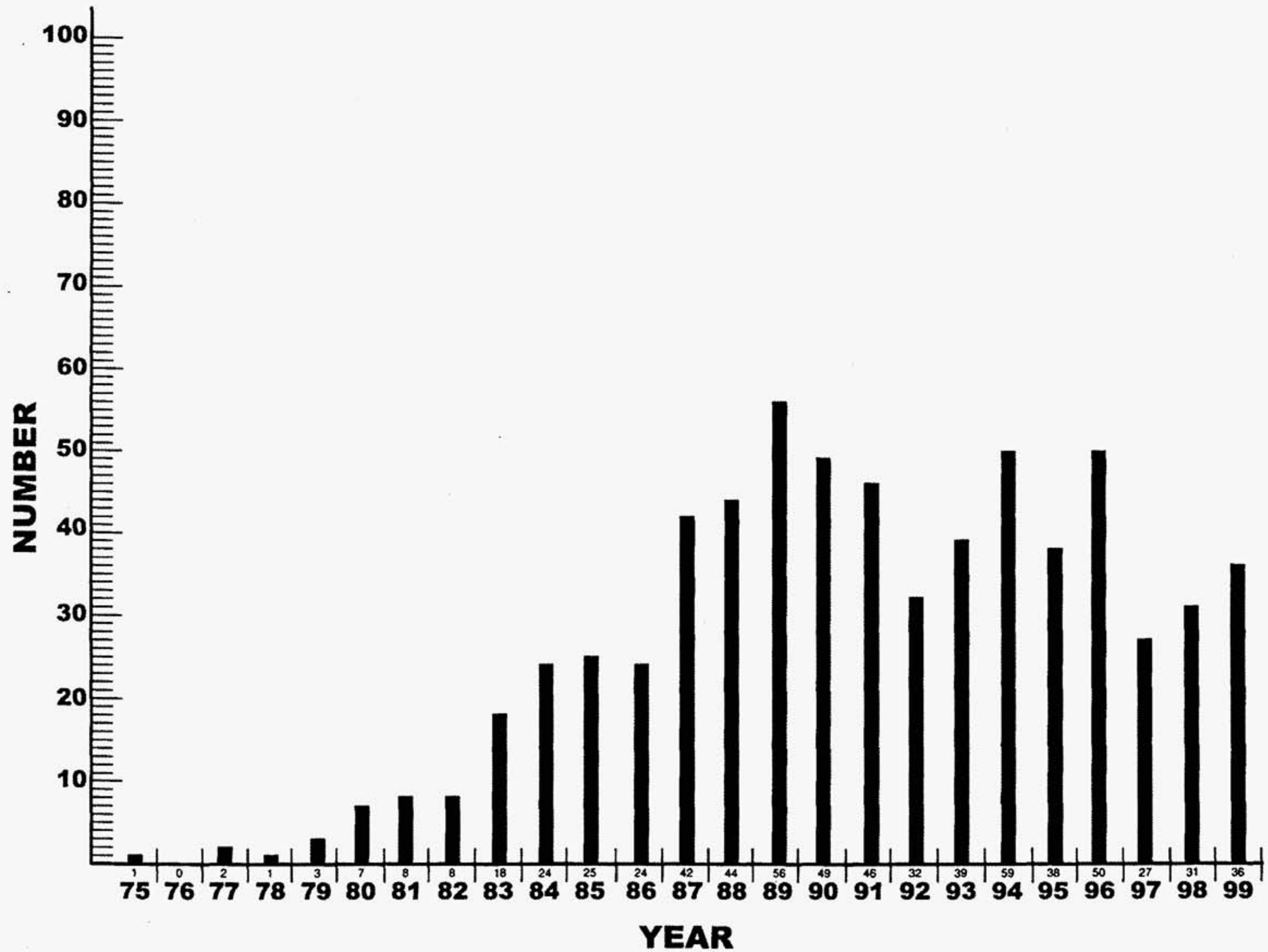

Figure 40. Patent Growth in MESFETS

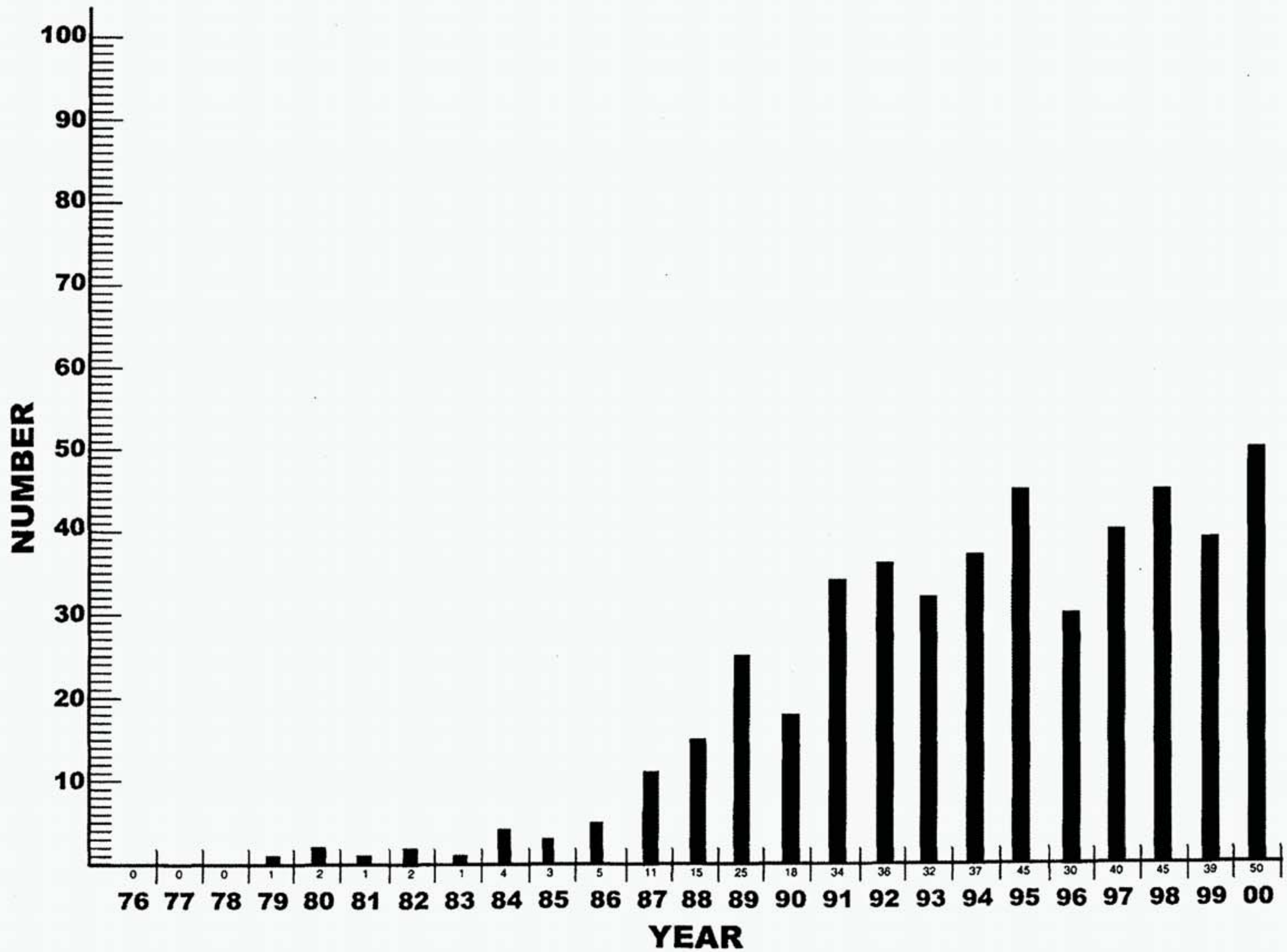

Figure 41. Patent Growth in HEMTS

XII. SCIENCE POLICY

A. Limitations of The Vannevar Bush Science Policy

The MIMIC program was formulated during this period when the loss of U.S. leadership in global markets brought about searching reexaminations of the limitations of Post-World War II science policy framed by Vannevar Bush. Bush saw basic research as the principal fountainhead of all progress that is "performed without thought of practical ends" and adds to the pool of general knowledge that "provides the means of answering a large number of practical problems." Although Bush saw an inherent tension between basic and applied research, progress was achieved by linear progression from the pool of general knowledge through applied research, product development, and manufacturing:

> "New manufacturing industries can be started and many older Industries greatly strengthened and expanded if we continue To study natures laws and apply new knowledge to practical Purposes." [2]

In the defense sector, the linear model provided the basis for the way the Defense Department categorized the different phases of the weapon acquisition process. This so-called "linear model" viewed basic research as the principal source of innovation, but in reality, it applies to a restricted set of conditions where the progression is from research breakthroughs to markets for radical discoveries rather than incremental advances. However, the U.S. was defeated in an area where technological innovation is market-driven in incremental steps.

The Council on Competitiveness identified a key U.S. weakness derived from the flawed science policy:

> "Much of the U.S. failure to exploit technology for commercial advantage for commercial lies in not adequately appreciating the importance of manufacturing and not properly balancing short-term and long-term goals. The neglect of manufacturing arose largely out of complacency of the 1950s and 1960s when the U.S. dominated international markets. Top managers began to focus on marketing and finance at the expense of manufacturing, and as a result, failed to manage the investments in worker skills, plant and equipment necessary for strong manufacturing capability. Today (1988) foreign companies are often beating U.S. companies not with low wages, but with more efficient manufacturing processes. For example, Japanese manufactures spend two-thirds of their R&D budgets on process innovations, while manufacturers spend only one-third." [145, 3]

The findings of the Council on Competitiveness was consistent with the results of other studies. A key to improving competitiveness was to compress the product development cycle. Bernard Slade explored this question with 21 professors and 200 senior executives. [146] Most of the academics attributed the decline in U.S. competitiveness to weakness in manufacturing, and as Figure 42 shows, 40.6 percent of the senior executives identified integrated design teams as the factor needed for shortening the product development cycle. Investing in total quality was at the top of the list for meeting future challenges (Fig. 43). Slade learned from a professional colleague the difference in the manner in which the design manufacturing linkage was managed in Japan and the U.S. The Japanese were puzzled by the question from their American guest on how they handled "design for manufacturability." The question could only come from a culture that practiced "over the wall" coupling of design and manufacturing. Design and manufacturing were so well integrated in Japan that the term "design for manufacturability" had no meaning. Robust design achieves a balance between cost, reliability, and performance; a central goal of the MIMIC program.

B. Congress Examines the Limitations of the National Science Policy

In the charge to the House Committee on Science, the Speaker of the U.S. House of Representatives acknowledged on 12 February 1997, that the science policy framed by Dr. Vannevar Bush in 1945 was no longer valid, and the speaker requested "a new, sensible coherent, long-range science and technology policy." As a result, the committee held seven hearings, two roundtables, and encouraged interaction between the scientific and policy communities. A website was also set up to allow public participation. [147]

The flaws in the Bush policy have been examined by a number of scholars and may be summarized briefly as follows: the distinction between basic and applied research is no longer valid; the social sciences were not included in the Bush policy; Bush saw basic research as the principal source of innovation that generated a one-way flow of events and ideas in time that resulted in products and services to meet the needs of society, without considering the feedback effects on basic research. These points were brought out very well in the testimony, but some observers believe there is a general lack of awareness of how deeply the Bush model influences daily behavior in universities, industry, and Government.

The implication of the ideal that basic research is the principal source of innovation is that basic research is more intellectually demanding than what follows and, therefore, society should apportion rewards accordingly. The consequence of this was felt in the 1980s when it was revealed that a principal weakness in U.S. competitiveness in global markets was in manufacturing, and a lack of insight into the total product realization process. The response was a series of actions by the Congress, the Executive and the private sector in the 1980s to encourage technology development, promote partnerships, improved educational institutions, and increase productivity in the R&D process. In a 1988 report to the Secretary of Defense, the Under Secretary of Defense for Acquisition identified the weakness in Weapons development:

> "In large measure the inability of American managers to achieve results in manufacturing equal to those of Japanese mangers in the U.S. stems from management theory and practice, as taught in American universities (where for example, good management is management by financial control; good managers can manage anything, individual achievement is important, not teamwork; manufacturing is an unimportant function). Engineering schools in American universities also focus inadequately on manufacturing, training engineers for careers in product research and development. Few faculty members have industrial experience or expertise. Emphasis on specialization results in engineering professionals who all ill-equipped to understand total manufacturing systems." [125]

The science policy changes in the 1980s, and those leading to UNLOCKING OUR FUTURE in the 1990s have been characterized as "fine tuning," rather than a reaction to a crisis that leaves some observers wondering if there is a real understanding of the depth of the crisis. [147, 148]

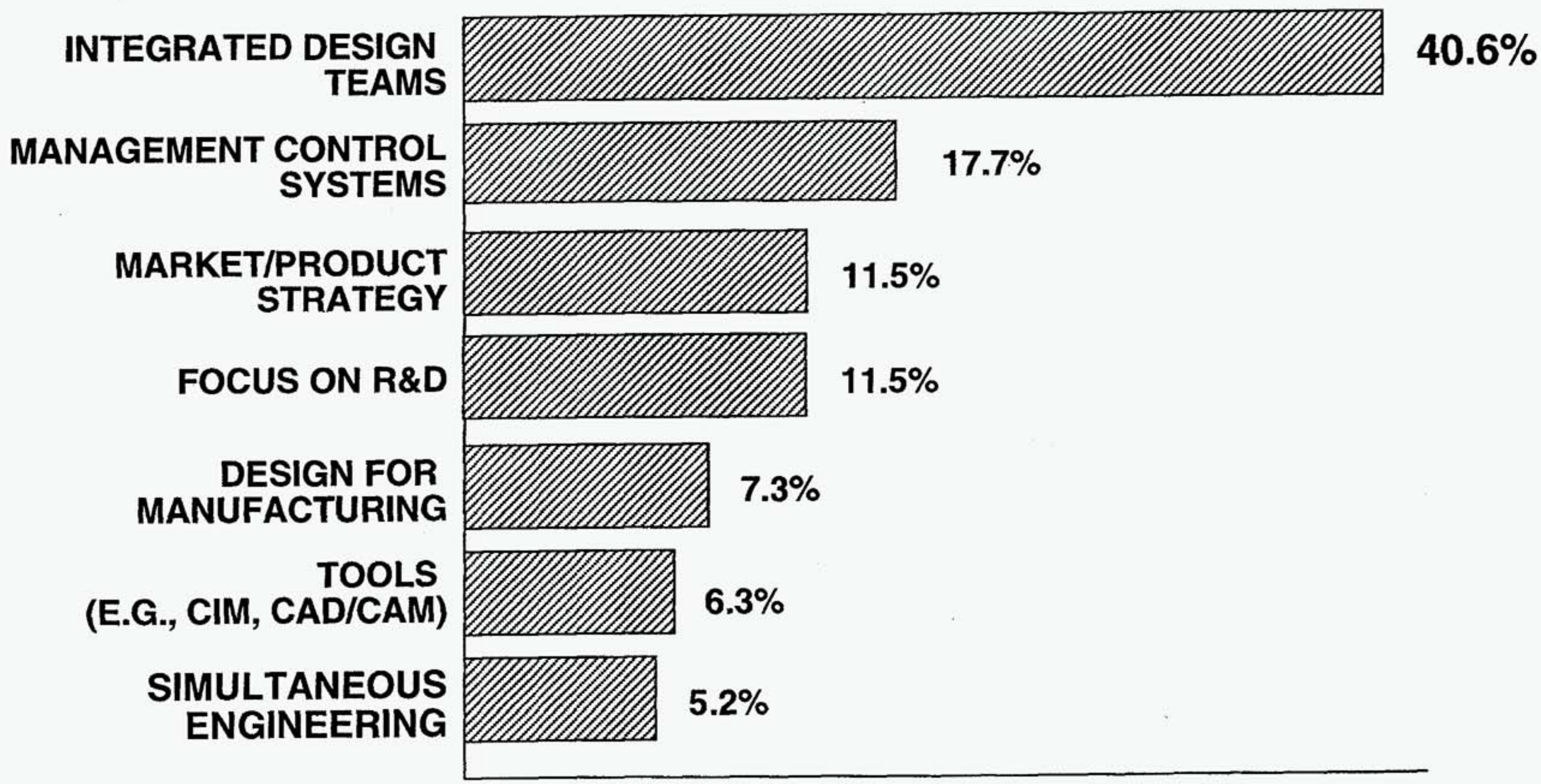

Figure 42. Factors for Shortening the Development Cycle [146]

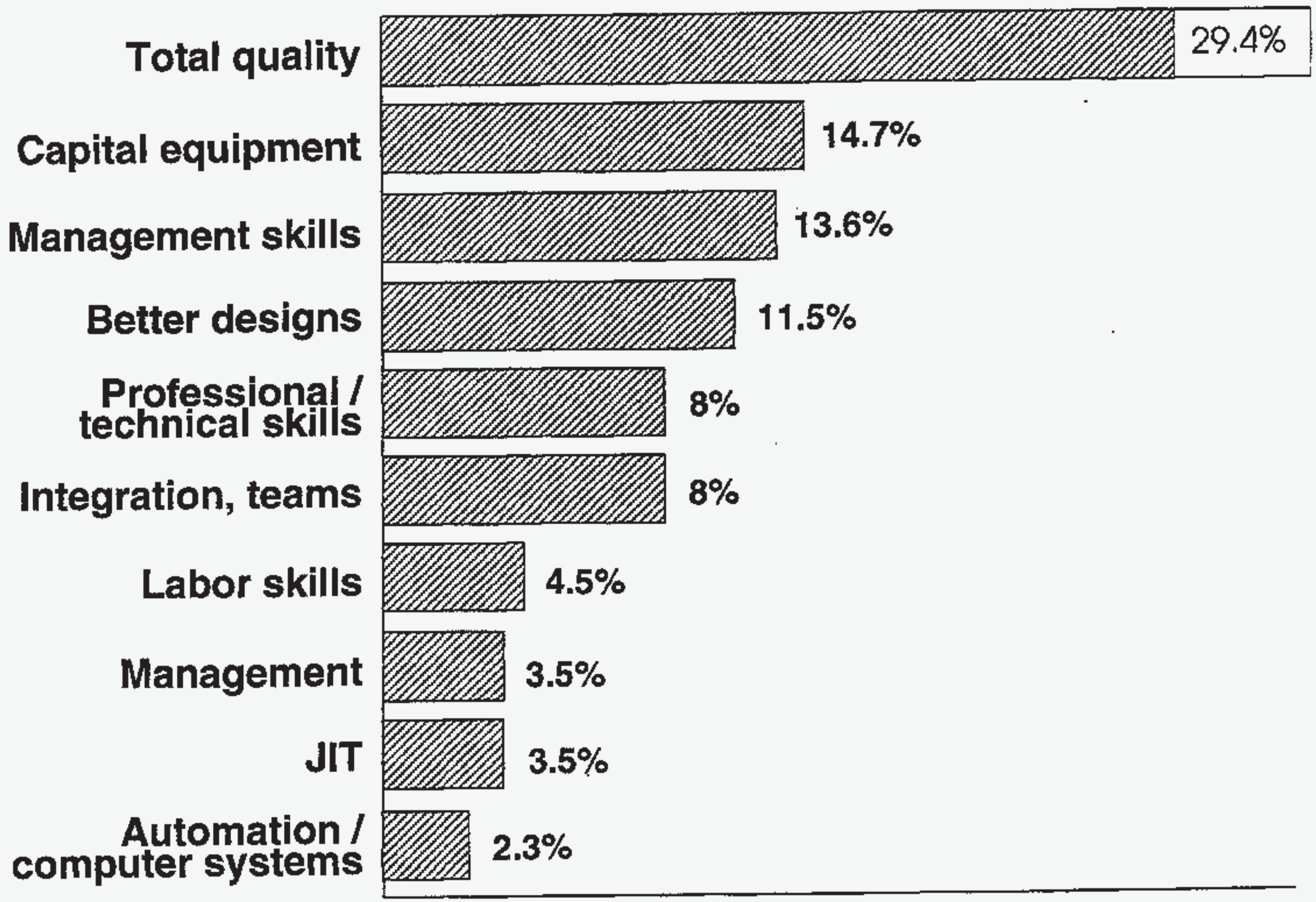

Figure 43. Investing to Meet Future Challenges [146]

C. The Emergence of a New Science Policy

The importance of understanding driven research as a critical factor in maintaining the Nations economic strength is reaffirmed by the House Science Committee, and the fundamental soundness of the Bush policy is validated. According to one study, publicly-funded research provided part or all of the foundation for 73 percent of the patents cited in the study. The public and private rates of return on the basic research investment are impressive. However, what is being discussed is a process that is one way in time; the feedback effect from later stages of the development process on basis research itself are not accounted for, and may be so complex that a determination of these effects is not possible. The principal conclusion of the committee was that the overall process is healthy and the goal of the House Committee's work was to "fine tune" the process to maintain and improve the health which required an inquiry into the workings of the process itself.

The report recognizes that the distinction drawn between "basic" and "applied" research by Dr. Bush are artificial distinctions, although budget line items are sometimes still organized today along these distinctions. It was brought out in testimony that the two motives of understanding and use can coexist in the same person, which can lead to creativity and productivity in the scientific enterprise. One witness testified that "a consistent virtue of U.S. basic research has been the pursuit of fundamental knowledge with a sharp eye for downstream applications." The DoD received the applause of the Committee for its success in funding research in this vein. Dr. Bush understood that the motives of understanding and use could coexist in the same person from the illustrious career of Louis Pasteur, but anyone who has worked in a large R&D organization with a wide spectrum of activities understands the inherent tension between basic and applied research during a budget squeeze that could have led Dr. Bush to observe: "applied research invariably drives out pure." Basic research is an easy target for budget cuts to solve short-term crises since the consequences of the reduction will not be felt in the short term.

D. MIMIC and VHSIC and the Linear Model

It is of interest to examine the formulation of VHISC and MIMIC in terms of two models of scientific research: The Bush linear model, and Pasteurs Quadrant. In the Bush "Linear Model," there is a one-way flow of activities in time from basic research to a useful product (Fig. 44), but the manner in which these activities are coupled together is left undefined. The motivation for basic research according to Bush was to increase "the general knowledge and understanding of nature and its laws," but basic research is conducted without "thought of practical ends," thus implying a conflict between basic and applied research. However, his observation that basic research is "the pacemaker of technological progress" implies some coupling mechanism undefined. How applied research, development, design, and manufacturing are coupled is also undefined as shown in Figures 46 and 47.

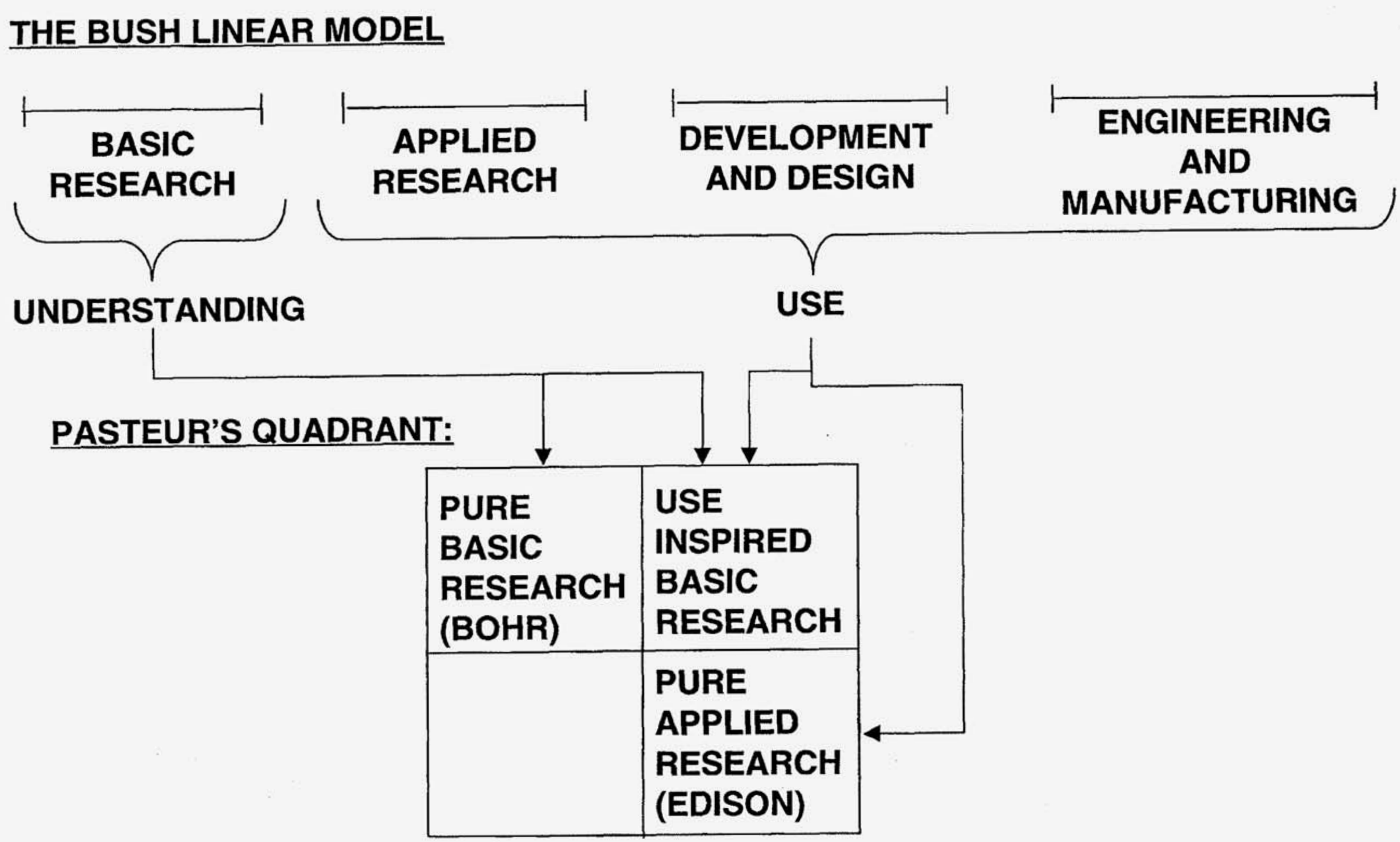

Figure 44. Comparison f the Bush Linear Model and Pasteur's Quandrant [2, 149]

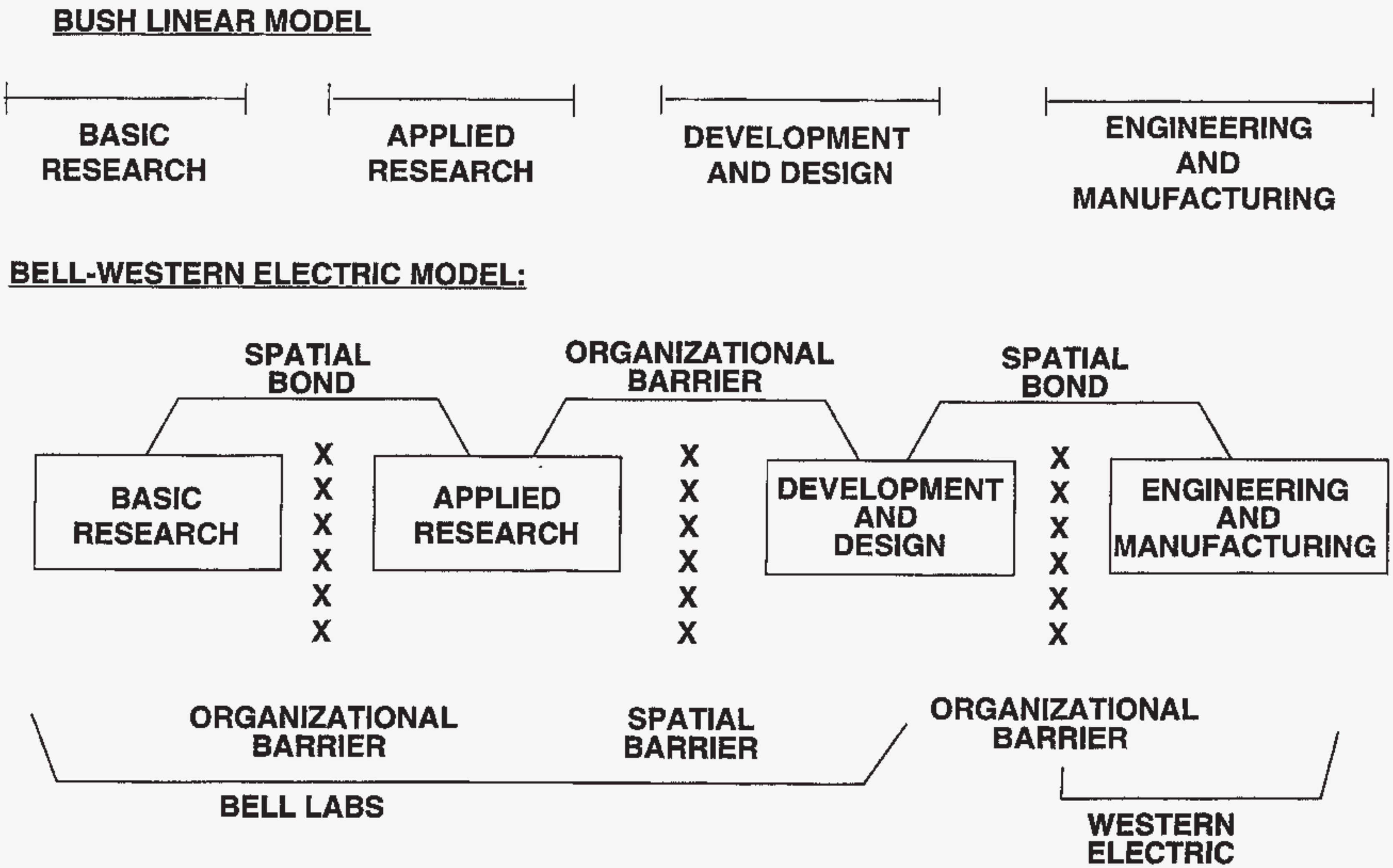

Figure 45. Comparison of the Bush Linear Model and the Bell-Western Electric Model [2, 149]

Although there is a long history of the institutionalized separation of pure and applied research, there is widespread recognition today that the one-dimensional flow of events in the Bush linear model does not correspond to reality. The one weakness of the model is that it does not account for the feedback effect that applied research may have in raising questions for basic research investigations. In fact, the motivation of both basic and applied research may reside in the same person, and this is reflected in the career of Louis Pasteur. To account for this, Stokes has reformulated the model of scientific research in two-dimensional form as shown in Figure 46, to allow the identification of use-inspired basic research in "Pasteur's Quadrant." [149]

An alternative model of the flow of events over the entire product cycle has been provided by Jack Morton, Vice President, Electronics Technology, Bell Telephone Laboratories. [150] This model may be interpreted as an information-processing network with feedback loops and forward information channels modulated by spatial and organizational bonds and barriers, as shown in Figure 45. For example, the organizational barrier between basic and applied research preserves the autonomy of the basic research group, but the spatial bond means that the two groups work in close physical proximity that encourages communications. Both an organizational barrier and spatial barrier separates applied research and development and design, which imply these functional areas are only loosely coupled. The organizational barrier between development and design, and engineering and manufacturing prevents crises in either area from disrupting operations in the other, but the spatial bond means that the Bell Labs development and design group was located in close physical proximity to the Western Electric engineering and manufacturing group.

The MIMIC and VHSIC programs were designed not only to couple the flow of events and feedback loops over the product cycle as illustrated in the Morton paper, but across multiple corporate boundries to produce and deploy multiple products in four application areas: radar, communications, smart weapons, countermeasures and counter-countermeasures. By framing the goals of the program in system terms, a coupling mechanism is established between the materials research, device design modeling, simulation testing, and system architecture that provides the motive force for innovation, that may take place not only at the basis research end of the process, but anywhere downstream as a result of the feedback process. The program formulation thus features the design of spatial and organization bonds and barriers and feedback loops across multiple corporate and government organizational barriers for multiple products in the four application areas cited. Both programs not only had clear application goals, but the goal of increased knowledge and understanding that places it in Pasteur's Quadrant. The structure of the program also provides a synergism that generates research questions for both Edison's quadrant and Bohr's quadrant.

Jack Morton has portrayed the evolutionary process of this model in Figure 45. In the first generation of electronic communication technology, macroscopic properties of a few materials to establish magnetic, electrical, insulating and mechanical properties of the materials for tube design and manufacture. Research in materials, devices, circuits, and systems were only loosely coupled. With the invention of the transistor, the breadth of knowledge in each of these categories increased as shown by overlap in the categories along the horizontal axis. Materials and devices were more tightly coupled as were circuits and systems. In addition, the intensity of knowledge increased as reflected by the growing height of the curves along the vertical axis. At the time Morton wrote his paper, the microcircuit revolution was just getting underway. The integrated circuit had been introduced in 1962, and the first steps had been made toward monolithic integration for both digital and analog applications in silicon and gallium arsenide. The first MEMS patent was issued in 1968, the year before publication of Morton's paper.

The microcircuit technology is no longer along one line as shown in Morton's chart, but has split into a series of microcircuit technologies with the evolutionary process described by Morton over 30 years ago continuing in each of them. The DARPA Microcircuit Technology Offices (MTO) manages the development of the microcircuit family under what DARPA defines as "our three core areas:" electronics, photonics and MEMS, as shown in Figure 46. The materials research areas are managed by the Defense Sciences Office (DSO), and the intimate coupling between materials research and device development is reflected in the fact that materials research projects can be found in both the MTO programs as well as the DSO programs. Eliot Cohen's analysis of the trends in active element phased arrays found eight cost drivers, all of which were sensitive to the quality of the starting material for this gallium arsenide-based technology (Fig. 47).

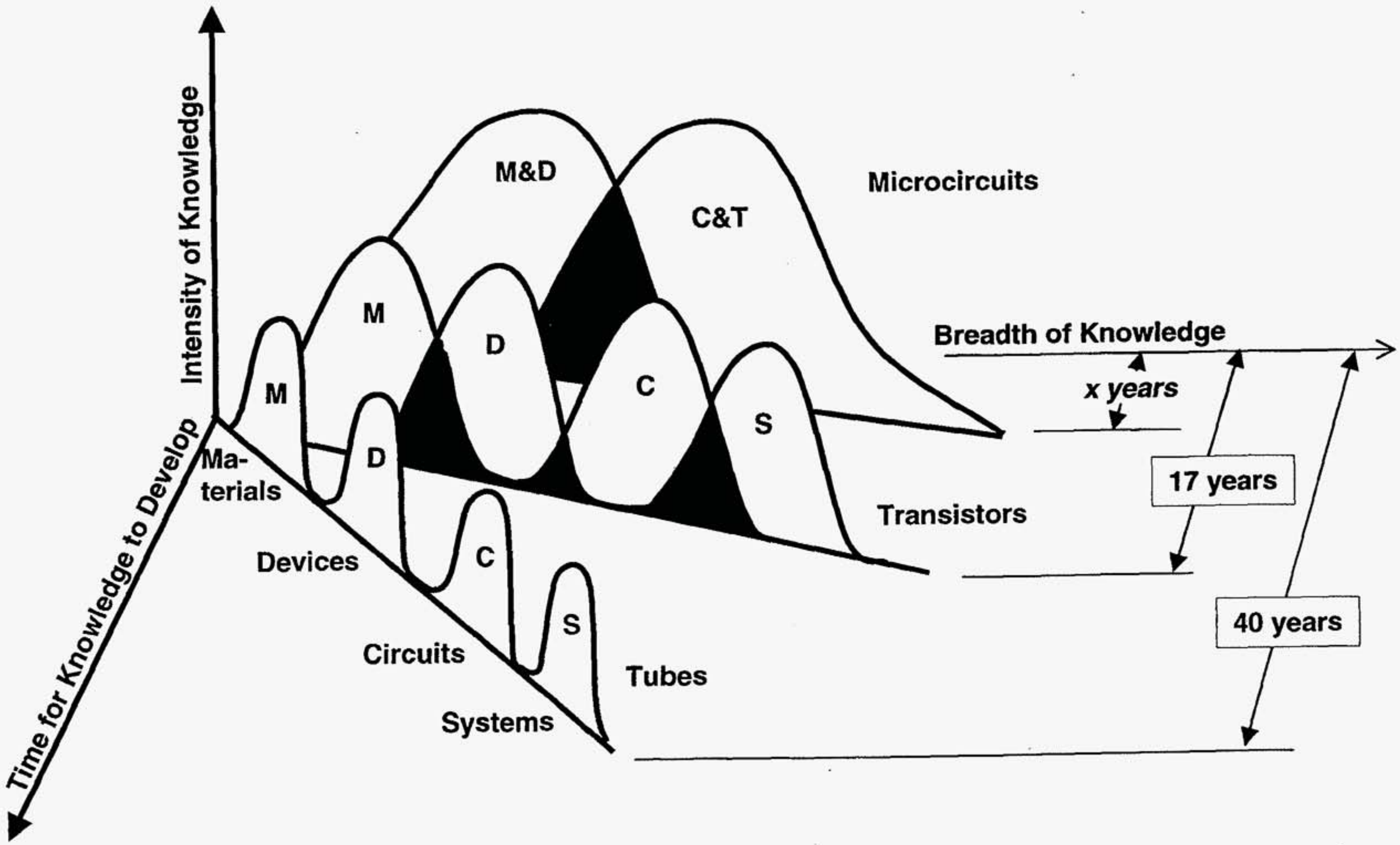

Figure 46. Speedup in Development of Knowledge as One Moves From One Technology Track to Another in Electronics: Knowledge Intensifies and Broadens [150]

- STARTING MATERIAL COSTS
- MATERIAL QUALIFICATION AND PREPARATION COSTS
- EFFECTIVE USE OF WAFER “REAL ESTATE”
- PROCESSING YIELD (LINE YIELD, DC YIELD, VISUAL YIELD)
- TEST (ON-WAFER AND POST PROCESSING)
- VISUAL INSPECTION
- PACKAGING
- FINAL TEST AND QA

Figure 47. Factors Impacting MIMIC Costs [136]

E. The Payoff of MIMIC

The program that began with the concern of the smart weapons community for the cost of millimeter wave missile seekers was completed in 1995, but was followed by an extension to the program called MAFET. [152] It was one of the most successful programs conducted by the DoD that established MIMIC as a robust dual-use technology with applications not only in smart weapons, electronic warfare, radar and communications, but in satellite communications, automobile anti-collision radars, wireless local area networks, and digital, cellular, and cordless phone services. As Defense Department budgets declined, the microwave industry was well positioned by the MIMIC investment to respond more effectively to DoD needs, as well as to the newly emerging commercial markets with the resultant benefit in the following application areas.

The maturation of MIMIC technology is already having a profound effect on smart weapons development. The Aviation and Missile Research, Development, and Engineering Center (AMRDEC) formed a key technology thrust in Precision Guidance of Small Diameter Weapons in response to the revision in 1993 of FM-100-5 OPERATIONS in order to better match the mission capability of the Center to the needed capability of the Army for fighting and peace keeping in the information age. For small diameter missiles with RF data links, MIMIC offers the potential for better integration of the missile-borne power amplifiers with the missile antennas to achieve much-needed efficiency in missile systems. One of the most pervasive enabling technologies for advancing the art of precision guidance of small diameter weapons is Microelectromechanical Systems (MEMS), and since both MEMS and MIMIC have common origins in microelectronics, it can be expected that the merging of the two technologies will be an important factor in achieving the goals of precision guidance of small diameter weapons. MIMIC and MEMS technology will allow the packaging of millimeter wave homing seekers in smaller diameter missiles. For missiles too small to feature a homing seeker, MIMIC sources integrated with symmetrically configured end-fire arrays may offer an alternative.

Another key technology thrust is multispectral missile seekers. The MIMIC now offers a mature front-end millimeter-sensing alternative that may be combined with other millimeter or infrared wave bands. As an example, in 1993 the BAT Project Office began a P3I effort to upgrade the homing seeker to engage additional targets and improve performance in adverse weather. The millimeter portion of this millimeter-infrared seeker will be able to capitalize on the advances in MIMIC technology that were achieved after the work on the MLRS-TGW seeker under Manufacturing Methods and Technology programs.

The MIMIC program offered a more economical sensing option for millimeter wave seekers but shrinking budgets and the downsizing environment provided further stimulus for the development of the concepts of flexible manufacturing in such programs as the DARPA-Tri-Service Affordable Multi-Missile Manufacturing (AM3). This Advanced Technology Demonstration effort has the objective of reducing the production cost of ongoing missile programs by 25 percent, the development and production cost of new missiles and upgrades by 50 percent, and the reduction of the development cycle time by 50 percent. [151] The principal focus of the program is on missile seekers and guidance and control sections which represents more than 60 percent of the missile unit production cost.

Monolithic design of high-speed photo detectors and photo-emitters on semi-insulating gallium arsenide provided the foundation for coupling fiber-optic communication and information processing, and the progress in MIMIC technology enhanced the potential for coupling the areas of lightwave and millimeter and microwave technologies. Peter Herczfeld served as guest editor of the May 1990 issue of the Joint IEEE Transactions on Microwave Theory and Techniques, and the Journal of Lightwave Technology that contained 50 papers in this area organized in two categories: (1) distribution of microwave and millimeter wave analog signals, and (2) optically controlled devices and circuits. [152] In the first category, work at the AMCOM RDEC, has provided a means for using multispectral seekers on a fiber optic guided missile by independently transmitting millimeter and infrared sensor imagery over the fiber optic link to a ground control station. [153] In the second category, photonics and millimeter wave technology have been integrated into a millimeter wave transmit-receive module that can provide the basis for either a radar or communication relay. [154] In 1992, Herczfeld proposed microwave-photonics integrated circuits as a follow-up to MIMIC. [155] In a statement before the Subcommittee on Emerging Threats and Capabilities Committee of the Senate Armed Services Committee, Dr. Frank Fernandez reported that the goal of the Radio-Frequency Lightwave Integrated Circuits program (R-FLICS) was "to product photonics technology that will enable development of high-performance radio frequency circuits that can route, control, and process analog radio frequency signals in very broad, but militarily crucial range of .5 to 50 gigahertz." [156]

The conduct of the MIMIC program provided a valuable model in public and private sector cooperation in achieving broad national objectives. Although the MIMIC program had its origins in the concern of one segment of the defense community for the cost of its products (smart weapons), there was also recognition in the technical community that the technology had broad applicability in commercial applications such as automobile radar, direct-broadcast TV, and wireless communications that could be traced back to the emergence of microwave monolithic integrated circuits. The automobile electronics market is being pursued not only by American automobile manufacturers, but a host of Japanese and German firms as well. MIMIC is a key technology in enabling the direct broadcast television industry to meet not only the technical challenges, but remain competitive in a rapidly expanding market. But direct broadcast satellites provided only one part of the communication revolution to which MIMIC is making a contribution: Satellite links with the capability to provide video conferencing, voice, data fax and two-way paging are already providing services in a rapidly expanding market.

Would MIMIC have happened anyway without the stimulus of the DoD program? There is absolutely no support for this. In 1985, the year DoD made the decision to start the MIMIC program, it was recognized that the U.S. would be confronting the Japanese in head-to-head competition in gallium arsenide technology, as well as in silicon technology. The U.S. leadership in the semiconductor market was already in sharp decline including the loss in market share of U.S. semiconductor equipment and materials suppliers, such as lithography equipment, etching systems, deposition systems, and semiconductor materials, and others. In addition to other systemic problems in the industry including the cost of capital to U.S. suppliers as compared to that in Japan, the working relationships between U.S. suppliers and the U.S. semiconductor manufacturers was poor in contrast with these relationships in Japanese industry.

Since this loss in leadership was in the relatively mature silicon technology, it is hardly reasonable to expect that the U.S. could have achieved a position of leadership in the relatively immature gallium arsenide technology without the stimulus of the DoD program.

XIII. THE ELEMENTS OF A SUCCESSFUL PROGRAM

A. Introduction

The MIMIC program was formulated in the decade when the U.S. was reeling from the blows of foreign competitors. In 1986, the year before the MIMIC program was launched, the U.S. suffered the first high technology trade deficit. Approximately half of all patents awarded were going to foreign inventors. That same year, W. Edwards Deming presented a plan for the transformation of American industry based on his 14 points [167] and Genichi Taguchi introduced a new concept of quality engineering based on the loss function [168]. There was growing recognition of the need to reexamine the framework for the Federal Government is support of science and technology derived from the Vannevar Bush report, "Science, The Endless Frontier," 1945, which advanced the thesis that support of basic research, the principal fountainhead of innovation, was a proper role of the Federal Government, and the more applied areas were left to industry. The principal Federal Government investment areas for basic research were defense and health, which left a policy void in the area of research leading to the commercialization of technology. The consequence of this policy accorded low status to manufacturing technology and left the U.S. vulnerable to foreign competition. According to the report by the Council of Productivity, this Post World War II research-driven model of the innovative process:

> "Viewed innovation as a linear process - - starting with a major scientific breakthrough, progressing through design, development and production, and ending with marketplace distribution. Consequently, the model emphasized basic research. The research-based model must be supplemented by another view that focuses on market-driven applications of the technology." [3]

The success of the MIMIC program can be attributed to the strong leadership of the DoD and service directors of the program and their many top associates in Government, industry, and academia, who not only possessed an intimate knowledge of the technology, but the managerial agility to navigate in an era of national soul-searching and provide the following characteristics of the program.

B. Unprecedented Atmosphere of Cooperation

The leadership of the MIMIC program recognized that if the microwave industry was to produce millimeter and microwave monolithic integrated circuits with acceptable costs for defense applications, it would also have to provide the foundation for profitable manufacturing to allow the industry to compete with volume production in the global marketplace. To achieve this goal, Cohen identified four tasks the industry teams would have to achieve: (1) Robust and controllable processing capabilities to allow chip fabrication with high yield, (2) Highly automated on-wafer testing to characterize and screen chips early in the fabrication process, (3) Comprehensive computer-aided design system with an open architecture framework, and (4) Invoking modern production discipline in all the design, fabrication, assembly, and test procedures in order to transform them into sustainable, low-cost production operations. [141]

Achievement of the program goals required that the national interest take precedence over the interest of the individual companies. Cohen observed that:

> "If these tasks are to be accomplished efficiently an unprecedented degree of cooperation must take place between the many companies engaged in the program. The cooperation must extend over all the various technical disciplines that contribute to the design, fabrication, and use of microwave and millimeter wave hardware. The MIMIC program was specifically structured to foster and manage such interactions." [141]

As a result of this guidance, the barriers to the free flow of information were removed within the teams and between the teams. Problems common to the industry in the areas of Computer-Aided Design (CAD), interfaces, and modeling received special attention in the collective efforts, thus allowing a higher productivity of research and development investments. As part of this cooperative effort, the Raytheon-TI team and the ITT-Martin-Marietta team formed joint ventures to achieve program goals with significant savings of time and money.

C. The Framework for Continuous Improvement

W. Edwards Deming conceived his 14 points as the basis for transforming industry into organizations producing quality products at lower cost in shorter cycle times through a process of "continuous improvement." Continuous improvement in the Deming Model is concerned with reducing the variations in manufacturing the process about some target value. [167] The MIMIC technology offered a broad array of target values for metrics that managers utilized to provide the framework for continuous improvement. E.D. Maynard provided the guidance for establishing more detailed metrics for some of the advantages offered by MIMIC: (1) reduction in size and weight (10:100:), (2) improvement in reliability (100:1), (3) reduction in parts count (30:1), and (4) lower life cycle cost (10:1). [118] The program was also framed in such a way that metrics for improvements within both Phase I and Phase II could be established for yield, cost and power added efficiency for power amplifiers. [135] In some instances, according to Cohen, retrofit of MIMIC hardware into existing modules and subsystems had the purpose of reducing cost and improving reproducibility, reliability, and performance, although generally a retrofit in an existing system did not result in space savings or significant improvement in performance. For future systems, MIMIC offered two advantages: (1) increasing functionality within reduced space requirements with advantages of reduced cost and improved reliability, and (2) enlarging the opportunity to design and produce systems not achievable in the older technologies. The opportunities for improvements in existing and planned systems in 1991 were presented in Reference 134.

The potential advantages offered by MIMIC for phased array radars in terms of reduced cost, size, weight, and improved reliability and power-added efficiency were recognized in the mid 1960s, and the transmit-receive module was the focus of concentrated effort from the beginning of the MIMIC program. At the 1996 IEEE International Symposium on Phased Army Radars, Cohen reported that an order of magnitude reduction in GaAs MIMICs cost had been achieved since 1988, by focusing on both the nonrecurring and eight recurring cost factors: starting material cost; material qualification and preparation; effective use of wafer real estate; processing yield; testing; visual inspection; packaging; final test; and quality assurance. [136]

Nonrecurring cost reduction was the focus of a major effort under the Microwave Analog Front End Technology Program (MAFET) to introduce virtual prototyping in the first cycle of design-build-test, and reduce the number follow-on cycles from 3 or 4 to 2. A major program goal in the High-Density Microwave Packaging Program was to reduce the T/R module cost by an order of magnitude or more at required performance levels with lower weight and cost in a given form factor. [155]

D. Focusing on the Entire Product Development Cycle

The declining U.S. competitiveness in the late 1970s and early 1980s provided the motivation for a number of studies that concluded that the major barrier to U.S. leadership was not external factors, but was within the corporations themselves. Bernard Slade explored this question with 21 professors and 200 senior executives .[146] Most of the academics attributed the decline in U.S. competitiveness to weakness in manufacturing, and 40.6 percent of the senior executives identified integrated design teams as the factor needed for shortening the product development cycle. Slade attributed the problems of U.S. industry to the failure to adapt to technological change from the 1950s when the product cycle was much shorter than it is today; risk were lower, and the product cycle was determined primarily by what happened on the factory floor; since the communication process between the design engineer and the manufacturer was a straightforward process. The arrival of high technology and the impact on manufacturing brought about disruptive change that made U.S. vulnerable in global markets. Part of the solution has been to provide for intensive management of technology development in a separate S&T organization to 'mature' the technology to a high readiness level before handoff to a product or program development organization. General Accounting Office studies have found that application of this process improves the probability of success for both commercial and military programs, but it is more difficult to provide the incentives to operate with this model in Government than in industry where the motivation is built in.

The findings of the Slade study were consistent with the conclusions of studies by the National Research Council. In one National Research Council Study it was found that:

> "Effective design and manufacturing, both necessary to produce high quality products, are closely related. However, effective design is a prerequisite for effective manufacturing; quality cannot be manufactured or tested into a product, it must be designed in. Unfortunately, the overall quality of engineering design in the United States is poor." [157]

In another study, the National Research Council found:

> "Progress in U.S. manufacturing technologies and competitiveness faces significant barriers: inflexible organizations; inadequate technology; inappropriate performance measures; and lack of appreciation for the importance of manufacturing. These barriers are addressed in this report of the Committee on Analysis of Research Directions and Needs in U.S. Manufacturing, Manufacturing Studies Board, Commission of Engineering and Technical Systems, National Research Council. The report identifies and analyzes research needs in five critical areas of manufacturing: intelligent manufacturing control, equipment reliability and maintenance, advanced-engineered materials, manufacturing skills improvement, and the product realization process." [158]

The product realization process must match the product development, deployment, and support to market requirements. The MIMIC program placed strong emphasis on the product realization process:

> "MIMIC contractors are required to prepare a business plan which is updated on a regular basis and includes a comprehensive market analysis for MIMIC products, an assessment of which MIMICs are needed for insertion into military subsystems, plans for effecting these insertions with the lowest possible risks, cost analyses and approaches to making MIMIC chips/modules available to all other prospective DoD buyers. Each contractor must also establish an additional independent source of supply for the chips that it manufactures." [140]

A vision of a new industrial America incorporating the changes in the product realization process is presented in Reference 159.

E. A Model for Concurrent Engineering or the Integrated Product-Process Development Concept

The weakest link in the product development cycle grew with the impact of high technology on manufacturing; the recognition grew that management had to confront three issues that have a major impact on the length of the product cycle. According to Slade these three issues are: (1) How to make the product concept and performance specifications responsive to the market and customer needs, (2) How to know when and how to decide among several possible design alternatives, and (3) How to determine the magnitude of the technical and performance advances that can be achieved with technical risk. [146]

In recognition of these changes in strategic vision in industry, DARPA sponsored a Workshop on concurrent engineering, in 1987. A Follow-up study was performed by the Institute for Defense Analysis (IDA) entitled The Role of Concurrent Engineering in Weapon System Acquisition, December 1988. [160] In the IDA study of concurrent engineering in 11 firms, it was shown that substantial reduction in cost and product cycle time could be achieved. The basic idea is that R&D and manufacturing process development are worked on concurrently. The definition of concurrent engineering by Winner, et al. in the IDA study suggested that shortening the product cycle involved more than improving the linkage between design and manufacturing through the issues cited by Slade:

> "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements." [160]

In the formulation of the MIMIC program, there was recognition that incorporating these principles could serve as a catalyst in bringing about needed change. The industrial base analysis conducted in the early 1980s prior to the formulation of the MIMIC program, had found that there were 40 firms with IR&D programs in microwave and millimeter integrated circuits, but manufacturing process development work was nearly nonexistent as formal programs. The background papers and memoranda developed by the military services and DoD recognized that the MIMIC program could not be just "more of the same" of what industry was already doing. The MIMIC program would have to be a structured program formulated and executed by interdisciplinary teams, with a strong component of manufacturing process development in the foundation of the program. The requirement for the teams to develop business plans encouraged the teams to view the product development cycle from fundamental research to the customer.

MIMIC contractors were required to prepare a business plan which is updated on a regular basis and includes a comprehensive market analysis for MIMIC products, an assessment of which MIMICs are needed for insertion into military subsystems, plans for effecting these insertions with the lowest possible risks, cost analyses and approaches to making MIMIC chips/modules available to all other prospective DoD buyers. Each contractor must also establish an additional independent source of supply for the chips that it manufactures.

F. Lessons Learned From the Very High Speed Integrated Circuits Program

The formal structure of the MIMIC program was similar to that of the VHSIC program and featured the concept of strong DoD management with service program directors to draw on in-house and industry resources in a coordinated manner for program planning and execution. The focus of VHSIC was on digital systems and was based on a relatively mature base in silicon, while MIMIC was to advance microwave and millimeter analog technology based on the more intractable material of gallium arsenide. The two technologies were viewed as having a complementary role for defense applications. According to Maynard, who directed both programs:

> "The MIMIC program will provide advantages to the 'eyes and ears' of systems similar to the 'brains' by VHSIC, advantages in performance, size, weight, cost, power and reliability." [90]

However, VHSIC and MIMIC were distinctly different in the level of maturity of the two technologies. At the time the VHSIC program was initiated, DoD was a customer for less than 10 percent of the silicon microelectronics market, so it was becoming difficult to get the attention of industry for defense applications. DoD was concerned about the long lead time between advancements in the technology and the introduction of these advancements in weapon systems. The VHSIC response to this problem was a two-phase program that included bipolar, NMOS, and CMOS technology. Under Phase I, the objective was chips with 50,000 gates with 1.25 micron size and 25 Mhz clock rates. The VHSIC Phase I program objective was to speed up the insertion of Very Large Scale Integrated (VLSI) circuits into military systems. [120] Under Phase II, the objective was chips with 100,000 gates with .5 micron size with clock rates of 50 Mhz or higher. At the close of Phase II, the goal was to reduce the delay between commercial 1990 VLSI technology and military insertion to two years. On the other hand, when the MIMIC program was initiated, DoD was the principal customer for the technology, but there was widespread recognition of the potential of the technology for commercial application and realizing this potential was implicit in the MIMIC program goals.

The VHSIC program was not just about producing high-speed chips for military systems, but included a comprehensive program in equipment development, manufacturing processes, and testing technology that provided a more mature manufacturing technology base for MIMIC. Both programs focused on the design environment with the emphasis on hardware description languages to provide for easy interchange of models and designs, tool integration, and tool interoperability. However, although the analog CAD market has been growing well since the completion of MAFET in 1995, it represented only about 10 percent of the CAD market in 1996, the year MAFET was initiated. [160, 161] The MAFET program provided an effective stimulus in the development of microwave and millimeter wave analog design tools. [160]

A very important lesson from the VHSIC-MIMIC experience is that the health of the semiconductor industry in global commercial markets is an essential foundation for also meeting defense needs. High-volume production is essential for the health of the semiconductor industry, but this is provided by commercial markets, not military markets. However, semiconductors also provide the most powerful leverage in achieving technological superiority in weapon systems, but this cannot be achieved with an ailing industry. This logic was the principle theme of the report of the Defense Science Board Task Force "Defense Semiconductor Dependency." [122] This inextricable linkage between defense and commercial interest was acknowledged by Caposell:

> "The MIMIC program benefited from lessons learned during the VHSIC effort. VHSIC was successful in moving digital INTEGRATED CIRCUITS technology forward at an accelerated pace; however many of the VHSIC foundries did not succeed after the conclusion of the program largely because of a lack of orders for VHSIC parts. This resulted in part, from the VHSIC program guidance that emphasized generic chips for which it turned out, there was almost no market. Fortunately, the strong commercial interest in the technology quickly provided a home for VHSIC, mostly in the form of application specific ICs and memory chips." [135]

G. Integration of Metrology and Standards with Technology Development

1. Air Force GaAs Material/Device Correlation Study

Starting material quality held the key to the success of the MIMIC program. Cohen identified eight factors impacting recurring costs, and materials quality impacts each of the eight. [136] A well-timed research effort was initiated by the Air Force Materials Laboratory in fall of 1983, three years before the Phase 0 MIMIC BAA was issued with the objective of improving the quality of undoped semi-insulating liquid encapsulated Czochralski GaAs material. [162] One contract was awarded to Texas Instruments Central Research Laboratory for low-pressure growth, and a second contract was awarded to Rockwell International Aeroelectronics Research and Development Center for high-pressure growth. Deliverables under the program were test boules of minimum length and diameter sliced into 40 wafers and prepared for further analysis and device processing.

The second step in the program was undertaken in 1984, when the wafers were distributed under four contracts to Raytheon Research Division, Texas Instruments incorporated, Hughes Aircraft Company, and Raytheon, for evaluation and processing of five wafers from a boule into several semiconductor devices followed by documentation of materials, processing, and device measurements. The test data from the program was collected by the Microwave Technology Branch, and the computer program WAFER was developed in conjunction for this effort. [163]

Although the program was based on mature device technology, an immediate finding was that numerous variations in wafer processing and device testing procedures made it difficult to establish an unambiguous relationship between material quality and device performance, and underscored the importance of some form of standardization for basic materials-type classification. [164]

2. National Bureau of Standards

A most fortunate circumstance was the participation of the NBS in formative stages of the MIMIC program. The principal concern when the market for MIMIC was primarily military was that the absence of calibration standards during weapon development and acquisition would leave the Government at the mercy of contractors for system performance test and evaluation. In 1986, Brian Belanger, of NBS, conducted a review of DoD directives, instructions, and MIL standards and measurement requirements and came to the conclusion that there were no formal DoD regulations or directives explicitly requiring those managing various aspects of the program to consider and address measurement standards requirements. NBS began immediately (1986) formulating a program on metrology and standards that would be integral to the development and application of MIMIC technology with the primary focus on military applications.

The growing awareness of the weak Federal role in research for commercialization of technology led to the 1988 Omnibus Competitiveness and Trade Act that transformed NBS into the NIST with enlarged responsibilities in this area. The following year, the first annual MIMIC conference was held at Gaithersburg, MD with NIST serving as host. As the MIMIC program unfolded, the customer base for the technology shifted from military applications to commercial wireless applications, and formal link between U.S. competitiveness and metrology and standards as a key element in global strategy was recognized in the National Technology Transfer and Advancement Act of 1995, the year the MIMIC program ended.

H. MIMIC: A Dual-Use Technology

The Defense Science Board Study concluded that the health of the semiconductor industry was inextricably linked with the development of advanced semiconductor devices for defense applications. The health of the industry was dependent on a high-volume commercial market, but the semiconductor device was a key component in advanced weapon design, and the required numbers were relatively small for this application. A major goal of acquisition reform was to unify the defense and commercial industrial bases so that defense needs could be met, and the health of the industry maintained in global markets. [165] The DoD identified three pillars of the dual-use technology policy: (1) investment in R&D on dual-use technologies, (2) integration of military and commercial production, and (3) insertion of commercial capabilities into military systems.

The MIMIC program was a key dual-use technology that was initiated when the market for the technology was principally military. Since so few MIMIC devices were required for defense, the prices were high, therefore part of the dual-use strategy was to encourage the industry to seek commercial applications for analogous defense devices or subsystems so defense needs could be met at lower prices. One example cited on the application of this strategy was the Air Force phased array radar that used 2000 MIMIC TR modules with an original cost of $8,000 each. By reducing the time and cost of the front-end design process, the cost of the TR modules was reduced to about $2,000, but DoD supported efforts to apply the technology in collision avoidance systems, for automobiles, wireless communication, and air traffic control signal processing.

The development of a family of radars under the Modular Airborne Radar (MODAR) program by the Westinghouse Electronic Systems Group for both the commercial and military aviation markets provides another model of the application of MIMIC in the dual-use concept. The application of the family of radars was for detection of wind shear in time for the aircraft to avoid the hazard. The MODAR integrated product-process development team included the MIMIC designer, power amplifier designer, transmitter designer, manufacturing engineering, and test engineer. The team conducted careful trades of various transmitter power source architectures including IMPATTs, TWTs, and MESFET amplifiers. The MESFET power amplifier was selected as the building block for the transmitter. Achieving the cost and performance goals required an intensive effort to identify the materials, processing, and testing cost. The process led to a successful design that was applied in MODAR-3000 for the commercial market and the MODAR-4000 for the military tanker/transport market. [164] According to the Defense Science Board Study: "The results of the MODAR program were quite startling. The product development cycle for a new prototype was reduced by more than 50 percent (from 12 months to 5 months). The prototype development cost was also reduced by 50 percent. Hardware integration and harmonization took two weeks instead of eight. The radar worked and performed all of its basic functions in its first flight test 22 weeks after program start." [166]

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ACRONYMS

AM3	Affordable Multi-Missile Manufacturing
AMC	Army Materiel Command
ARDEC	Armaments Research, Development, and Engineering Center
BRL	Ballistic Research Laboratories
CAD	Computer Aided Design
CCG	Calibration Coordination Group
CMOS	Complimentary Metal Oxide Semiconductor
DARPA	Defense Advanced Research Project Agency
DDR&E	Director of Defense for Research and Engineering
DOD	Department of Defense
DOFL	Diamond Ordnance Fuze Laboratory
DSARC	Defense Systems Acquisition Review Council
DSO	Defense Sciences Office
ECL	Electronics Components Laboratory
ET&DL	Electronics Technology and Devices Laboratory
FET	Field Effect Transistor
FM-CW	Frequency Modulated-Continuous Wave
GAO	General Accounting Office
GE	General Electric
HBT	Hetrojunction Bipolar Transmitter
HEMT	High Electron Mobility Transistor
IDA	Institute for Defense Analysis
IPPD	Integrated Product and Process Development
IR&D	Independent Research and Development
IRE	Institute of Radio Engineers
M^3I	Monolithic Millimeter and Microwave Initiative
MAFET	Microwave Analog Front End Technology Program
MANTECH	Manufacturing Technology
MEMS	Microelectromechanical Systems
MERA	Molecular Electronics for Radar Applications
MIC	Microwave Integrated Circuits
MICOM	US Army Missile Command
MIMIC	Microwave and Millimeter Monolithic Integrated Circuits
MLRS-TGSM	Multiple-Launch Rocket System-Terminally Guided Submunition
MM&T	Manufacturing Methods and Technology
MOA	Memorandum of Agreement
MODAR	Modular Airborne Radar
MOFA	Multi-Option Fuze for Artillery
MRSS	Microwave Radiometer Seeker Subsystem
MTO	Microcircuit Technology Office
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NMOS	N-Metal Oxide Semiconductor
PEMA	Procurement of Equipment and Missiles, Army

ACRONYMS (CONT)

PEP	Producibility Engineering Planning
PESO	Product Engineering Service Office
PNMS	Promote National Measurements Standards
R&AT	Research and Advanced Technology
RDB	Research and Development Board
RDT&E	Research, Development, Test, and Engineering
RF	Radio Frequency
SADARM	Search and Destroy Armor
SCEL	Signal Corps Engineering Laboratories
SCORE	Signal Communication via Orbiting Relay Equipment
SEMATECH	Semiconductor Manufacturing Technology
SMDO	Space and Missile Defense Organization
TEM	Transverse Electromagnetic Mode
TGSM	Terminally Guided Submunition
TGW	Terminally Guided Warhead
TR	Transmit/Receive
TRADOC	US Army Training and Doctrine Command
TWT	Traveling Wave Tube
URSI	International Scientific Radio Union
US	United States
USDRE	Under Secretary of Defense for Research and Development
VHSIC	Very High Speed Integrated Circuit
VLSI	Very Large Scale Integrated

APPENDIX A
MILESTONES LEADING TO THE DEPARTMENT OF DEFENSE MICROWAVE AND MILLIMETER MONOLITHIC INTEGRATED CIRCUIT PROGRAM

Thanks are due Dr. Robert Heaston, Staff Specialist, Office of the Under Secretary of Defense (IR&AT), and Director, Guidance and Control Information Analysis Center, and Mr. Jerry Dickson, electronics engineer, Systems Engineering and Production Directorate, RDEC, AMCOM, for their contribution to this section of the report.

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

INTRODUCTION

The Department of Defense (DOD) Microwave and Millimeter Wave Monolithic Integrated Circuit (MIMIC) Program conducted in the 1980s and 1990s, was the culmination of advances in materials research, physics of semiconductor devices, transmission media, modeling and simulation, device development, manufacturing process development with roots in research conducted prior to and during World War II. A primary objective was to achieve compact, low-cost, and highly reliable millimeter and microwave circuit functions that could withstand extreme environments in weapon systems. 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, communications, countermeasures - counter-countermeasures, and smart weapons. Economy was achieved by fabricating both the active and passive circuit functions and inter-connections in monolithic form in semi-insulating gallium arsenide wafers.

When the program was being formulated in 1986 the market was principally military, but when it ended in 1995, the market was primarily commercial. The success of the program makes it a useful model for the design of other programs to achieve national objectives, for defense or competitiveness in international markets. The objective of this report is to summarize the milestones leading to the formulation and execution of the program.

Two key technologies that provided the foundation for radio proximity fuze program in World War II were miniature vacuum tubes for hearing aids that had to be ruggedized for application in bombs, missiles and projectiles, and printed wiring technology that not only could be adapted for making the electrical connections to the circuit elements in an automated process, but the fabrication of the passive circuit elements including resistors, inductors, and capacitors. At the close of World War II, in anticipation of commercial applications of the technology , the National Bureau of Standards published a comprehensive technical report on printed wiring technology as well as the 1948 IRE journal article on printed circuit technique. The transistor quickly replaced the miniature tubes in radio circuits, and the emergence of low cost transmission media allowed the first planar fabrication of microwave printed circuits in the early 1950s that could be conceived of at several levels of "integration" hence the term microwave integrated circuits or more correctly "hybrid integrated circuits" since they are not fabricated in monolithic form.

In a program as complex and extending over such a long period of time, no two observers would be likely to select the same list of milestones for the program. This list represents the author's view that favors milestones in the Army contributions to the MIMIC program since the author had a better knowledge of the Army efforts than those of the other services. If the contributions of the other services and industrial and university sectors have been slighted on the list, it can be attributed to the authors ignorance. Heavy reliance has been placed on open source publications such as the Microwave Journal, IEEE Transactions on Microwave Theory and Techniques, Journal of Electronic Defense, Symposium Proceedings, and unpublished papers briefing, correspondence and memoranda concerned with program formulation and execution. In addition, Dr. Robert Heaston, a member of the office of Undersecretary of Defense for Research and Engineering kept a log of several of the key decision milestones that have been included in this report.

The milestones presented includes a mixture of scientific and technical as well as programmatic milestones. No attempt has been made to capture a comprehensive treatment of all the methods of printing circuits some of which had origins in U.S. British and German Work in the 1930s. The methods employed up to the time the Brunetti - Curtis paper was published in 1948 included painting, spraying, and die-stamping. The principal advantages of printed circuits included uniformity of production, reduction assembly and inspection time, cost, live rejects, and purchasing and stocking problems.

Also, no attempt is made to present all the device and process developments in genesis of the transistor. The key active device in the formulation of the MIMIC program was the Metal Semiconductor Field Effect Transistor (MESFET). William Shockley had investigated and made a record of a field effect transistor before World War II, but it was decades later after a better understanding of the physics, and advances fabrication the the first gallium arsenide field effect transistor was fabricated, and reported by C.A. Meade, in "Schottky-Barrier Field Effect Transistor", Proc. IRE Letters Vol 54, pp-307-308, February 1966.

The Research, Development, Engineering and Missile Systems Laboratory (RDE&MSL) had a pivotal role in the formulation of the MIMIC program that was based on a cordial working relationship with the Electronics Technology and Devices Laboratory who provided the technology base in millimeter wave technology in response to the smart munitions requirements from RDE&MSL. It was the technical and cost data derived from the MICOM Mantech program on millimeter wave seekers and other MICOM industrial base analysis and the work of the DOD M^3I committee that led to the conclusion that the industrial base in manufacturing was inadequate to provide for economical production of millimeter wave seekers for the MLRS-TGW. This led to the decision by USDR&E James P. Wade, Jr., to establish the DOD MIMIC program in a letter to the military services and DARPA dated 1 February 1985. During the formulation of the program in 1985-86, three key workshops were held at Redstone Arsenal that are shown in the milestones the evolution of the program itself provided the motivation for a major Manufacturing Technology effort keyed to smart weapon applications that provided several key milestones that have been included in this report.

MILESTONES LEADING TO THE DEPARTMENT OF DEFENSE MICROWAVE AND MILLIMETER MONOLITHIC INTEGRATED CIRCUIT PROGRAM

1930s - The six methods of printing circuits presented in the Burnetti-Curtis paper have their origins in numberous U.S. British and German research efforts and patents dating back to the early 1930s. An example is U.S. Patent 2,136,024 PROCESS AND APPARATUS FOR PRODUCING METALLIC COATINGS ON VARIOUS ARTICLES, filed May 3, 1935, issued Nov 8, 1938

1940-1951 - Shockley had investigated field-effect structures both before and after World War II and concluded that the effect could lead to amplification, and made the first record of a Schottky gate transistor in his laboratory notebook at Bell Labs on 20 February 1940, and filed the original patent for the junction field effect transistor (U.S. Patent 2,744,970) on August 24, 1951.

1948 - Publication of the paper "Printed Circuit Techniques: by Cledo Brunetti and Roger W. Curtis, Proceedings of IRE, January 1948

1947-1948 - The functioning of the transistor was demonstrated to management of Bell Labs on Christmas Eve 1947, but announcement was delayed until June 1948 to gain more understanding of the device and its potential applications.

1952 - First conception of planar fabrication of microwave printed circuits was made by Robert M. Barrett with the introduction of the strip transmission line.

1959 - Jack S. Kilby filed an application for a patent on February 6, 1959, that resulted in U.S. Patent 3,138,743, MINATURE ELECTRONIC CIRCUITS being issued June 23, 1964.

1960s-1970s - Ballistic Research Laboratories conducted a systematic program in the potential applications of millimeter wave technology to missile guidance over this decade that included propagation effects, multipath target signatures, and instrumentation development. This provided some broad bounds for MIMIC hardware development.

1960s - First active array Transmit-Receive module developed by Texas Instruments for the Air Force based in silicon technology under the MERA program.

1965 - A group was formed under Vladimir Gelnovatch in the Army Electronic Components Laboratory at Fort Monmouth to provide a focus for the development of hybrid microwave integrated circuit technology.

1966 - The letter "Schottky-Barrier Field Effect Transistor" was published in Proceedings of IEEE February 1967 by C.A. Mead

1968 - The paper "Computer-Aided Design of Wideband Integrated Microwave Transistor Amplifiers on High Dielectric Substrated" by T.F. Burke and V.G. Gelnovatch was Published in the IEEE Journal of Solid State Circuits, June 1968

1969 - The slot transmission line on a dielectric substrate was reported by S.B. Cohn. "Slot Line Characteristics", IEEE MTT Transactions, Vol 17, No 12, December 1969

1969 - The coplanar waveguide reported by C.P. Wen in "Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Reapproval Gyro-Magnetic Device Applications" IEEE MTT Transactions MTT-17, No. 12, December 1969.

1970 - The Paper "Environmental Effects on Radar and Radiometric Systems at Millimeter Wavelengths" at the Symposium at Polytechnic Institute of Brooklyn March 31, April 1-2, 1970, established the broad bounds on the choice of millimeter wavelengths for smart weapon applications.

1970s - The Electronics Technology and Devices Laboratory conducted a program of development of microelectronics including microwave integrated circuits supporting Army smart munitions development.

1972 - Source Selection on Millimeter Wave Seekers was held at Aberdeen Proving Ground. (Hammond Green). The pioneering work of ET&TL, BRL, MICOM, the Air Force, and Sperry influenced the choice of sensing options for this development.

1975 - Side-by-Side Testing of 35Ghz and 95Ghz Missile Seekers was completed at Redstone Arsenal. (TR-RE-75-39) (Hammond Green)

1976 - MM&T Project 38131 - "Production Methods for Millimeter Wave Radiometric Seeker for Submunition Applications" was developed and submitted for the MM&T budget.

1976 - First known gallium arsenide MMIC was fabricated at Plessey, LTD., by Ray Pengelly and James Turner.

1977 - Manufacturing Methods and Technology Five Year Plan FY-79-83 (Project 38131 above was part of plan)

1978 - U.S. Patent for High Electron Mobility Transistor issued to Dingle, et al, Bell Telephone Laboratories (Patent 4,163,237)

1980 - Contract awarded to Sperry Corporation for MM&T project 3139 on Millimeter Wave Seekers for Terminal Homing, Contract DAAH01-80-C-1977.

1980 - First demonstration of High Electron Mobility transistor by Dingle, et al, University of Illinois.

1981 - Contract awarded to Sperry Corporation for the second phase of MM&T Project 3139 on Millimeter Wave Seekers for Terminal Homing, Contract DAAH01-81-C-B239.

1981 - SPIE Conference on INTEGRATED OPTICS and MILLIMETER and MICROWAVE INTEGRATED CIRCUITS held 16-19 November 1981, Von Braun Civic Center, Huntsville, Alabama (SPIE Volume 317, November 16-19, 1981)

1981 - An outline of a structured MIMIC program analogous to VHSIC was presented at the above conference entitled: "Potential of Integrated Optics and Millimeter and Microwave Integrated Circuits for Future MICOM Systems".

1982 - Sperry Gyroscope Corporation submitted the final report "Manufacturing Methods and Technology for Millimeter Seekers for Terminal Homing" MM&T Project 3139, January 1982 (conclusion was millimeter seekers cost 10 times too much).

1983 - Sperry Gyroscope Corporation submitted the final report on Phase II of "Manufacturing Methods and Technology (MM&T) Project for Millimeter Wave Seekers" in February 1983 (MM&T Project 38131).

1983 - "Government Systems and GaAs Monolithic Components" RCA Review Vol 44, p-507, 1983 by Kenneth Sleger December 1983. This paper provided a global view of MIMIC systems and technology for military applications .

1984 - Technical Requirements for a follow-on phase to the Sperry Contract were developed and issued. The project was canceled just short of contract award in a restructuring of MM&T by the Under Secretary of the Army.

1984 - IR&D industrial base analysis performed at Redstone Arsenal on millimeter wave integrated circuit analysis submitted to USDRE as part of document request in August 1984. Results showed about 40 firms working in MIMIC and MIC (hybrids) but little manufacturing process development was being done.

1984 - As follow-up to the above analysis, a task was issued from MICOM through the Guidance and Control Information Analysis Center (GACIAC) to perform a more detailed industrial base analysis on MIC and MIMIC as an amendment to a solicitation dated 30 July 1984. (This was performed by Naresh C. Deo and Peter P. Toulious and published as "State-of-the-Art Review of Microwave and Millimeter Wave Monolithic Integrated Circuits" 1985).

1984 - Seminar conducted at Harry Diamond Laboratories on Millimeter Wave Standards and Measurements Requirements, March 1984.

1984 - The IEEE Society for Microwave Theory and Techniques formed the Committee to Promote National Measurement Standards chaired by Doug Rytting of Hewlett-Packard.

1984 - A proposal for an Army wide "A Structured Program in Microwave and Millimeter Circuit Technology for Smart Munitions" August 1984, was submitted to the Army Materiel Command, after coordination with Picatinny Arsenal and the Army Electronics Technology and Devices Laboratory. The document outlined an Army-wide plan for 38 million dollars.

1984 - A request was made of the Advanced Sensors Directorate by the Office of Under Secretary of Defense (James Wade) in August 1984 for cost and technical data the MICOM had developed on the subject of producibility of millimeter wave seekers (Telephone request).

1984 - In response to the above request, the proposal submitted to the Army was expanded into a document "IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY" and submitted to USDRE as part of the document request in August 1984. The plan outlined a DOD-wide program for 100 million dollars. Also included in the package was the result of the IR&D industrial base analysis.

1984 - First draft of "Technological Status Microwave and Millimeter Wave Integrated Circuits" completed and submitted in September 1984 under the task order from MICOM, GACIAC-SR-84-07.

1984 - On 28 September 1984, the lack of maturity of Millimeter Wave Technology was a topic of discussion at the DSARC for MLRS-TGW. As a result, the Assistant Secretary of Defense (ASD), (Acquisition Management), asked the Product Engineering Services Office (PESO) to look into the state-of-the-art of millimeter wave components.

1984 - A preliminary assessment of millimeter and microwave monolithic integrated circuit technology was given to the Acting USDRE on 11 December 1984. The same briefing was given to the Service Secretaries and DARPA.

1984 - The Concept Definition Phase of the international program, MLRS-TGW began in November 1984.

1984 - 11 Decenber 1984 - Dr. Robert Heaston briefed USDRE James P. Wade, Jr., on the work of the M^3I Committee

1985 - 5 January 1985 - As a result of the questions raised about the state of the art of millimeter wave technology in conjunction with the MLRS-TGW DSARC, Dr. Robert Heaston prepared correspondence for the signature of James Wade, Under Secretary of Defense (R&E), to the Service Assistant Secretaries for Research and Development and DARPA, requesting that they designate two technical experts to serve on the M3I Committee chaired by Dr. Robert Heaston.

1985 - 1 February 1985 - USDRE James P. Wade, Jr., sent a letter to the Assistant Secretaries of the military services and DARPA on "OSD Microwave/Millimeter Monolithic Technology Initiative"

1985 - 11 February 1985 - Dr. Robert Heaston and Mr. Neal Sullivan prepared a POTENTIAL THRUST AREA on Monolithic Microwave and Millimeter Wave Initiative summarizing objectives of the initiatives.

1985 - 24-26 February 1985 - The U.S. Army Technology and Devices Laboratory served as host for the U.S. Army Gallium Arsenide Workshop with participants from industry TRADOC and Army Labs. Applications on EW, radar, communications and smart weapons were discussed.

1985 - GaAs Monolithic for Affordable Military Systems" by Kenneth Sleger, Journal of Electronic Defense p-27, August 1985. An excellent global view of MIMIC for military application.

1985 - 5 March 1985 - Mr. E.D. Maynard, Jr., prepared "GaAs MMIC Technology Initiative" and presented to the kick-off meeting of the M3I Committee.

1985 - 18-19 March 1985 - The M3I Committee held a workshop at Georgia Institute of Technology with representatives of the three services to discuss potential programs in MIMIC to meet service requirements.

1985 - 26 March 1985 - James S. Kesperis, U.S. Army Electronics Technology and Devices Laboratory, responded to Dr. Heaston's request at the meeting the M3I Committee meeting at Georgia Tech on 18 March 1982 to prepare material on Ultra-High Speed Microelectronics (digital gallium arsenide).

1985 - Seminar on Millimeter Wave Measurements and Standards Requirements held at U.S. Army Harry Diamond Laboratories April 1985.

1985 - On 26 April 1985 Sonny Maynard briefed the Acting DUSD (R&AT), Colonel Carter, on "The GaAs Situation and Program Proposal."

1985 - 9 May 1985 - Mr. E.D. Maynard, Jr., Director of the VHSIC Program, sent a Memorandum to the Deputy Under Secretary of Defense for Research and Advanced Technology DUSD (R&AT) recommending that an OSD initiative be mounted in M3I. Maynard noted that as a result of a DUSD Briefing (AM) to USDRE on DSARCII assessment of MLRS/TGW, DUSD (R&AT) was asked by Dr. Wade to look into the manufacturing options for the MLRS/TGW 94Ghz submunitions seeker electronics.

1985 - In the above letter dated 9 May 1985, to the DUSD (R&AT), E.D. Maynard, Jr., concurred in some points on the work of the work of the M3I Committee but objected to others. He offered recommendations of his own.

1985 - 14 May 1985 - A meeting of the M3I committee was held at the Georgia Institute of Technology.

1985 - 10 June 1985 - Mr. E.D. Maynard, Jr. briefed USDRE on Monolithic Microwave/Millimeter Wave Initiative that included a summary of current gallium arsenide monolithic funding, application of the technology, and deficiencies.

1985 - September - Monolithic Microwave and Millimeter Wave Initiative (M3I) Summary published (Findings and Recommendations of M3I Committee). GACIAC Special Report SR-85-14.

1985 - 5-6 November 1985 - The 1985 Conference on Producibility of Microwave and Millimeter Wave Integrated Circuits was held at Redstone Arsenal. In the introductory talk outlining the MIMIC program, E.D. Maynard, Jr., noted that the DOD MIMIC program was formulated in response to the concerns of the smart weapons community about the high cost of millimeter wave seekers. (See PROCEEDINGS OF THE 1985 CONFERENCE ON PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUITS, 5-6 November 1985).

1985 - December - The Committee on Critical Materials (formed from the Board on Army Science and Technology and the National Materials Advisory Board) was briefed at Redstone Arsenal on MM&T Projects involving electronic, electro-optical and electro-magnetic materials completed and planned. Committee members expressed concern about the status of gallium arsenide technology compared to that in Japan. (See ACHIEVING LEADERSHIP IN MATERIALS TECHNOLOGY FOR THE ARMY OF THE FUTURE 1986).

1986 - Mr. E.D. Maynard, Jr. was appointed MIMIC Program Director.

1986 - Dr. Eliot Cohen, Navy Director of the VHSIC program was recruited to be the Deputy Director of the MIMIC program.

1986 - Service program directors for MIMIC were appointed:
CG Thornton, Army Electronic Technology and Devices Laboratory;
D. McCoy, Office of Assistant Secretary of the Navy for Research Engineering and Systems;
W.J. Edwards. Air Force Wright-Aeronautical Laboratories.

1986 - MIMIC Phase 0 BAA prepared, modified in August 1986.

1986 - Phase 0 MIMIC BAA Issued in October 1986.

1986 - 4-5 November 1986 - Conference on Producibility of Millimeter and Microwave Integrated Circuits held at the Redstone Arsenal Post Theatre.

1986 - 6-7 November 1986 - Conference on Millimeter and Microwave Measurement Standards for Miniaturized Systems held at the Redstone Arsenal Post Theatre. (The National Bureau of Standards outlined program to support MIMIC development).

1987 - February - Phase 0 MIMIC Contract Awards made. Completed, February 1988.

1987 - 23 September 1987 - The National Bureau of Standards held Meeting to establish Industrial Consortium for MIMIC Standards, at Gaithersburg, Maryland.

1987 - The paper "W-Band Microstrip Integrated Circuit Transceiver" was published in the Microwave Journal, October 1987 p-115 by Yen, Y.E., English, D., Grote, A., Hayashebarn, G., Pham, T., Nyan, T.C., Yen, P, Wandinger, L., Frerburg, E. This paper pointed the way to W-Band Monolithic Integrated Circuit Transceiver.

1987 - December - Source Selection on MIMIC Phase One was held at NRL. (Jerry Dickson)

1988 - The MIMIC program was transferred to DARPA in September and Dr. Eliot Cohen assumed the role as Director.

1988 - Phase 1 MIMIC contracts awarded in May 1988.

1989 - January issue of MICROWAVE JOURNAL article, "The MIMIC Program: A Technology Inpact Report".

1989 - First Annual MIMIC Conference held at the National Institute of Standards and Technology in Garthersburg MD, in March 1989.

1989 - The Concept Definition Phase of the international MLRS-TGW program was completed. The millimeter wave seeker had been identified as a risk actor, but was deemed moderate enough for the program to enter system demonstration.

1989 - First pseudomorphic High Electron Mobility Transistor (PHEMT) reported by Aust, et al, of TRW.

1990 - The System Demonstration Phase for the International MLRS-TGW program began.

1990 - A four-year MANTECH effort began with TRW on a MICOM contract for 94Ghz MILLIMETER WAVE SEEKER (The goal was to leverage the MIMIC effort to provide delivery of hardware).

1990 - A four-year Manufacturing Technology effort began with TRW on a MICOM contract entitled, "94GHz MILLIMETER WAVE Transceiver" (Jerry Dickson) Goal was to insert MIMIC devices developed by ETDL into the U.S. work share of the MLRS-TGW seeker.

1990 - July - Source selection on MIMIC Phase 2 was held at Evans Field New Jersey. (Jerry Dickson)

1991 - Phase 2 MIMIC began in August 1991.

1992 - The United States withdrew from the international MLRS-TGW program.

1992 - The first W-band active image reject receiver was developed by TRW under the MICOM Manufacturing Technology effort entitled "94GHz Millimeter Wave Transceiver" (Jerry Dickson). The receiver contained a low noise amplifier with an image reject mixer. This module empirically confirmed that the noise figure of the Low Noise Amplifier (LNA) predominantly sets the noise level of the entire system. This 2-channel received, which employed a single LNA for each channel, laid the technology framework for the Longbow KA-Band 2-channel single LNA Cost Reduction received configuration and the BATP3I W-band receiver configuration.

1993 - The first W-band upconverter power amplifier module was developed by TRW under the MICOM Manufacturing Technology effort entitled, "94GHz Millimeter Wave Transceiver" (Jerry Dickson). This module contained two MIMIC power amplifier chips and one driver output chip. This module empirically established that the power amplifier chips (input states) must be driven hard into saturation at room temperature to sustain the required output level at hot temperature. This module replaced the MLRS-TGW GUNN diode amplifier assembly in the W-band transmitter.

1994 - The Manufacturing Technology Division at MICOM performed MIMIC based transceiver and sensor testing in Paris, France. (Jerry Dickson). Results of the MIMIC based transceiver, which was eventually integrated into US residual MLRS-TGW hardware, convincingly demonstrated that the MIMIC based sensor had the best overall performance of the previously 20 built and tested MLRS-TGW sensors.

1995 - Program completed in August 1995. Final Annual Meeting was held August 30 - September 1, 1994 at the Hyatt Regency in Crystal City.

APPENDIX B
A STRUCTURED PROGRAM IN MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

ROUTING AND TRANSMITTAL SLIP

Date 21 June

TO: (Name, office symbol, room number, building, Agency/Post)

		Initials	Date
Dr Em 1.			26 June
2.			
3.			
4.			
5.			

	Action		File		Note and Return
	Approval		For Clearance		Per Conversation
	As Requested		For Correction		Prepare Reply
	Circulate		For Your Information		See Me
	Comment		Investigate		Signature
/	Coordination		Justify		

REMARKS

Why are we offering Bob Oswald this (undoubtedly excellent) advice - if we really want him to do some of this, we should start it & allow him to "take it away from us" (ha-ha) -

DO NOT use this form as a RECORD of approvals, concurrences, disposals, clearances, and similar actions

FROM: (Name, org. symbol, Agency/Post)	Room No.—Bldg.
REV, B. Pittman	Phone No. 7778

5041-102

☆ U.S. G.P.O. 1979-285-092

OPTIONAL FORM 41 (Rev. 7-76)
Prescribed by GSA
FPMR (41 CFR) 101-11.206

DEPARTMENT OF THE ARMY
UNITED STATES ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35898-5000

AMSMI-REX

SUBJECT: Proposal for a Structured Program in Microwave and Millimeter Integrated Circuits to Support the Smart Munitions Thrust

Commander
US Army Electronics Research and Development Command
ATTN: AMDEL-CT/Dr. R. B. Oswald
2800 Powder Mill Road
Adelphi, MD 20783

1. We are deeply concerned that emerging technology of microwave and millimeter integrated circuits that would help the Army achieve the goals of affordability, producibility, and packing density for smart munitions does not have sufficient focus to achieve those goals. The present method of resource allocation leaves the research objectives in this area only loosely coupled with the Smart Munition Thrust. To provide some improvement in coupling, the subject proposal would provide a program element for a structured effort that would insure strong correlation between the work in microwave and millimeter integrated circuits and the program needs in smart munitions. This program element would be assigned to MICOM as the lead command for smart munitions.

2. We are exploring the feasibility of additional program elements in infrared sensors and integrated optics for smart munitions that would have the same purpose as the subject proposal.

3. Comments from ERADCOM would be appreciated before the proposal is submitted to the Army Materiel Command.

FOR THE COMMANDER:

1 Encl
Proposal

For use of this label, see AR 340-15; the proponent agency is The Adjutant General's Office.

INITIALS

SIGNATURE or INITIALS marker

DA LABEL 116, 1 Feb 69

PROPOSAL

A STRUCTURED PROGRAM IN MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

AUGUST 1984

US ARMY MISSILE LABORATORY
US ARMY MISSILE COMMAND

OBJECTIVE:

The objective is to conduct a structured VHSIC-like program in microwave and millimeter integrated circuit technology to achieve goals of affordability, producibility, and packing density in support of the Army thrust in smart munitions. There is already in progress some excellent basic work that supports these objectives but is not focused, and program gaps have not been systematically identified as they relate to smart munitions objectives. The underlying premise of the proposed approach is that there are generic elements to the technology common to a number of applications throughout the major subordinate commands of the Army Materiel Command, and a limited family of components and subsystems can be identified through a systematic needs analysis as the basis for the first phase of the program. The effort would include the fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of the first phase as the prelude to a yield enhancement program that would follow.

The advantages of this approach would be: (1) gaps in research, and problems would be discovered that would not otherwise be found; (2) the approach would make more efficient use of RDT&E resources since problem solving would take place on the generic level thus avoiding unwanted duplications of effort; and, (3) some time saving could be achieved by conducting the program off-line to the ongoing programs throughout AMC and then relying on technology insertions. To achieve program objectives would require the realignment of resources in AMC and the establishment a new program line assigned to MICOM under the Lead Laboratory for Smart Munitions.

BACKGROUND:

The application of integrated microwave and millimeter integrated circuit technology in smart munitions will allow the achievement of high packing densities for sensors in small diameter munitions, and permit a shift away from labor-intensive manufacturing technologies to the planar processes of integrated circuit fabrication. The program can thus synergistically couple with the investment being made under the Department of Defense (DOD) Very High Speed Integrated Circuit Program (VHSIC) on advanced lithographic methods, epitaxial materials growth, diffusion, ion implantation, and advanced materials processing.

The potential of millimeter integrated circuits to reduce cost, size, and weight was demonstrated in any analysis conducted during the course of an MM&T program on the seeker shown in Figure 1. With the Assault Breaker millimeter seeker as the baseline, four levels of millimeter technology were examined with the results shown in Figure 2. Although the cost figures are optimistic, the trend is the right direction. An analysis of the seeker showed that nearly 80 percent of the cost was for four components, and a big potential for cost reduction was in the front end. As a result of a redesign of the front end under the MM&T effort, the parts count was reduced by 37 percent and the data for the "semi-integrated" version in the second line of Figure 2 was produced. Line 3 of Figure 2 is a projection that can be achieved with microwave and millimeter integrated circuits in the near term and the fourth line depicts the ultimate goal of fabricating all the circuit functions, both active and passive in a single substrate material under the monolithic approach.

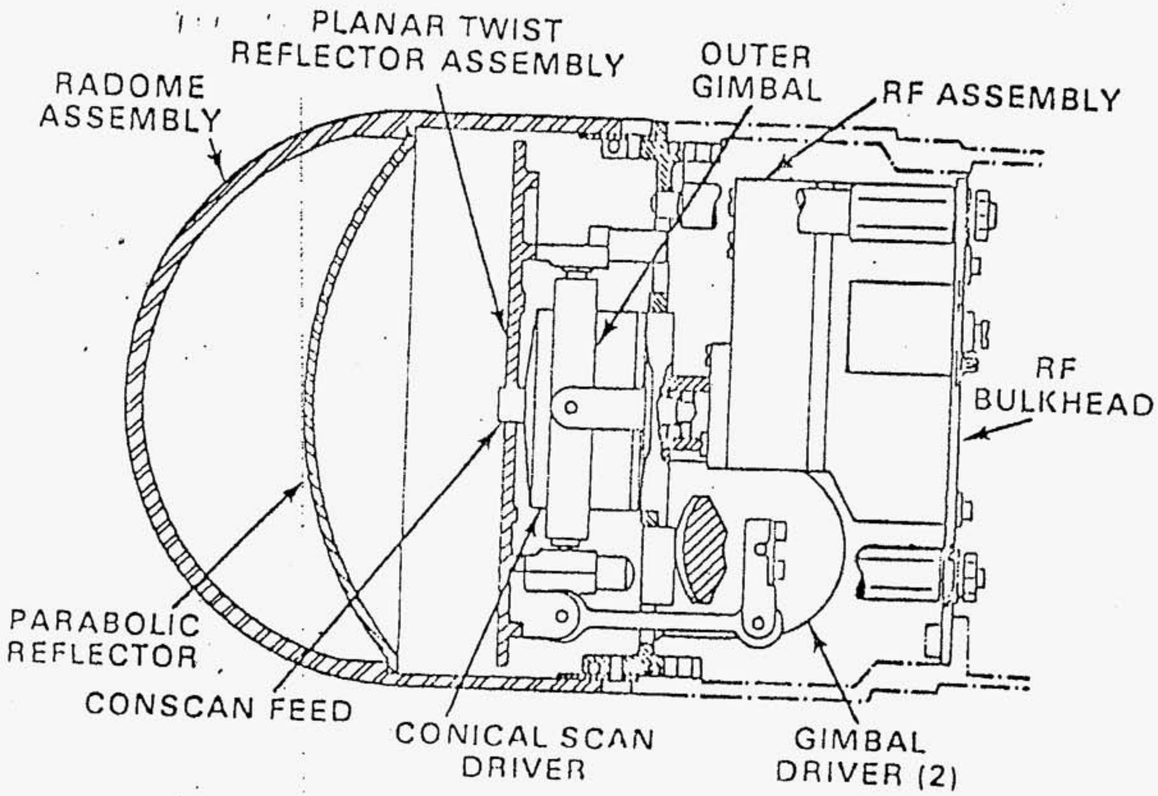
ELEMENTS OF THE PROGRAM

The first step will be to identify an array of needs from an analysis of the programs throughout the major subordinate commands of AMC that may include programs in exploratory development through fielded systems. This array of needs will generate a set of technical constraints that will then be applied to the array of available microwave and millimeter wave integrated circuits technologies. Figure 3 illustrates five of these technologies and Figure 4 summarizes the salient characteristics of each. Each of the approaches illustrated in Figure 3 provides a transmission line technology that is adaptable to batch manufacturing that can incorporate both passive and active functions to provide microwave and millimeter subsystems, each with its own distinctly different set of problems in achieving an integrated subsystem design as shown in Figure 4.

By filtering these candidate technologies through the needs, not only will leading technologies emerge, but gaps in research will be uncovered that would remain undiscovered under the present method for allocating resources for this area. Without the proposed approach, the transfer of these technologies into systems is painfully slow. The examination of microwave integrated circuit technology is part of the Army Missile Laboratory program in digital beam-forming, and also an MM&T program for a 94 GHz integrated transceiver that is coordinated with the ET&D Laboratory, but these are the exceptions rather than the rule. The potential cost advantage of these technologies may be lost for some applications if it is necessary to design expensive transitions to conventional wave guide plumbing, but this problem will never be uncovered in the first place without the systematic analysis of the technologies against program needs. For a sensor system for target recognition, the specification for a high purity waveform may pose a problem in choosing the technology that minimizes the dispersion, but again the problem must be uncovered and examined in a systematic way against the specific application.

The choice of the specific technologies for subsystem development will be done in design studies lasting six months. Each performer in the program would be free to make his own choices of the particular technologies, materials, processes, and technical approaches to integration, thus providing a spur to innovation that would not be present in the current method of technology transfer. The development, test and evaluation phase following this would include the development of a cost model for the fabrication process as the basis for allocating funds for the yield enhancement program. Technology insertion programs and manufacturing technology efforts would be developed for funding under separate program elements. The proposed program element would also include unstructured research on electronic materials and materials growth and characterization. The overall program schedule is summarized in Figure 5.

MILLIMETER WAVE SEEKER HEAD



FOCUS OF MM&T

- IMPROVED ASSEMBLY
- AUTOMATED INSPECTION
- AUTOMATED TEST EQUIPMENT
- CHANGES IN MATERIALS, FINISH, TOLERANCE AND GEOMETRY

FIGURE 1

COST COMPARISONS FOR THE FRONT END

OF A W-BAND FM-CW MILLIMETER SEEKER

TECHNOLOGY TYPE	UNIT PRODUCTION COST ESTIMATE	RELATIVE VOLUME (CUBIC INCHES)	PRODUCTION AVAILABILITY
DISCRETE COMPONENT	$14,000	26	1978
SEMI-INTEGRATED (REDESIGNED BASE UNIT)	6,500	9	1979
FULLY-INTEGRATED	2,300	6	1984
MONOLITHIC	900	1	1986-88

FIGURE 2

TRANSMISSION LINE TECHNOLOGIES FOR HYBRID MICROWAVE AND MILLIMETER WAVE

CIRCUIT TECHNOLOGIES

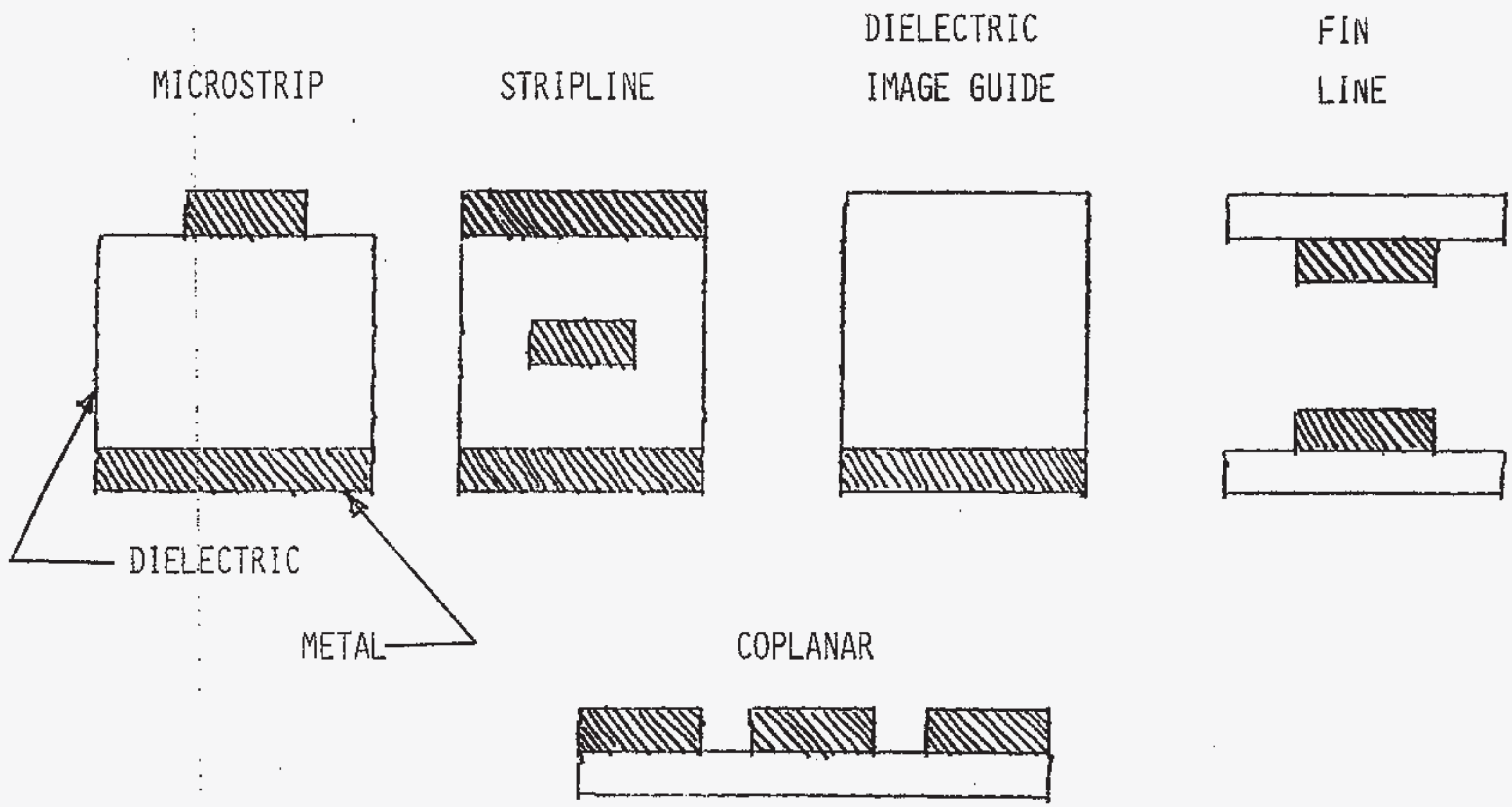


FIGURE 3

COMPARISON OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUIT APPROACHES

CHARACTERISTICS	MILLIMETER INTEGRATED CIRCUIT MEDIA				
	MICROSTRIP	STRIPLINE	DIELECTRIC IMAGE GUIDE	FIN LINE	COPLANAR-WAVE GUIDE
TRANSMISSION LOSS	MEDIUM	HIGH	LOWEST	LOW	HIGH
FREQUENCY OF OPERATION (GHZ)	UP TO 100	30-100	BEYOND 70	30-100	UP TO 20
CHARACTERISTIC IMPEDANCE RANGE ( )	20-125	40-120	25	10-400	40-150
RADIATION LOSS	LOW	LOW	MEDIUM	LOW	HIGH
DISPERSION, MULTIMODING	LOW DISPERSION, POTENTIALLY MULTIMODED	LOW DISPERSION	DISPERSIVE, OFTEN HEAVILY MULTIMODED	DISPERSIVE, POTENTIALLY MULTIMODED	DISPERSIVE, MULTIMODED
ACTIVE AND PASSIVE DEVICE COMPATABILITY AND INTEGRABILITY 1) SHUNT MOUNTED	DIFFICULT	EASY	DIFFICULT	EASY	EASY
2) SERIES COST	EASY LOW COST	EASY MODERATE COST	DIFFICULT MODERATE COST	EASY LOW COST	EASY LOW COST

FIGURE 4

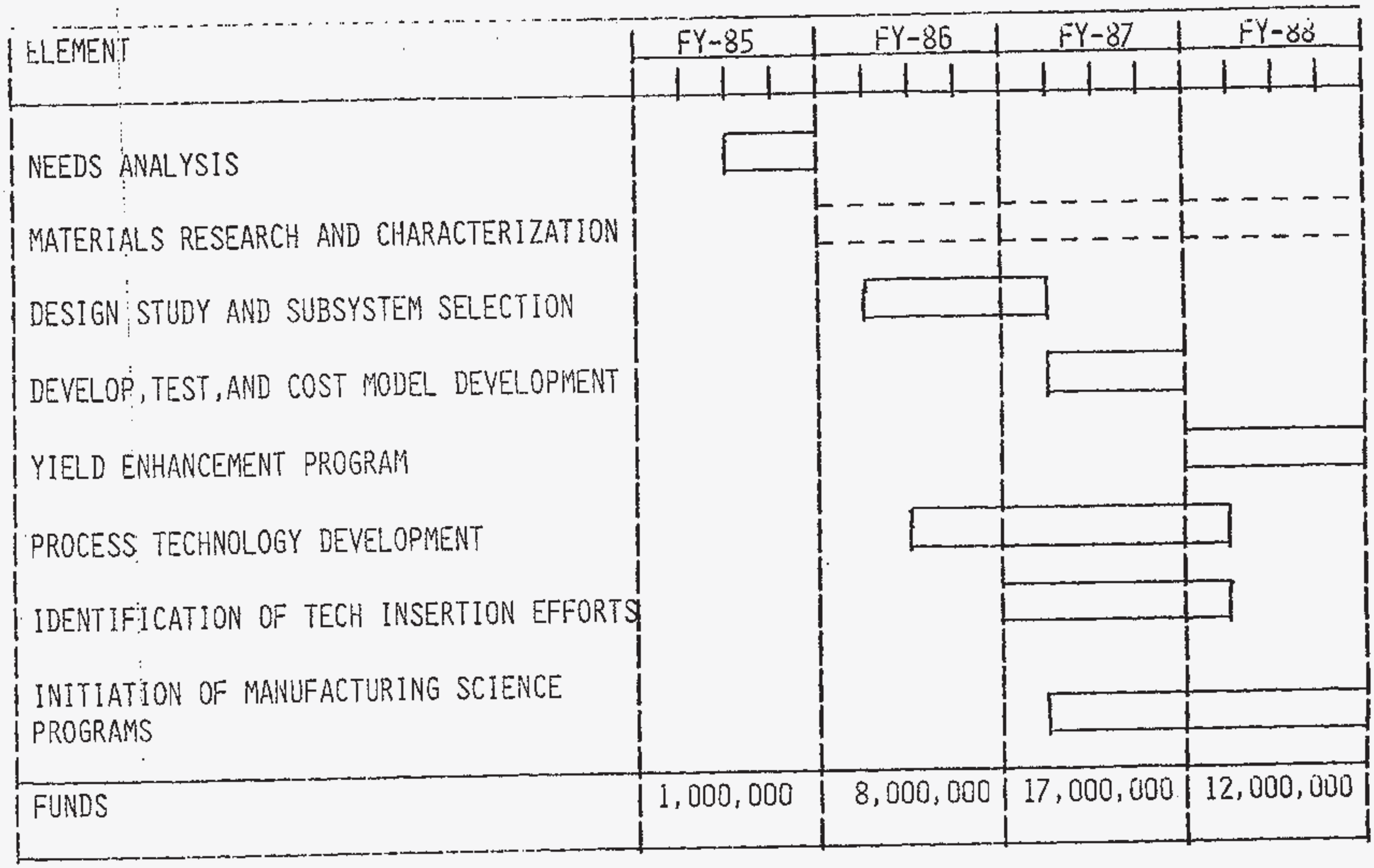

ELEMENT
FY-85
FY-86
FY-87
FY-88
NEEDS ANALYSIS
MATERIALS RESEARCH AND CHARACTERIZATION
DESIGN STUDY AND SUBSYSTEM SELECTION
DEVELOP,TEST,AND COST MODEL DEVELOPMENT
YIELD ENHANCEMENT PROGRAM
PROCESS TECHNOLOGY DEVELOPMENT
IDENTIFICATION OF TECH INSERTION EFFORTS
INITIATION OF MANUFACTURING SCIENCE PROGRAMS
FUNDS
1,000,000
8,000,000
17,000,000
12,000,000

FIGURE 5

DEPARTMENT OF THE ARMY
UNITED STATES ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35898

DRSMI-REX

SUBJECT: The Need for VHSIC-Like Programs in Infrared Detectors and Millimeter and Microwave Integrated Circuits

Commander
US Army Electronics Research and Development Command
ATTN: DRDEL-CT, Dr. R. B. Oswald
2800 Powder Mill Road
Adelphi, Maryland 20783

1. The progress being made in the advanced fabrication technologies for the Department of Defense (DOD) Very High Speed Integrated Circuit (VHSIC) program can have a synergistic coupling with other emerging technologies that are vital to the achievement of the goals of affordability in the Army thrust on smart munitions. Manufacturing cost analyses performed under the Missile Command (MICOM) Manufacturing Methods and Technology (MM&T) projects have shown that by shifting from labor-intensive manufacturing processes currently used in fabricating microwave and millimeter sensors to the planar processes of integrated circuit technology, large reductions in the per unit production cost can be achieved. It is, therefore, suggested that the Electronics Research and Development Command (ERADCOM) consider the feasibility of VHSIC-like programs in infrared detector arrays and microwave and millimeter integrated circuit technology to serve the needs of all the major subordinate commands.

2. This investment strategy would begin with the recognition that there are generic elements to these technologies common to a number of applications that could provide the basis for structured programs analogous to VHSIC. Under this approach, limited families of components and subsystems would be chosen from an application analysis to be pursued in the first phase of the program. This would include fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of this first phase as a prelude to a yield enhancement program that would follow.

3. The advantages of this approach would be: (a) gaps in research and problems would be discovered that would not otherwise be found; (b) the approach would make more efficient use of Research, Development, Test, and

Evaluation (RDT&E) resources since problem-solving would take place on the generic level, thus avoiding unwanted duplication effort; and (c) some time-saving could be achieved by conducting the programs off-line to the ongoing RDT&E efforts and then relying on technology insertion as is being done in VHSIC. The availability of a credible data base on cost, yield, and producibility would also provide the Government better control over downstream acquisition costs in major weapon acquisition programs.

4. An essential element of such programs must be the improvement in availability and cost of the underlying materials technology. The Army Missile Laboratory (AML) is already working with the Night Vision and Electro-Optics Laboratory (NV&EOL) to improve the quality of cadmium telluride substrates for the fabrications of mercury cadmium telluride detectors by the liquid phase epitaxy process. There are also a number of actions that need to be taken to improve the cost and availability of millimeter wave substrate materials including sapphire, quartz, alumina, and duroid.

5. An applications analysis is recommended for the FY 85 ERADCOM program that would provide, in matrix form, the potential technologies keyed to the applications of the major subordinate commands.

FOR THE COMMANDER:

APPENDIX C
IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

2/28/85

RFF: 160-85

IMPROVING THE AVAILABILITY, AFFORDABILITY, AND PRODUCIBILITY OF MICROWAVE AND MILLIMETER CIRCUIT TECHNOLOGY FOR SMART MUNITIONS

AUGUST 1984

US ARMY MISSILE LABORATORY

US ARMY MISSILE COMMAND

OBJECTIVE:

The basic assumption under this proposed program is that availability, affordability, and producibility of microwave and millimeter integrated circuits cannot be achieved within the framework of individual programs such as MLRS-TGW or the new Air Force follow-on to WASP even with supporting MM&T efforts throughout DOD. Although there is a large industry IR&D effort in this area (370 man years in FY84) very little of this is devoted to establishing a design base for the technology, and the manufacturing processes for cost effective production and tests of microwave and millimeter integrated circuits. The latter effort requires substantial capital investments that are beyond the threshold of individual MM&T efforts and which industry will not allocate out of IR&D.

The objective therefore is to conduct a structured VHSIC-like program in microwave and millimeter integrated circuit technology to achieve goals of affordability, producibility, and packing density in support of the Army thrust in smart munitions. By structured program is meant an array of activities from basic research through producibility engineering, manufacturing technology and technology insertion that are keyed to a specific set of subsystems. There is already in progress some excellent basic work that supports these objectives but it is not focused, and program gaps have not been systematically identified as they relate to smart munitions objectives. The underlying premise of the proposed approach is that there are generic elements to the technology common to a number of applications throughout the major subordinate commands of the Army Materiel Command, and a limited family of components and subsystems can be identified through a systematic needs analysis as the basis for the first phase of the program. The effort would include the fabrication of a limited number of these units for laboratory test and evaluation to investigate the relationships between the fabrication processes and performance. The development of a cost model of the manufacturing processes would be part of the first phase as the prelude to a yield enhancement program that would follow.

The advantages of this approach would be: (a) gaps in research, and problems would be discovered that would not otherwise be found; (b) the approach would make more efficient use of RDT&E resources since problem solving would take place on the generic level thus avoiding unwanted duplications of effort; and, (c) some time saving could be achieved by conducting the program off-line to the ongoing programs throughout AMC and then relying on technology insertions. To achieve program objectives would require the realignment of resources in AMC and the establishment of a new program line assigned to MICOM under the Lead Laboratory for Smart Munitions.

BACKGROUND:

The application of integrated microwave and millimeter integrated circuit technology in smart munitions will allow the achievement of high packing densities for sensors in small diameter munitions, and permit a shift away from labor-intensive manufacturing technologies to the planar processes of integrated circuit fabrication. The program can thus synergistically couple with the investment being made under the Department of Defense (DOD) Very High Speed Integrated Circuit Program (VHSIC) on advanced lithographic methods, epitaxial materials growth, diffusion, ion implantation, and advanced materials processing.

The potential of millimeter integrated circuits to reduce cost, size, and weight was demonstrated in an analysis conducted during the course of an MM&T

program on the seeker shown in Figure 1. With the Assault Breaker millimeter seeker as the baseline, four levels of millimeter technology were examined with the results shown in Figure 2. Although the cost figures are optimistic, the trend is the right direction. An analysis of the seeker showed that nearly 80 percent of the cost was for four components, and a big potential for cost reduction was in the front end. As a result of a redesign of the front end under the MM&T effort, the parts count was reduced by 37 percent and the data for the "semi-integrated" version in the second line of Figure 2 was produced. Line 3 of Figure 2 is a projection that can be achieved with microwave and millimeter integrated circuits in the near term and the fourth line depicts the ultimate goal of fabricating all the circuit functions, both active and passive, in a single substrate material under the monolithic approach.

STRONGER DESIGN BASE NEEDED:

A strong design base is a prerequisite to undertaking a program in improved manufacturing processes. The design process must begin with the specifications of the subsystem that the millimeter or microwave circuit must meet within the system, then alternative ways of distributing the different electromagnetic functions in integrated circuit form to meet the specifications must be examined within the available constraints of device physics and the available manufacturing processes. The different electromagnetic functions in close proximity will result in interaction between the different circuit elements that makes the problem of establishing and applying physical models extremely difficult, since physical models of individual circuits must be modified by these interaction effects. Part of the process of establishing the base for analysis and design must therefore be to develop approximation techniques that allow the application of high speed computers.

By focusing the design effort on a limited family of generic components and subsystems identified in the needs analysis, maximum creativity can be brought to bear on the problem solving. This family of generic components and subsystems may include several of the hybrid technologies as well as monolithic depending on the program schedules and maturity of the different technology options, ranging in frequency from 30 to 100 GHz. The individual components and subsystems may include receivers, transceivers, amplifiers, digital beamforming modules and others. The packaging of this portion of the program would allow participation of universities, millimeter and microwave components houses as well as the Government laboratories and other contractors.

DEFICIENCIES IN CURRENT MANUFACTURING METHODS:

The current manufacturing processes for Gunn, varactor, IMPATT and mixer diodes for integration with microstrip or one of the other hybrid technologies are highly labor intensive and performed by engineers and scientists. Efforts are needed not only to automate the manufacturing processes, but to design the individual components for easy integration with the appropriate transmission technology. Current methods for bonding of individual millimeter components with the transmission medium requires an accuracy not found in the currently available pick-and-place equipment. Tuning millimeter wave circuits after fabrication is highly labor intensive and therefore costly. The application of automatic laser trimming equipment to make cuts in the microstrip while simultaneously monitoring performance is one alternative for solving this problem. Some efforts to achieve solutions to these problems are in progress under Army MM&T programs, but the full range of problems to be solved and the capital investment costs are too high for the relatively small individual MM&T

efforts. Also, very little is being done by industry on these problems under industry IR&D.

To establish a firm manufacturing base in microwave and millimeter integrated circuits will also require a well-established measurements standards and reliable test, measurements, and diagnostic equipment for the production of microwave and millimeter integrated circuits, and the investment level is such that the objectives cannot be achieved under individual MM&T efforts or major programs such as MLRS-TGW, but only under a service-wide or DOD-wide program. There is currently available on the market, laboratory instrumentation for measuring fundamental signal parameters such as power, frequency, signal spectrum, and noise of millimeter circuits, but the need here is the specialized production test instrumentation that reduces the labor-intensiveness of the overall process. Again, some limited efforts have been done on DOD contracts. For example, Rome Air Development Center sponsored a contract to establish a detailed approach to cost effective automatic test procedures for monolithic microwave integrated circuits, but much more must be done. Recently published data shows that 46% of the total fabrications cost of millimeter integrated circuits for direct broadcast satellite receivers was in production testing.

MONOLITHIC TECHNOLOGY:

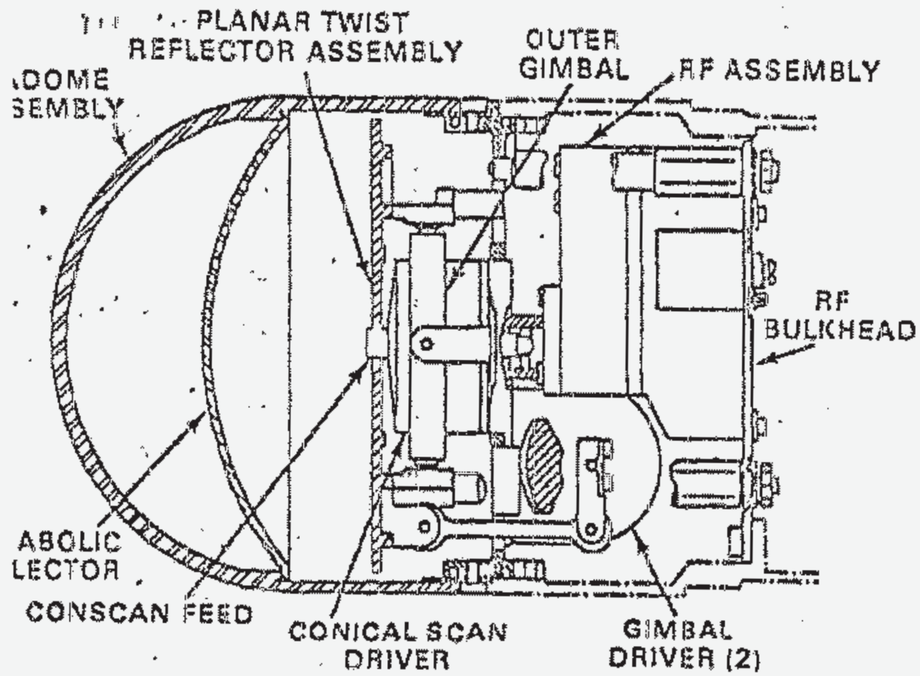
Figure 3 illustrates five of the transmission technologies for the hybrid options, and Figure 4 summarizes the different set of problems in achieving an integrated subsystem in each of these options. Farther in the future, both active and passive components may be fabricated in a single substrate to yield a monolithic subsystem such as a transceiver, but many difficult problems must be solved before that can be achieved. The process technology for gallium arsenide is the most advanced for this application and Gunn oscillators have been fabricated in gallium arsenide. However, Gunn oscillators yield higher power in indium phosphide, but unfortunately the technology of indium phosphide is much farther behind that of gallium arsenide. The sharply different doping profiles required of the different circuit elements in the monolithic technology poses a difficult technical challenge that must be met before monolithic circuits can be realized. Monreciprocal circuit elements will also be difficult to achieve in monolithic technology, and there is still much research to be done in radiating elements. Monolithic technology is lagging the hybrid technologies by at least 5 years.

ELEMENTS OF THE PROGRAM:

The first step will be to identify an array of needs from an analysis of the programs throughout the major subordinate commands of AMC that may include programs in exploratory development through fielded systems. This array of needs will generate a set of technical constraints that will then be applied to the array of available microwave and millimeter wave integrated circuits technologies. Figure 3 illustrates five of these technologies and Figure 4 summarizes the salient characteristics of each. Each of the approaches illustrated in Figure 3 provides a transmission line technology that is adaptable to batch manufacturing that can incorporate both passive and active functions to provide microwave and millimeter subsystems, each with its own distinctly different set of problems in achieving an integrated subsystem design as shown in Figure 4.

By filtering these candidate technologies through the array of needs, not only will leading technologies emerge, but gaps in research will be uncovered

MILLIMETER WAVE SEEKER HEAD



FOCUS OF MM&T

- O IMPROVED ASSEMBLY
- O AUTOMATED INSPECTION
- O AUTOMATED TEST EQUIPMENT
- O CHANGES IN MATERIALS, FINISH, TOLERANCE AND GEOMETRY

FIGURE 1

COST COMPARISONS FOR THE FRONT END OF A W-BAND FM-CW MILLIMETER SEEKER

TECHNOLOGY TYPE	UNIT PRODUCTION COST ESTIMATE	RELATIVE VOLUME (CUBIC INCHES)	PRODUCTION AVAILABILITY
DISCRETE COMPONENT	$14,000	26	1978
SEMI-INTEGRATED (REDESIGNED BASE UNIT)	6,500	9	1979
FULLY-INTEGRATED	2,300	6	1984
MONOLITHIC	900	1	1986-88

FIGURE 2

TRANSMISSION LINE TECHNOLOGIES FOR HYBRID MICROWAVE AND MILLIMETER WAVE

CIRCUIT TECHNOLOGIES

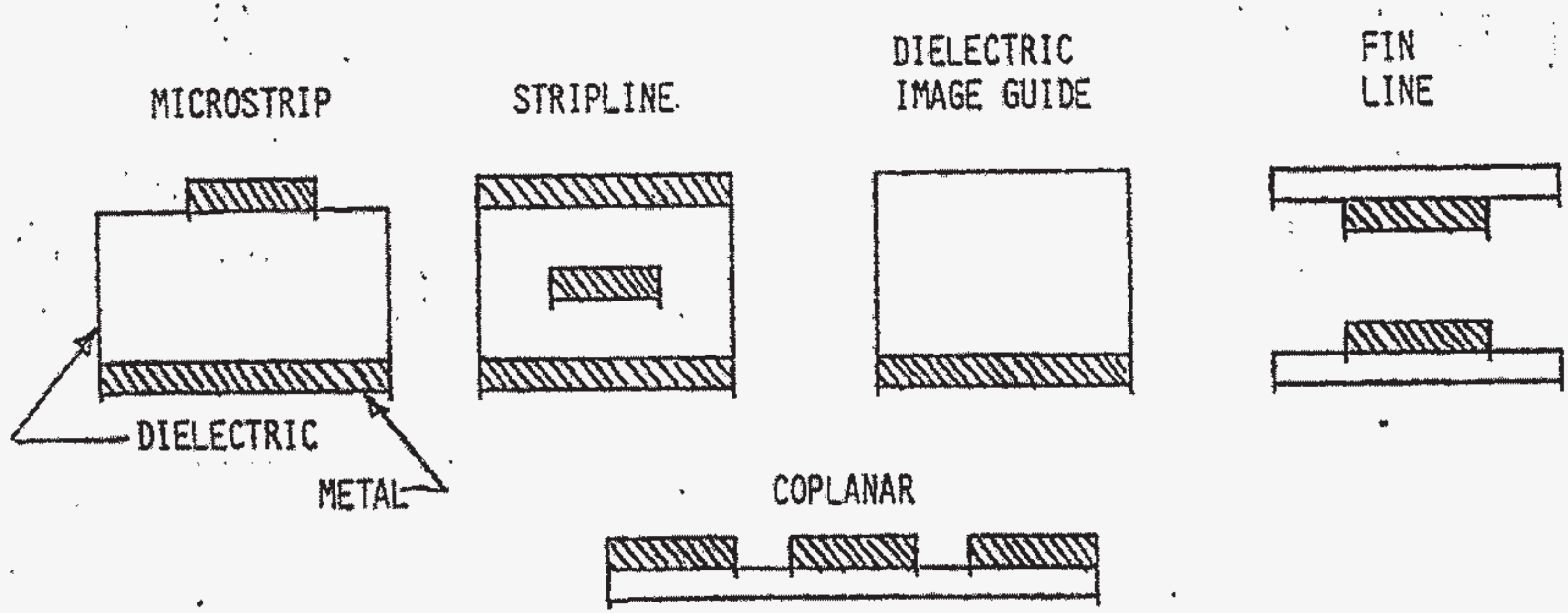


FIGURE 3

COMPARISON OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUIT APPROACHES

CHARACTERISTICS	MILLIMETER INTEGRATED CIRCUIT MEDIA				
	MICROSTRIP	STRIPLINE	DIELECTRIC IMAGE GUIDE	FIN LINE	COPLANAR-WAVE GUIDE
TRANSMISSION LOSS	MEDIUM	HIGH	LOWEST	LOW	HIGH
FREQUENCY OF OPERATION (GHZ)	UP TO 100	30-100	BEYOND 70	30-100	UP TO 20
CHARACTERISTIC IMPEDANCE RANGE ( )	20-125	40-120	26-	10-400	40-150
RADIATION LOSS	LOW	LOW	MEDIUM	LOW	HIGH
DISPERSION, MULTIMODING	LOW DISPERSION, POTENTIALLY MULTIMODED	LOW DISPERSION	DISPERSIVE, OFTEN HEAVILY MULTIMODED	DISPERSIVE, POTENTIALLY MULTIMODED	DISPERSIVE, MULTIMODED
ACTIVE AND PASSIVE DEVICE COMPATABILITY AND INTEGRABILITY 1) SHUNT MOUNTED	DIFFICULT	EASY	DIFFICULT	EASY	EASY
2) SERIES	EASY	EASY	DIFFICULT	EASY	EASY
COST	LOW COST	MODERATE COST	MODERATE COST	LOW COST	LOW COST

FIGURE 4

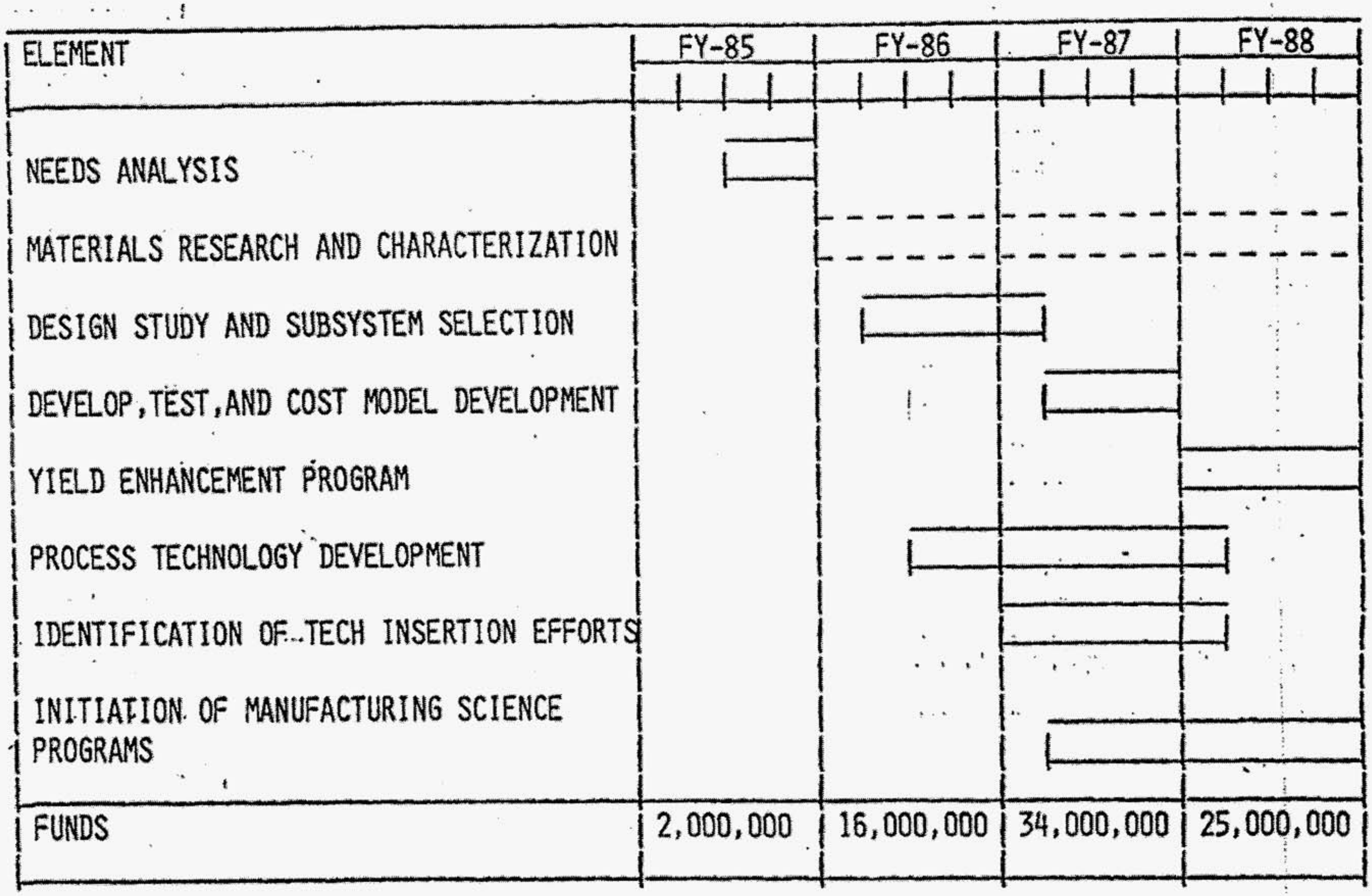

ELEMENT
FY-85
FY-86
FY-87
FY-88
NEEDS ANALYSIS
MATERIALS RESEARCH AND CHARACTERIZATION
DESIGN STUDY AND SUBSYSTEM SELECTION
DEVELOP,TEST,AND COST MODEL DEVELOPMENT
YIELD ENHANCEMENT PROGRAM
PROCESS TECHNOLOGY DEVELOPMENT
IDENTIFICATION OF TECH INSERTION EFFORTS
INITIATION OF MANUFACTURING SCIENCE PROGRAMS
FUNDS
2,000,000
16,000,000
34,000,000
25,000,000

FIGURE 5

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