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Robert E. Fulton and George C. Salley

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Hampton, Virginia 23665

IPAD: A UNIQUE APPROACH TO GOVERNMENT/INDUSTRY COOPERATION FOR TECHNOLOGY DEVELOPMENT AND TRANSFER

Robert E. Fulton
The George Washington University
NASA-Langley Research Center

George C. Salley
Structures and Dynamics Division
NASA-Langley Research Center

FOREWORD

The IPAD project was a very unique, exciting and rewarding experience for those associated with it. It combined the sciences of engineering, computing, manufacturing, management, and human behavior into a very intensive effort to first define a problem and subsequently pose a solution. It addressed the critical issues of engineering/manufacturing productivity at the core of an aerospace company's operation, namely how it develops its mainline products. IPAD generated strong opinions and attracted talented people. In the final analysis, it appears to have helped set directions on a national scale in a very complex area. This document attempts to summarize some of the issues and experiences which appeared important to the authors during these more than ten years with IPAD. One IPAD feature was that while many people had different views of IPAD, all who participated in it appeared to derive something from it. Undoubtedly, this report will be viewed similarly. Hopefully, however, the authors have captured the essence of lessons learned from the IPAD experience and this report will benefit others who might embark on such a venture. Finally, the authors would like to express appreciation to those ITAB members and observers and IPAD staff who contributed to this report by reflecting on their IPAD experiences and lessons learned and to Susan J. Voigt, former Asst. IPAD Project Manager, for her editorial assistance on the report.

Robert E. Fulton, IPAD Project Manager
George C. Salley, Deputy IPAD Project Manager

SUMMARY

A key element to improved industry productivity is effective management of CAD/CAM information. To stimulate advancements in this area, a unique joint government/industry project designated Integrated Programs for Aerospace-Vehicle Design (IPAD) was carried out from 1971-1984. The goal was to raise aerospace industry productivity through advancement of computer based technology to integrate and manage information involved in the design and manufacturing process. IPAD research was guided by an Industry Technical Advisory Board (ITAB) composed of over 100 representatives from aerospace and computer companies. The project complemented traditional NASA/DOD research to develop aerospace design technology and the Air Force's Integrated Computer-Aided Manufacturing (ICAM) program to advance CAM technology. IPAD had unprecedented industry support and involvement and served as a unique approach to government/industry cooperation in the development and transfer of advanced technology. This paper summarizes the IPAD project background, approach, accomplishments, industry involvement, technology transfer mechanisms and lessons learned from the project.

INTRODUCTION

For the United States to remain competitive in the world market, improvements in industrial productivity are essential. A key element to improved productivity is the advancement, introduction, and effective use of computer-aided design/manufacturing (CAD/CAM) technology. To stimulate advancements in CAD/CAM technology, a unique joint government/industry project, denoted Integrated Programs for Aerospace-Vehicle Design (IPAD), was carried out from 1971-1984 (fig. 1). The project goal was to raise aerospace industry productivity through advancement of technology to integrate and manage information involved in the design and manufacturing process. IPAD was carried out initially under the sponsorship of NASA's Office of Aeronautics

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and Space Technology; in 1982 the Navy's Material Command became a cosponsor. The program complemented traditional NASA/DOD research to develop aerospace design technology and the Air Force Integrated Computer-Aided Manufacturing (ICAM) program to advance CAM technology. Work under the IPAD project was done principally through a prime contract to the Boeing Commercial Airplane Company under the guidance of an Industry Technical Advisory Board (ITAB) composed of members of aerospace and Navy contractors and computer companies (fig. 2). ITAB quarterly reviews provided a regular forum for over 100 engineering and computer organizations to hold indepth discussions of critical CAD/ CAM issues which directed IPAD research and spurred internal company efforts. For its size IPAD had unprecedented industry support and involvement and provided a unique approach to government/industry cooperation in the development and transfer of advanced technology. Some of the IPAD reports, technical papers and software releases are included in references 1-96 and Appendices A-C. This report summarizes the IPAD program, from the perspective of its industry involvement, technical approach, programmatic approach and technology transfer. The report also includes a discussion of some of the lessons learned which should be addressed in future IPAD-like projects.

INDUSTRY INVOLVEMENT IN IPAD DEVELOPMENT

The definition of the IPAD project evolved over many years from a study and critique process that included extensive aerospace industry involvement. Two in-depth studies of the feasibility and possible forms of an IPAD system were carried out in 1972-73 by The Boeing Commercial Airplane Company and General Dynamics/ Convair (see ref. 1,2). The total cost of these studies over a 17-month period was $611,000. Each study contractor undertook a careful dissection of the vehicle design process to delineate those functions and tasks that can be beneficially supported by computer hardware and software and then defined the format and elements of a software system that could substantially improve the design process. They also assessed the impact of this IPAD system on company computer hardware requirements and on the performance of company staffs and evaluated its cost and benefit potential.

One company examined these questions in the context of design of three kinds of vehicles--a large subsonic transport, a supersonic transport, and a hydrofoil--and developed a comprehensive, detailed picture of the design process as a multilayered network of functions. The other examined intensively the tasks and interfaces of individual designers and groups and analyzed carefully the information flow in design. They considered the effects of the detailed constituent parts of the design process and extrapolated their experience with existing software systems to arrive at computer requirements, costs, and benefits of IPAD software. Both concluded that an IPAD system is feasible and will fit on existing computers. They arrived at software systems that differed in detail, but exhibited the same general characteristics and order-of-magnitude costs. Projected benefits included 25-90 percent time and 20-60 percent cost savings in design, better management visibility, and reduced risk and cost resulting from greater depth in early trade-offs, on-time designs, and fewer design changes during production.

Results of these studies were presented in four oral reports that were well attended by representatives of industry; for example, 83 industry representatives attended the final oral presentations. Following completion of the studies, the results were critiqued by teams from McDonnell Aircraft Company; Lockheed-Georgia Company; Grumman Aerospace Corporation; Rockwell International, Los Angeles Aircraft Division; Control Data Corporation; IBM Corporation; and Sperry Univac. These firms examined such questions as completeness of the studies, credibility of the proposed systems and projected development parameters, user acceptance, and government and industry roles. They expended significant effort over four months, employing 31 team members and about 100 part-time consultants. The critique reports (ref. 3) reveal a wide spectrum of views, but strong consensus that IPAD system developmet should proceed, should not include technical modules development which should remain largely the prerogative of industry, and should provide early delivery of software and user involvement. Because of the inevitable budget limitations, it was recommended that NASA limit its specific objective to production of a truncated, but "working", system.

Other early evaluations of the IPAD system concept included an Army-funded study by McDonnell Douglas Astronautics Company of its benefit potential for missile design (ref. 4) and a small NASA-funded study by Battelle Columbus Laboratories of its potential for non-aerospace application (ref. 5). In addition, the NASA Research and Technology Advisory Committee (RTAC) on Materials and Structures sponsored a colloquium of high-level aerospace managers at MIT on January 30-31, 1974, at which IPAD was examined and discussed. NASA prepared an IPAD "Prospectus" in February 1975 which set forth the plan for development, initial maintenance, and release of IPAD; for an Industry Technical Advisory Board (ITAB) to advise the IPAD contractor; and for a user-controlled organization to accept maintenance responsibility for IPAD software. NASA then conducted a survey of 41 aerospace companies seeking their commitment to become a member of ITAB during IPAD development; to evaluate IPAD software before it is generally released; and to financially support, in the context of a user-controlled organization, maintenance and improvement of IPAD software after its value to their company had been demonstrated. Two messages of a general nature were apparent in the company responses. First, support for the IPAD system concept and willingness to provide advice and counsel through the ITAB was very good from the large and medium airframe companies for whom IPAD software would be primarily tailored. Second, most companies prudently preferred to defer hard commitments beyond ITAB participation until they had a chance to assess results. A few companies specifically declined commitments to participate in the IPAD project, and these fell in two categories - either IPAD software did not appear to meet the needs of their particular design process, or they saw IPAD software aimed at design problems larger than their company activity. Several such companies wished to remain informed on IPAD progress with an opportunity to re-evaluate their position later.

Based on industry willingness to support the IPAD concept, NASA established an official IPAD project and an IPAD development contract was awarded through competitive procurement to the Boeing Commercial Airplane Company in 1976. The initial IPAD development contract with Boeing continued until 1984. A second (sole source) contract was awarded to Boeing in 1983 to support the continued IPAD project as well as any subsequent redirections. The official IPAD project was terminated in May 1984 and a smaller redirected effort is currently underway. The two Boeing prime contracts in 1976 and 1983 were with the Boeing Commercial Airplane Company with the bulk of the computer science support provided by Boeing Computer Services. Boeing also subcontracted with a number of aerospace and computer companies for various support tasks. The total Boeing contractual effort from 1976-1984 was approximately $ 23 M. Several small independent contracts were also awarded by NASA to such organizations as Kentron International, Information Research Associates and George Washington University to provide independent test and evaluation of IPAD products. This independent effort totaled approximately $3 M. In addition, government provided civil service staff and facilities directly assigned to the IPAD project totaled approximately $4 M. In total, the government support provided to the IPAD project from 1976-1984 was approximately $30 M.

ITAB OPERATION

The major focus for broad industry involvement in the IPAD project was through the Industry Technical Advisory Board (ITAB). ITAB was formed by the development contractor soon after contract initiation to afford industry the maximum opportunity for influencing the course of IPAD development. NASA invited ITAB companies to participate and the development contractor established the Board composition subject to NASA approval. Board members were typically high level executives having overview responsibility for company CAD/CAM related work. They were supported by senior technical staff where appropriate. ITAB was deliberately limited to 20 members which was felt to be a manageable but representative group. Observers, who were also permitted, began with a handful and eventually grew to over 80. The total Board, representing major U.S. aerospace and computer companies, met at approximately 3 month intervals. ITAB activities included review of planning and technical documents, critique of key development decisions, prioritization of IPAD activities, identification of demonstration programs, sponsorship of symposia, and evaluation of prototype software. As the IPAD software was released, ITAB member companies and other potential IPAD users aided in its evaluation and use.

The ITAB chairman was selected from industry and was supported by an ITAB executive officer on the contractor's staff but independent of and detached from the development group. The relationship between ITAB, the contractor (Boeing) and NASA is shown in Figure 3. This arrangement ensured direct communication between ITAB and the contractor for ongoing work while at the same time permitted strong communication with NASA at both the IPAD Project Office and at NASA Headquarters. A list of the final members and observers of ITAB is listed in Appendix D.

Operationally, a typical ITAB meeting met at different ITAB member sites, was composed of various status reports, and resulted in a series of recommendations to the contractor. Figure 4 outlines a typical meeting agenda. ITAB recommendations were drafted by an ITAB Control Board, finalized by ITAB members and meticulously tracked at subsequent meetings. Special ITAB audit committees were often established to conduct on-site technical reviews of Boeing work at specific major milestones. The work of these audit committees often provided the background for ITAB recommendations. Each meeting usually contained extensive technical discussions and varied opinions which provided an excellent forum for education, information exchange, and clarification of issues. The resulting recommendations provided program direction and recommendations were tracked to insure contractor response.

ITAB members were a highly participating group and assumed many responsibilities which significantly aided the program. Some of their efforts are noted on Figure 5. All member organizations and several observers actively participated in hosting meetings, technical exchanges and software or document evaluations. A few companies (such as those noted in the figure) contributed staff and/or products to support specific research or development tasks. Government funding was provided to support ITAB travel but these funds were never fully used by ITAB. The total ITAB effort was so extensive and pervasive that, if contracted, it would likely have equaled the government funds contracted for the IPAD technology development.

TECHNICAL APPROACH

The IPAD project was technically an engineering/computer science R & D effort to use computer technology to improve the integration of engineering analysis/design/manufacturing processes. The technical approach contained several phases, each of which was the basis for subsequent developments. The IPAD technical approach described here was not only useful in addressing integration issues but also could serve as a guide for other technology programs associated with engineering software development. The basic stages are summarized below with a brief description of results (see Figure 6 for an approximate schedule). The basic strategy was to dissect the aerospace design process, both from an engineering system viewpoint as well as for specific engineering scenarios, establish functional requirements for a future CAD/CAM system, conduct the preliminary design of a future system (denoted

"Full IPAD") which best meets all requirements, and develop prototype communication and data management software to meet some of these requirements (Figure 6,7). Close coordination was maintained with CAM technology being developed in the Air Force ICAM progam.

Feasibility/Definition Phase 1971-1976

This phase included two competitive contractual studies to investigate the potential need, approach and benefits from use of computers to support companywide integration of design (Figure 8). Each contractor worked independently for 6 months; evolving results were then presented at 3 month intervals to industry forums for review and critique. One study (Boeing) developed a systems viewpoint of the total work process for product development (ref. 1). The other study (General Dynamics) investigated a spectrum of design tasks from the viewpoint of individual disciplines (ref. 2). These two studies provided a gross characterization of the computer aided design capabilities needed to support future product developments as well as the benefits of such a capability (Figure 9). Such benefits included improved designer productivity, improved work environment, reduced design cost and reduced downstream manufacturing rework cost. Also considered was why NASA should lead such an effort (Figure 10). Industry reviews (ref. 3, 4, 5) of these and other IPAD activities (Figure 11) concurred with the results, recommended NASA proceed with IPAD and expressed willingness to aid development (Figure 12). This phase culminated in the selection of a single prime contractor, the Boeing Company, to lead subsequent phases.

Design Process Definition Phase 1976-1977

The goal of the IPAD project was to develop a future integrated CAD system. Since development of such a system was unprecedented, not only the requirements but also the approach to defining the requirements was unknown. The approach taken was to organize a multidisciplinary design team to conduct a systems analysis of the development process for a recent aerospace product, a Boeing 747 commercial air transport. The team prepared detailed logic charts of all stages of design, characterizing design levels, the major engineering steps within these levels, interfaces among steps, design iterations, and analysis and design computer programs used to support this work (Figure 13). The 747 study was subsequently expanded to consider other vehicles including a future advanced aircraft (SST), military aircraft (fighter), and a non-aircraft vehicle (hydrofoil).

The system analysis work was also broadened to investigate design interfaces to manufacturing and where major data exchanges take place (Figure 14). This aspect of the study was limited to design/manufacturing interfaces since the ICAM program was well underway to investigate technology associated with detailed manufacturing processes. The studies did, however, include an investigation of how an engineering development was managed through schedule and resource control, tracking and assessment processes. The above work (ref.9-11) provided a system level description of a representative aerospace design process, the first such description available in the literature.

The aerospace design process description was used to conduct an investigation of the detailed information flow through the design process. Charts were prepared for defining in detail the quantities and types of data flowing among the various design stages (ref. 12). Figures 15 and 16, for example, show the data flow associated with preliminary design of an aircraft fuselage frame. A complementary study was also conducted to identify the individual tasks engineers wanted computers to do and how engineers would like to interface with the computer (ref. 13). This work characterized and quantified the data flow through a design process, quantified the daily information work load on a company having several products under simultaneous development, and established a list of user interface capabilities needed by engineers to control a future integrated design process.

Requirements Definition Phase 1976-77

The design process definition phase provided the basis for development of a list of functional requirements for a future integrated CAD system (see Appendix A: Document D6-IPAD-70040-D). These requirements were compiled by a joint engineering and computer science team through a very demanding review and assessment process. In developing the requirement list, the effort focused on user need rather than the feasibility of satisfying a need. Great difficulty occurred in bridging the communication gap between the two different technical cultures of engineering and computer science. To help resolve this, each requirement was supported by an abstract of an acceptance test to determine if a requirement was satisfied. No requirement could be included if an acceptance test could not be conceived.

The requirements document was subjected to intensive review by ITAB and NASA staff and several major reviews were held. These reviews often caused major reworks to consider areas overlooked, correct deficiencies and clarify issues. The final requirements document (see Appendix A: IPAD Document D6-IPAD-70040-D) was prepared and edited by a 4-person technical team composed of a senior engineer and computer analyst from both Boeing and NASA working together on site for approximately one month. Figure 17 shows the number of requirements according to various categories. User interface and information access, transfer and management needs made up the bulk of the requirements. For example, the management of data required a demanding set of functions greatly exceeding existing software capabilities (Figure 18) and a typical company would require rapid access to trillions of words of design data (Figure 19).

Preliminary Design of a Future Integrated CAD System 1977-1978

Preliminary design of a future IPAD system was developed to meet the IPAD requirements. Software design was carried out through a top down approach coupling requirements to system design. This coupling was not always possible since there was not a one-to-one connection between specific requirements and software functions and since there was heavy reliance on distributed operating system technology not available. Ultimately, a level 3 preliminary design of this future advanced system was developed with down to third level components and with varying levels of further details for each component (see ref. 24 and Appendix A: Document D6-IPAD-70036-D). The resulting system denoted "Full IPAD" could be viewed as a general-purpose interactive integrated computer-aided design system developed to support engineering design processes. It would be built on the operating systems of a distributed, heterogeneous computing complex. Its primary function would be to handle engineering data associated with the design process. Full IPAD software would be installed by each company on its computers and used in a manner similar to vendor-supplied operating system software. The Full IPAD software would augment, rather than replace, existing operating system software. It would support the continuous design activities of a typical company mix of multiple development projects. The Full IPAD system would serve management and engineering staffs at all levels of design (conceptual, preliminary and final) and aid in the assembly and organization of design data for manufacturing processes.

The Full IPAD system would support generation, storage, and management of large quantities of data. Its capacity would only be limited by the computer hardware configurations selected by each company. The system would be used in a distributed computing environment having one or more central host computing systems and many remote computing systems. One such arrangement of Full IPAD components is given in figure 20. The number of terminals might be several hundred or more and may be distributed across the host and remote systems. The Full IPAD software would function on the computer complexes in use today by aerospace corporations, but would achieve its full potential on the computers in the next decade.

The functions of the three major IPAD software components illustrated in figure 20 are (1) executive software (IPEX) to control user-directed processes through interactive interfaces with a large number of terminals in simultaneous use by engineering and management personnel and to provide communications between computer hardware within and outside the IPAD distributed computing system; (2) data management software (IPIP) to provide a comprehensive, versatile capability for efficiently storing, tracking, protecting, and retrieving exceptionally large quantities of data maintained on multiple storage devices; and (3) geometry and graphics utility software to provide a wide range of capabilities for information and geometry creation, manipulation and display functions including design/drafting and interactive and display graphics.

Libraries within the data bases might include analysis/design computer programs utilized by various disciplinary specialists and extensive quantities of data. The analysis/design computer programs would not be part of the Full IPAD system, but would be provided by each company to form the complete design-software system; selected publically available technical programs might be included in IPAD releases to demonstrate capabilities. The data in the data base would include all official project information defining the characteristics of current baselines and alternative designs and their performance, as well as archival "handbook" information forming the technology base for company designs. Simultaneous access to the same baseline design information by all disciplinary groups would thus be possible. Temporary storage for design information being actively used by individuals or teams would also be provided.

A Full IPAD system would not be a hands-off "automated design" system and would not constrain company design methods. The quality of future aerospace designs generated in an IPAD environment would depend on the same primary factors as in today's design environment: creativity of designers, quality of technical staff, quality of analysis tools and design data, and coordination of design and manufacturing information. IPAD should also be a tool to improve manufacturing direct access to engineering data. While support for the manufacturing process was not a specific requirement for the Full IPAD system, it is believed that many manufacturing needs are met by the resulting system design.

A preliminary design of each of these above components was carried out to understand key elements, logic interfaces and scope required for development and/or technology advancement. Development of the total Full IPAD system was estimated in 1978 to be a high risk effort costing in excess of $100 M, and well outside of scope of an R & D effort. Two critical components which required major technology advances were IPIP and IPEX. After extensive reviews by ITAB it was decided to focus the next phase on development of prototype software to manage engineering data. While there was strong sympathy for IPEX, a distributed engineering operating system, it was felt that computer vendors, with greater resources, would continue to address this issue, and that there could be a higher payoff to engineering for the IPAD project to concentrate on advancement of data management technology.

Prototype Software Development 1979-1984

Under the guidance of ITAB, the IPAD project developed prototype computer software to meet many CAD/CAM information management requirements (see refs. 26-29, 40, 92 for overviews of technical accomplishments). Some of the basic requirements driving CAD/CAM systems development (refs. 48-57) include (fig. 21): (1) accommodate many different views of data from a variety of users and computing storage devices; (2) allow many levels of data descriptions to support a wide variety of engineering organizations and tasks; (3) permit easy changes in data definition as work progresses; (4) allow data to be distributed over networks of computers of various manufacture; (5) permit data definitions to be readily extended as needs arise; (6) store and manipulate geometry information; (7) embody adequate configuration management features; and (8) provide extensive capability to manage information describing stored data. The IPAD approach taken was to conduct appropriate research and develop prototype software for a future network of computers (refs. 58-59). Data structure models considered and their status in 1978 included heirarchical network, relational and three schema (Fig. 22). To provide the required CAD/CAM functionality, and yet meet software performance requirements, data base management would be staged at two or more levels with different software capabilities needed for both the local (user) level and global (project) level (fig. 23). With such a tiered data base management approach, current inconvenient file-oriented procedures (fig. 24) would be replaced in an IPAD environment by future procedures (fig. 25) where convenient user languages efficiently create, store, manipulate, access, and control information in accordance with CAD/CAM requirements.

Prototype software was developed under the IPAD project at both the local and global levels (Figure 23). A system denoted Relational Information Management (RIM) was developed for local-level data management. RIM is based on the highly flexible relational model which organizes and manages engineering and scientific information according to tables and relationships among tables. Its features include interactive queries, report writer, and FORTRAN interface. RIM was first operational in 1979 and is now a mature system (Fig. 26). In 1981, it served as a critical information management capability to support NASA investigations (ref. 60) of the integrity of 30,000 tiles on the space shuttle orbiter (fig. 27). The success of RIM in such evaluations led to its continued development and enhancement by government and industry. Over 300 copies of RIM (Fig. 28) were distributed by the IPAD project and a public Version 5.0 is available from COSMIC* for CDC, IBM, DEC, UNIVAC, PRIME,

*Computer Software Management and Information Center
112 Barrow Hall
University of Georgia
Athens, GA 30602

and Harris computers. Commercial organizations have continued to enhance RIM and now provide compatible RIM derivative software (e.g., BCS/RIM and MicroRIM) and associated maintenance and support for such software operational on a wide range of computers (from personal computers to super computers). Commercial versions of RIM are being used extensively by industry (refs. 61-64), and one version has been adopted by the Naval Sea Systems Command for use in its early stage ship design integration process. NASA used RIM as the common data management system (Fig. 29) to integrate several engineering disciplines through development and application of a prototype system denoted Prototype Integrated Design System (PRIDE) (ref. 94-95).

IPAD research has continued on development of a global data base management system denoted IPAD Information Processor (IPIP). The approach taken in IPIP is to provide the capability within one system to manage information composed of a wide variety of data structures including hierarchical, network, relational, and geometric. The IPIP approach is based on the concepts of ref. 28 and Document D6-IPAD-70036-D (Appendix A) and uses multiple levels of information formats (schemata) to permit unlimited reorganization of information as work progresses (fig. 30).

Each IPIP schema is connected to other schemata via a general-purpose mapping capability (language). It provides a new concept called structure processing (Figure 31) where an unlimited number of layers of data structures and interconnecting schema appropriate for different uses can be created on top of the basic data base. IPIP is a new concept, still in test and evaluation phases, and is currently operational only on a CDC computer. Its approach to management of geometric data together with nongeometric data is a unique concept which could be very important to future integration of design and manufacturing such as the application illustrated in Figure 32. A critical technical challenge in IPIP development has been to provide the high degree of engineering user flexibility and yet achieve acceptable response times. In late 1983, a test system (denoted IPIP version 5.0) which has average user responses for test problems of less than 0.2 seconds per data manipulation command was provided to selected ITAB organizations to support evaluations such as that illustrated in figure 33. One vendor (CDC) has established IPIP as an "as is" commercial product and is providing limited support for its installation and evaluation. IPAD results to date in defining CAD/CAM data management requirements and in developing prototype software have helped stimulate development of commercial CAD/CAM data management software (refs. 65-68), and several computer vendors plan release in 1984/86 of relational-type data management systems which address many of the CAD/CAM requirements identified in IPAD research. IPAD results have also helped stimulate infusion of data base management technology into university engineering research (refs. 69-71).

A critical CAD/CAM requirement not yet contained within any available or planned commercial data management system is the ability to efficiently manage geometry information as data in concert with other engineering data (fig. 34). Through use of its multischema capability, and the structure processing concepts, IPIP provided the first approach to management of geometry information within a data management system (refs. 48, 49). The IPIP approach provides software capability to create on top of the basic geometric data an information structure having an unlimited number of geometric descriptions (schemata). One geometry schema includes the evolving geometry/graphics standard, Initial Graphics Exchange Specifications (IGES). This IPIP information structure concept opens the door for convenient integation of geometric information with other types of information associated with a CAD/CAM development process (fig. 35). At the time of this report, an evaluation of the IPIP geometry concept is underway, and comparisons are being made with other approaches in which management of the geometric data takes place in a "geometry engine" outside a basic relational data base manager.

CAM Data Management Requirements Phase 1982-84

The IPAD requirements were continually revised as the subsequent development phases progressed but a major revisit to requirements definition occurred in 1982 triggered by Navy cosponsorship of the IPAD project as well as by a growing awareness of the need to address CAM data management requirements. This CAM requirements effort work built on earlier studies of manufacturing interaction with design (Figure 14), a limited study of the information flow of a sheet metal part (Figure 36) during fabrication, comparable studies by Grumman for three other parts (ref. 43), several ICAM studies, and a joint IPAD/ ICAM workshop in 1980 focused on CAM Data Management Issues. The results of these efforts were integrated into an assessment of the data base management requirements to support CAM (Fig. 37) and IPAD Document-70046 (Appendix A). At the time of this report, a Navy supported follow-on effort with the remaining IPAD team was continuing work to define CAM data management requirements and to develop prototype software and applications to test the CAM requirements and to correlate IPIP functionality with these requirements. Close coordination was also continuing between Boeing and ICAM studies such as the Product Data Definition Interface by McDonnell Douglas (ref. 42) and the Integrated Information Support System by General Electric (ref. 43).

IPAD PRODUCTS AND THEIR USE

Over its lifetime the IPAD Project produced a large number of products which were widely distributed to ITAB members, observers and other organizations. These products which were extensive in number took the form of technology reports, prototype software and technology exchange processes (Figure 38). Due to the nature of the products and the early release distribution process it is difficult to document their extensive use. Informal discussions indicate the IPAD technology permeated deeply into numerous organizations. Several unique concepts were developed on the IPAD project which were critically important to achieving a future integrated CAD/CAM capability. Figure 39 shows the approximate timeline for completion of some of the products. Some of the IPAD products and their representative uses include:

1. Description of an Aerospace Design Process and its interfaces to manufacturing

   Use: The aerospace design process description has been used by several companies including Lockheed Georgia (Figure 40) and Rockwell (Figure 41).

2. Requirements and methodology for defining future CAD/CAM system

   Preliminary design of a future integrated CAD system based on a unified data management approach

   Use: The requirements definition and full IPAD preliminary design work has been used by many computer vendors as a basis for their CAD/CAM products. For example, IBM acknowledges significant use of the IPAD requirements in definition of its CAD/CAM products; CDC's major CAD/CAM product ICEM (Integrated Computer Aided Engineering and Manufacturing) is based on IPAD requirements and the Full IPAD software preliminary design.

3. Relational Information Management (RIM) system which provided a relational data management system for engineering use

   Use: RIM is used at hundreds of organizations and is becoming a national data management standard, is embedded in company products at Mentor Graphics, ICARUS, EXXON, EXECUCOM; has spawned two new companies MICRO-RIM and RIM Technology to offer RIM-based products and services; and has formed the basis for a commercial software product BCS-RIM marketed by Boeing Computer Services.

4. Prototype Integrated Design System (PRIDE) which demonstrated the approach and benefit of a relational data management system and executive to integrate geometry, graphics and several disciplines to achieve a multidisciplinary computer-aided engineering capability.

   Use: The PRIDE system has served as the guide for several aerospace organizations in development of integrated engineering analysis systems based on RIM and other relational data base management systems.

5. Prototype future multischema Engineering Data Management System which encompassed in one system heirarchical, network, relational and geometry data structures

Use: IPIP has served as a baseline for advanced data management approaches and is being offered by CDC as a product denoted CDC-IPIP. Several vendors plan the release in 1984-86 engineering data base management systems based on relational and/or three schema approaches. A variety of approaches to management of geometry data is also under study.

6. Data networking approach for communication of data among heterogeneous computers

   Use: Networking software has been installed at several aerospace companies and was a prototype for several commercial networking products including Network Systems NETEX and CDC's LCN.

7. CAD/CAM standard activities to facilitate development of data management standards

   Use: IPAD has played a significant role in several national standards efforts including cosponsorship of the IGES effort to establish Initial Graphics exchange specification; IPIP Logical Schema Languages and Data Manipulation Languages were based on 1978 CODASYL Data Description and Data Manipulation Languages and RIM is becoming a standard for communication of engineering data among heterogeneous computers.

8. Unique Technology Transfer approach to speed use of high technology by industry.

   Use: The ITAB industry involvement mechanism has been used as a model for several major programs. For example, ITAB was specifically identified as a guideline in a November 1983 RFP for development of "Guidelines for Applying Computer Aided Engineering Systems to Generate Plant Designs" by the Electric Power Research Institute. A new Air Force program for engineering data management for logistics needs (Integrated Design Support System) also plans to establish an ITAB-like advisory board to guide its activities.

PRIORITIES FOR FUTURE CAD/CAM TECHNOLOGY DEVELOPMENT

There are many areas of technology which need attention to achieve the level of data base management required for integration of CAD/CAM activities in a major aerospace company. Some major priorities are noted here. A key data management requirement not yet commercially available is the ability to manage unified CAD/CAM information distributed across computers of different manufacture with the user flexibility provided by software such as RIM and IPIP. A typical company may have several different computers to support its combined engineering manufacturing activity; the addition of subcontractors introduces even more heterogeneity in computers.

Examples of recent high-technology developments include the NASA space shuttle (Fig. 42) and Navy advanced aircraft (e.g., Fig. 43), wherein major components were developed by many widely dispersed companies, each having different computer complexes. IPAD research has begun development of technology for distributed data management. The basic IPIP design was planned for a distributed complex, and the IPAD prototype networking software developed in 1980 provides high-speed (greater than 10^6 bits/sec) information transfer between CDC CYBER 730 and a DEC VAX 11/780; as noted earlier the latter has already been expanded by vendors into commercial products. IPAD research in 1984 investigated an initial distributed data management approach for a system composed of a CDC CYBER 835, an IBM 4341, and a DEC VAX 11/780, with each computer utilizing different data base management software (Fig. 44). Based on these and other studies ITAB, NASA, and the Navy identified critical needs for CAD/CAM related data management research over the next few years to include:

1. Development of distributed data management software capabilities
2. Development of executive software to control information management over a network of heterogeneous computers
3. Development of multidisciplinary analysis/design data management approaches for sequential and concurrent processing computers (Fig. 45)
4. Extension and evaluation of geometry data management software capabilities
5. Development of data management approaches to support expert engineering systems (Fig. 46)
6. Definition of the elements of expert systems technology to be utilized internally by advanced data management systems
7. Refinement and assessment of manufacturing data management requirements

A National Research Council report states (ref. 44): The use of computers in design and manufacturing offers the potential of an integrated information system that encompasses product planning, designing, manufactural engineering, purchasing, materials requirements planning, manufacturing, quality assurance, and customer acceptance. A single product definition data base containing an electronic description of the designed products that are being constructed or manufactured is a keystone to the successful utilization of CAD/CAM technology. The NASA/Navy IPAD project under the guidance of ITAB has helped focus unified government/industry technology development on this important national productivity need. A National Research Council study (ref. 96) has strongly recommended the IPAD effort be continued and that NASA use IPAD technology as a basis for an integrated CAD/CAM capability to support the space station program.

TECHNOLOGY TRANSFER MECHANISMS

Technology transfer is used here in the broadest possible context of ensuring that the appropriate technology is transferred to those that need it. The IPAD project in its totality was a major technology transfer mechanism and this technology transfer showed up in all facets of the project. There were, however, some major elements that should be highlighted as drivers to make the technology transfer process a success. IPAD research, for example provided ideas and focused attention on critical CAD/CAM integration issues which stimulated technology transfer among the triad of the IPAD team, computer vendors and aerospace computer users (Figure 47). A limited number of universities were also involved in the process. Thus IPAD research not only provided new technology but also was the catalyst for technology transfer between the users and producers of CAD/CAM integration technology. To facilitate this transfer, the effort was focused primarily around ITAB (Figure 48). To aid technology transfer NASA contractually required ITAB and Boeing work together as a team without NASA serving as mediator. NASA usually limited technical direction to situations where Boeing and ITAB could not resolve an issue. It turned out that NASA and ITAB usually had similar views on technical issues, however NASA views were not transmitted a priori to ITAB. The success of the ITAB/Boeing/NASA triad

(Fig. 49) was due partly to the contractural structure of the concept and partly to the committment of the leaders of the three groups. It was also facilitated by key Boeing staff, including technical submanagers, the ITAB Executive Officer and IPAD Program Support Manager who provided administrative and technical support to ITAB. After approximately one year of operation ITAB began to assume ownership of the IPAD project and its technology thrusts; this ownership lasted until the program's conclusion. The number of ITAB members and observers quadrupled over the project life and the group became active enthusiasts to facilitate CAD/CAM technology transfer through a variety of formal and informal mechanisms. ITAB was strongly opposed to ending the IPAD program because of its success as a technology transfer mechanism and because there were still many issues to be resolved.

PROGRAMMATIC PERSPECTIVE

Progammatically within NASA, the IPAD project had its genesis around 1970 with the Langley Research Center Director, Edgar M. Cortright who asked a technical team led by Richard H. Heldenfels, Deputy Director for Structures, to investigate whether computer technology could be used more effectively to support industry aircraft design processes. This initiative followed in the wake of NASA's successful development of NASTRAN, an advanced structural analysis software system and appeared to be an appropriate next step in computer applications to analysis and design. Figure 50 gives a chronology of major programmatic events.

Key people existed at NASA Headquarters (Dr. Leonard Harris), Langley (Dr. Robert E. Fulton) and Boeing (Dr. Ralph E. Miller, Jr.) who were experienced in finite element methods, interested in the next challenge in computer applications and saw the potential of computer technology to aid integration of analysis and design tasks. Two feasibility studies, noted earlier, helped provide program definition. The results of these studies were subjected to extensive critiques including a special programmatic workshop at MIT on January 30-31, 1974, attended by senior representatives from NASA, AF and industry. This workshop recommended IPAD be initiated but that the focus be on the core software capability such as executive and information management and that the applications programs be left to industry. There was great concern that NASA leave automation of design technology to industry but concentrate on core facilities to support that technology. There was a general feeling that existing vendor provided operating systems level capability was not satisfactory for engineering design and that expansion of that capability was needed by the aerospace industry.

A preliminary project plan was prepared in April 1973 which outlined the basic IPAD plan. This plan focused on development of a core composed of data management, executive and utility software and the utilization of application programs in the public domain. The total set of software would make up a future IPAD system. The phases of development included a software development plan followed by maintenance and operation plan. This plan had some similar ties to the plan for the NASTRAN program which was at that time in the maintenance and operation phase. The project was advocated and approved as a software development effort and was funded as a systems technology program in the OAST budget beginning in FY 75. Prior to final implementation and at the direction of Dr. Alan Lovelace, NASA OAST Associate Administrator, a prospectus of the proposed IPAD program was prepared in 1975 and sent to the chief engineering officer of most major aerospace companies to solicit their advice and support for the program. The response as noted in other sections was very supportive and final approval of NASA OAST to proceed was secured.

The effort was funded as a system technology program managed as the IPAD Project out of the R & T Structures and Materials Office at NASA Headquarters and the Structures Directorate at NASA Langley (see Figure 51). The basic elements of the Boeing contract are noted in Figure 52. On completion of the preliminary design phase for a Full IPAD it became clear that a future fully integrated CAD software system could not be developed for the resources anticipated for the IPAD project and that some redirection was required. ITAB and the IPAD Project Office held a major Preliminary Design Review in September 1978 and OAST held a major programmatic review in February 1979. As a result of these reviews, it was decided to redirect the IPAD effort toward development of a new software technology for engineering data management. Software development was concentrated almost exclusively toward IPIP development, a complex unprecedented data base management system. The original intent of an integrated software system was abandoned as being too expensive, inappropriate for NASA, and not the best use of the limited R & D resources. An advanced data management concept such as IPIP provided appropriate NASA research toward future advanced engineering software systems.

IPIP was in fact a very large undertaking for an engineering software effort but was felt to be a major high risk initiative needed to advance CAD/CAM data management technology. During development, there were several spin offs such as RIM, the networking software, PRIDE and various other systems software. The principal thrust, however, was IPIP and its associated technology. The nature of this single software system made it difficult to produce small early release products other than technology reports. As the complexity of the engineering data base management issues became more visible IPIP and RIM became the vehicle for evaluation of these issues. As a major programmatic event, RIM was successfully applied in 1980 to support the NASA space shuttle tile investigation and ultimately became a major commercial software product. The first version of IPIP became operational 1981 on a CDC CYBER computer in 1981. Subsequent IPIP versions significantly improved performance and added capabilities such as geometry data management (1982) and multiuser features (1983). These versions clearly proved the unique IPIP multischema data base management concept from a software implementation viewpoint.

However, due to the magnitude of the task and to limited resources, the IPIP versions at the completion of the IPAD project still lacked adequate performance and user features to support a reasonable engineering evaluation.

Industry through ITAB continued to show strong support for IPAD and one could see significant changes toward embracing IPAD concepts within the aerospace and computer companies working closely with IPAD. ITAB had far more priority items for development than available resources would permit and several companies provided direct support to the development effort. Throughout the program, coordination also continued with the AF ICAM program (Figure 53) and NASA/AF staff cooperated in programmatic issues and developing a Memorandum of Understanding. The Navy had shown continued interest in IPAD since its inception and in FY83 the Navy Manufacturing Technology program joined the IPAD program to fund increased activity in CAM data management needs (Figure 54). This led to a task to define CAM data management requirements and some limited investigations were carried out as noted earlier. As the IPAD program was ending in 1984, a NASA/Navy follow-on effort denoted Engineering Manufacturing Information System (EMIS) was being focused toward developing and assessing data management requirements to support CAD/CAM interface and CAM integration activities.

LESSONS LEARNED

The lessons learned from a complex project such as IPAD are many and difficult to document, particularly because IPAD was both a technology development and technology transfer program. Most of the lessons learned are contained in the attached list of references or in the professional experiences of the more than 500 CAD/CAM technical and management staff who had close contact with the program. The biggest lesson learned is that a project such as IPAD not only addressed important technical issues but it also served as a needed training ground for a significant percentage of the key people now responsible for integrated CAD/CAM and data management issues. The training of these technical and management staff through a focused research project activity was an excellent way to accelerate upgrading national expertise in a very complex technical area critical to improved productivity. Virtually all major CAD/ CAM and engineering data management efforts tracked IPAD and were influenced by its experiences. IPAD gave the CAD/CAM integration and data management issues national focus, credibility, direction, approach and specific technical contributions. The resources, while not adequate to achieve many needed technical accomplishments, appeared adequate to accelerate national attention, make selected technical accomplishments and achieve the desired technology transfer.

The government's (NASA/Navy) role in leading the IPAD effort and in providing the basic core funding was essential. Industry contributions probably matched the government funding and their informal cost sharing was essential to the viability of the project. The basic program plan was composed of (1) a flexible R & D prime contract with an aerospace company, (2) independent NASA in house plus contracted software evaluations, (3) the ITAB review and critique process and (4) a long term NASA commitment. This program plan appears to have been well conceived to address the required technology advancement and to speed technology transfer. The IPAD programmatic model is likely to be useful to other programs particularly those related to engineering/computer technology issues. The results of an ITAB survey on lessons learned together with some detailed observations on technical approach, programmatic support and technology transfer are summarized below.

ITAB Assessment Survey:

To provide insight into the lessons learned from IPAD a survey was made of ITAB members and selected observers. Table 1 extracts specific responses to the survey to gain insight into typical ITAB company reactions. The following lists the question (Q) asked and summarizes the ITAB response (R):

1. Q: How did IPAD help your company?

   R: IPAD helped through serving as an excellent national forum for key issues relative to integration and data management issues, largely not understood at IPAD's inception. It also greatly reinforced internal company efforts to address these issues lending both technical and management credibility to the issues.

2. Q: What results did you find most useful (either technical or management-wise)?

   R: The IPAD results found most useful included the design process methodology, IPAD requirements, and the CAD/CAM integration concepts which aided aerospace company efforts and influenced vendor products.

3. Q: What use did your company make of IPAD products? (requirements, prototype software, documents)

   R: Extensive use was made of the various technical reports and documents, RIM and the networking software. IPIP was useful to only a few organizations to provide advanced data base management insight.

4. Q: How effective was the ITAB process and why?

   R: The ITAB process was an overwhelming success and considered the "key to IPAD success". It was considered a "unique experience" as a technical advisory board which will have a long term impact due to the learning which took place and the contacts developed.

5. Q: Approximately how many of your personnel/organizations had contact with IPAD results?

   R: IPAD had direct contact with the core (10-50) technical and management leaders within each ITAB company who direct long term CAD/CAM technology. The overall number contacted in a second level of technical or management interfaces ranged well into the thousands overall.

6. Q: What could have been done better, and what were the major deficiencies?

   R: Areas which could have been improved included
   - more stable funding
   - projecting the image of a leading edge research effort rather than a software development project.
   - providing more visibility into applications and demonstrations
   - providing less emphasis on a large software product (IPIP) which had found little direct use at the time of project ended
   - concentrating technology developments on smaller modules, which greatly increase both probability of success and technology transfer
   - providing additional emphasis in such critical issues as standards, microcomputers, distributed data management and geometry data management

7. Q: Any other technical or management issues you think appropriate to comment on.

R: A general observation was that there was "no question IPAD significantly altered the collective opinions of a surprising number of decision makers,"that IPAD was an "excellent program for its times" and that they were "sorry to see momentum halted when industry needs data management research."

Technical Approach Issues:

Technical issues include both the concepts involved in the work and the approach to accomplishing the technical work. The unique technical concepts developed by IPAD are noted earlier in the report and documented more fully in the numerous references. Some lessons learned from the technical approach include:

1. Engineering and computer science are not only different disciplines but in some respects are different cultures; conflicts between the two groups are likely and should be anticipated. Within the IPAD team there was often a steady conflict between engineering and computer science on the goals of the project, requirements, software development approach, quality of the products and communication meanings. At the beginning, IPAD engineering management did not understand computer science, software development concepts, the differences between applications and system programming, and software terminology. Likewise, IPAD computer management did not understand engineering design, computer-aided requirements, the need for tutorials and demonstrations, and terminology. Each group had a different view of the research concepts required from such a project.
2. Software projects often have a continuous and high turnover in technical staff. The IPAD rate of 30+% per year caused difficulty in maintaining staff stability and competence sufficient to develop a large prototype software system such as IPIP. Use of a self documenting development language (PASCAL) may have been a salvation in accomodating this. A highly tuned configuration management system to support software and document development had to be established and was essential to the project.

3. A relatively new development language (PASCAL) can also be a major deterrent to software development. While PASCAL appeared to be a good technical base for system development, PASCAL support software was not sufficiently mature at the inception of major coding. Compilers, development utilities and resident expertise was not readily available which greatly affected code quality and productivity. A "machine independent" language was an important IPAD development requirement and PASCAL was the best of a poor set of alternatives at the time; the FORTRAN version available in 1978, appeared to be a worse choice to support the IPAD system coding anticipated.
4. The conflicting goals of "research" software versus "useful" software provides a continual problem for an advanced engineering software research project. Engineers want useful software products and computer scientists wanted to develop new concept software. With IPAD it was difficult to find a middle ground of new high risk computer science concepts which, at the same time, could be be embodied into useful prototype software. The term "useful" was often difficult to define.
5. In managing an advanced engineering computer systems project the principal leadership should have expertise in both the engineering need and computer systems development. It is usually impossible to get both capabilities in one person. The IPAD choice at both NASA and Boeing was for the program manager to be an engineering manager and the deputy program manager to be a software development manager. Experience in critical areas such as large advanced prototype system development or advanced data base management concepts was difficult to find within an aerospace company. IPAD project accomplishments suffered until this required experience could be found or developed from the project staff. More use of subcontractors for specific critical skill areas might have been useful.

6. Software engineering and top down design is a good concept but it has to be significantly modified in a research effort leading to prototype system software. After preliminary design is carried to the third or fourth level, coding should begin on prototype software in parallel to help refine the design. Such prototype coding is needed to clarify concepts, stimulate staff enthusiasm, and show substantive progress. Sometimes such code also turns out to be highly useful. For example, RIM was originally a data base management prototype developed internally within the project to understand relational concepts; it was rewritten several times before it became truly useful and was productized. The IPAD team carried out requirements definition and preliminary design for two years prior to beginning any coding and the first software products began to show up 3 years into the project. This was too long and some prototype coding should have begun no later than one year into the project with products beginning to evolve during the second year.

7. Performance of software is an important element and should be considered in the early stages. The initial software should have moderate performance, if possible, but hooks should be built into the software for performance probes to support subsequent performance assessment studies. Engineering users will not seriously evaluate software unless the performance is reasonable; thus performance thresholds need to be identified and met. The software design team needs to understand the role and importance of performance analysis and the required target levels. RIM was not evaluated outside the development team until its performance was acceptable. IPAD discussed the importance of performance in the IPIP design but, because of the complexity of the IPIP design, serious incorporation of performance issues was delayed until an initial system was operational. Earlier incorporation

of features to reduce known performance deficiencies in the system would have ameliorated the intensive performance enhancement effort that ensued and facilitated IPIP engineering evaluation.

8. The technical plan for a software research effort should aim toward modular products and for selected ones to be operational within two years. Selected software products which are low risk together with technical reports should be developed with a portion of the resources. Simultaneously a more expensive high risk set of software should be started so it can be in the pipeline for a much longer time. The basic technical plan should have a mix of modules composed of low and high risk products to be completed over a near term and longer term schedule and should allow for some failures as well as successes.

9. The contractual organization responsible for prototype software development should probably be separated from the research organization. While this may be in the same parent contractor, the research and development phases need to be separately organized, budgeted and managed. The research group should be required to document concepts or designs sufficient to support the prototype development, whether done by the development group or by an independent group. There is a natural tug between the research and development efforts both in terms of technical talent and available resources. In IPAD, research activities were often intertwined with prototype development and it was often progammatically unclear how resources were being distributed or how funding reductions impacted the two areas. Separating the two activities into two well defined organizationa would have helped put more discipline into documenting the research concepts and into conducting software development. It would have also helped clarify the status of the respective research or software products and identify how funding

reductions and schedule slippages impact other work. If funding falls below a critical level, development of products is then terminated and the documented research concepts and/or designs serve as program products.

Programmatic Support Issues:

The planning, advocacy, accomplishment and coordination required to ensure the funding of a program such as IPAD has many issues. Since research funds are scarce and the government is sensitive to negative criticism, a few detractors of a program can sometimes override the support of many. The fact that IPAD had a relatively long funding life for such a research project suggests there was good support. At the same time it went through several funding crises during its life and funding support had begun to erode near the end with its conclusion being relatively abrupt. Some programmatic support issues include:

1. A program needs a strong focused user advocacy group. IPAD's long life was due primarily to the existence of ITAB whose members met regularly with senior NASA/OAST staff. The ITAB companies also had representation on several NASA Advisory Committees. The strong support by ITAB and the IPAD benefits to them is seen in the ITAB assessment survey discussed earlier.

2. Project goals need to be clearly understood and regularly reviewed by those who have programmatic influence. After completion of the preliminary design phase, IPAD shifted from a development effort to research and this shift was not widely visible. Thus there was often a programmatic misconception of IPAD project goals as to whether the focus was on development of new research concepts in computer applications or on development of useful software for industry similar to the NASTRAN experience. Except for a few farsighted groups, the bulk of industry (including many ITAB members) viewed IPAD as a development effort aimed at a working system.

3. The image of an engineering software project and the resulting products need to be clearly defined and understood; deliverables should also begin in 1-2 years. Since IPAD was viewed by many as a system development effort rather than focused research, the lack of near term deliverables which could be evaluated was a programmatic deficiency. IPAD aimed toward a large prototype software product (IPIP) but the resulting research funds were incompatible with that goal. While the innovative IPIP was a bold strategy, it could be argued for programmatic reasons that a better project plan would have been to focus on several small software products to be spun off at 6 month to 1 year intervals for application by NASA and industry. The plan could also have included coupling the application to an ongoing NASA project. This strategy, while programmatically attractive, would likely never have yielded the new data base management concept in IPIP. And a modular IPIP did not appear technically feasible. The modular strategy would also have required scarce resources to be devoted to installation and demonstration in potential user sites since voluntary installation of major software modules did not prove viable except for RIM. Neither the enthusiasm of ITAB members, the critically important insight being derived by ITAB companies nor the numerous technical documents were sufficient to maintain program support. More quantitative software products such as RIM and validated applications outside the project are needed to maintain programmatic support for an engineering software program.

4. A research program emphasis needs to be compatible with the appropriate funding program office. While IPAD enjoyed good support, it did not have a natural home within the OAST program offices. IPAD technology cut across several disciplines and had an especially strong computer science application emphasis. It was managed within Structures and Materials office and

was strongly supported within that office. At the same time major CAD/CAM or computer science applications programs had little precedence within NASA and computer systems technology required for IPAD was not widely understood by senior NASA OAST management. IPAD naturally had programmatic difficulty wherever there was a change in OAST leadership.

5. It is useful if government in-house engineering programs benefit from a software technology effort. For example, NASA's in-house research staff primarily conduct basic research in the traditional engineering disciplines and could see little near term-benefit to their activities from IPAD's CAD/CAM data management thrusts. Their IPAD support was therefore mixed since significant scarce resources were going to industry in an area foreign to traditional NASA research. Better in-house support might have been achieved through near-term IPAD deliverables which benefited in-house programs or through use of some IPAD funds to cost share in-house CAD applications. While such an approach may divert resources away from other important areas, it can enhance programmatic support and strengthen needed applications.

6. Large contractual research programs need an appropriate contract vehicle to enhance, not inhibit conduct of research. The IPAD contractual arrangements of a flexible cost plus award fee prime contract was a very efficient way to conduct the program. This approach provided the capability to implement major changes in technical direction in response to ITAB reviews within a few days after a decision had been made. It also permitted appropriate subcontracts to be selected to conduct specialized and/or unplanned tasks as work progressed. The basic IPAD contract had 108 contract modifications from 1976-83, the majority of which were the result of technical issues which arose from the evolving research experiences.

7. It is important to recognize that in a computer applications research environment, funding sources typically speak in two different voices relative to program content. In the planning phase, a research voice seeks high risk innovative computer technology research beyond that which industry would pursue on its own. Funds provided are usually limited to that sufficient for proof-of-concept software to test ideas. During the development phase, however, a product voice arises which wants useful software products, their schedule for completion and an identification of who will or has used them. For IPAD the concepts embodied in the technology reports as well as in the unprecedented IPIP data base manager were high risk innovative data management issues which may have long term impact on technology. This work, however, did not provide the programmatic benefit of the near term development, use and subsequent commercialization of RIM. Thus, even in a long term far out research effort, engineering groups want useful products at reasonable intervals. This makes development of a large high risk engineering software system virtually prohibitive.

Technology Transfer Issues:

Technology transfer is the process through which the technology related to the program is transferred to those who need it. It can occur at one level such as between the government sponsored effort and users or at another level among the variety of groups following the effort. IPAD had technology transfer at many levels and across many groups. Some issues in technology transfer are as follows:

1. The ITAB review and critique process was an excellent technology transfer mechanism for an engineering software technology program. The reviews provided technology transfer between the development team and the ITAB members and their associated technical and management staff. It also

provided technology transfer among the ITAB members. There was, however, a long startup time before the process became effective; in IPAD it was about two years before real communication occurred between manufacturing, engineering, and computer representatives.

2. Inclusion of both users and commercial computer vendors on ITAB provided an important long term technology transfer result. While ITAB focused on officially communicating to the development team, they unofficially communicated with each other. Engineering users shared their technology status, plans and needs and conveyed their united needs to the vendors who could provide future IPAD-like commercial products. The impact of this on vendors could be seen by the dramatic change in vendor products over the IPAD life in providing capabilities responsive to many IPAD requirements. IPAD impact might have been enhanced through inclusion of more third party vendors on ITAB who marketed data base management software; the vendors, however, were not a viable force in 1976 when ITAB was established.

3. The actual costs for good technology transfer is high and may approach the cost of developing the technology. NASA spent about 10% of the program funds directly for technology transfer but the ITAB process allowed the companies to share in the cost and responsibility. The practice of providing travel costs where needed for ITAB was prudent even though it was not used consistently. Having an independent focal point at Boeing for ITAB interface, software and document dissemination and user support provided a drain on scarce research funds but was essential to technology transfer and facilitated the ITAB process.

4. Use of NASA's existing formal organization for document and software dissemination do not appear to be appropriate technology transfer vehicles for an ongoing research program when the products are still in the prototype

development stage. For IPAD products, it was important to provide working documents and initial prototype software to a small group of interested users to obtain rapid evaluation feedback. When documents and software (RIM) were sufficiently complete, these were sent to NASA distribution houses such as COSMIC* and NTIS** for subsequent dissemination.

5. The ITAB process not only impacted technical work in ITAB member companies but, perhaps more important, it impacted senior management directions. IPAD focused on technical issues pertinent to integration of computing, design and manufacturing. These three activities are basic to how a company does business and usually the responsibilities of separate major segments of an aerospace company, each with its own provincial view. The external government led IPAD project and the ITAB process had significant impact in bringing these segments together. The authors' on-site assessments of several aerospace companies in 1984 indicated that ITAB company management have a more advanced perspective of CAD/CAM integration issues than their counterparts in non-ITAB companies.

6. The NASA FEDD (For Early Domestic Dissemination) policy impacts technology transfer to U.S. companies but not necessarily as desired. Because of the importance of IPAD technology, IPAD was required to conform to the FEDD policy. Visits by the first author to Europe in 1983 indicate the FEDD policy appeared to delay dissemination of IPAD technology to key European technical groups. Visits to Japan in 1982, however, suggested the FEDD

* Computer Software Management and Information Center
112 Barrow Hall
University of Georgia
Athens, GA 30602

**National Technical Information Service
Port Royal Road
Springfield, VA 22161

policy heightened Japanese interest in CAD/CAM integration, made it more credible and thus may have helped accelerate Japanese internal activities. Visits to non-ITAB companies or organizations in the United States during the 1980's indicate the FEDD policy inhibited spread of IPAD technology within the U.S. For example, the computer science and university research community were often unfamiliar with the IPAD technical contributions since their medium for communication is the open literature and technical journals. The technology transfer to these groups was not as successful as might be desired due to the FEDD policy and these groups could have benefited greatly by ITAB technical details. Thus IPAD had a tight relationship with a key set of ITAB organizations but many other U.S. computer-related groups knew little of IPAD research contributions. Furthermore, the commercial exploitation by U.S. companies of IPAD technology was inhibited because such companies often market worldwide and do not draw demarkation lines between their U.S. and foreign products. Legal counsel for one ITAB member (IBM) severely limited company review of some IPAD documents. For another ITAB member (DEC) legal counsel did not approve of document reviews. IBM's concern was that it could not insure that documents would not fall into the hands of non-U.S. citizens who were working for IBM. This problem was ultimately resolved by NASA providing IBM some latitude in the review process. DEC's concern was that knowledge by their staff of IPAD concepts might ultimately require public release of company products that were similar to IPAD products. While this was not truly a FEDD issue, the FEDD restrictions interjected extensive legal scrutiny of the results and led to legal opinions which might normally not occur for research results. Thus it is unclear whether the net effect of the FEDD policy achieved its intended purpose of providing early domestic dissemination and inhibiting foreign exploitation. Rather the ITAB process itself appeared more effective than FEDD controls as an aggressive mechanism for early dissemination of preliminary results.

7. An engineering computing research effort has the potential for computer vendors to share in the research and in so doing to facilitate technology transfer and reduce hardware costs. Furthermore, the best technology transfer to vendors seems to occur if the prototype software is operational on the vendors' hardware. Although seemingly redundant, multiple vendor implementations of software is needed for effective technology transfer. ITAB also provided an excellent arena for engineering and computing representatives to meet and informally discuss critical CAD/CAM issues. Vendors could also contribute to the program via a prime contractor rather than directly to the government. Vendors indicated that due to competitive threats of industry collusion, etc., only the government could effectivly organize an ITAB-like body and that industry's best interests were served by the continuance of IPAD.

8. There is a critical mass of effort below which an ITAB-based technology transfer effort is not effective. For IPAD, the ITAB representatives indicated on several occasions that a $5 M per year level government funded program was needed to make sufficient progress to retain ITAB's interest. When the government funding for IPAD dropped to around $3 M per year, the accomplishments came too slowly, program interests began to wane and its termination became a foregone conclusion.

CONCLUDING COMMENTS

A unique joint government/industry project designated Integrated Programs for Aerospace-Vehicle Design (IPAD) was carried out from 1970-1984 with the goal of raising aerospace industry productivity through advancement of computer based technology to integrate and manage information involved in the design and manufacturing process. IPAD research was guided by an Industry Technical Advisory Board (ITAB) composed of over 100 representatives from aerospace and computer companies. The project complemented traditional NASA/DOD research to develop aerospace design technology and the Air Force's Integrated Computer-Aided Manufacturing (ICAM) program to advance CAM technology. IPAD had unprecedented industry support and involvement and served as a unique approach to government/industry cooperation in the development and transfer of advanced technology.

The IPAD project has made several contributions to CAD/CAM technology such as (1) development of methodology to integrate engineering activities, (2) definition and design of a future integrated CAD/CAM system, (3) demonstration of the need for relational data base management for engineering and (4) development and demonstration of new concepts for distributed data base management. It also demonstrated a unique and highly successful approach to joint industry/government cooperation in achieving technology transfer in an advanced engineering computer sciences research program.

The lessons learned from such a project suggest the basic IPAD program plan was appropriate and successful for the combined goals of technology development and technology transfer. A retrospective assessment identified issues which should be addressed in future IPAD-like projects including:

(1) the natural conflict between engineering and computer science disciplines,

(2) the high turnover rate in computer related technical staff,

(3) the conflict between research oriented and useful software products,

(4) the benefit of an involved user group from a programs inception,

(5) the need for a clear image of a software program throughout its lifespan,

(6) the importance of small modular useful products completed at regular intervals throughout a program's life,

(7) the critical need for and cost of technology transfer as a planned part of an engineering software research program.

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Appendix A: Boeing IPAD Project Documents (NASA Contract NAS1-14700)

Document No.	Document Title
D6-IPAD-70000-P	Documentation Plan
D6-IPAD-70001-P	Management Plan
D6-IPAD-70002-P	Technical Plan
D6-IPAD-70003-P	User Involvement Plan
D6-IPAD-70005-P	Configuration Control Plan
D6-IPAD-70010-P	Reference Design Process
D6-IPAD-70011-D	Product Manufacture Interactions with the Design Process
D6-IPAD-70012-D	Integrated Information Processing Requirements
D6-IPAD-70013-D	IPAD User Requirements
D6-IPAD-70015-D	IPAD Geometry Standards
D6-IPAD-70016-D -1,2,3	First-Level IPAD User Requirements, Vols. 1,2,3
D6-IPAD-70020-M	IPAD Executive Summary
D6-IPAD-70035-D	Product Program Management Systems
D6-IPAD-70036-D	Vol. 1 IPAD System Design Overview
	Vol. 2 User Interface Preliminary Design
	Vol. 3 IPAD Evaluations and Alternatives
	Vol. 4 IPEX Preliminary Design
	Vol. 5 IPIP Preliminary Design
	Vol. 6 IPAD Graphics
	Vol. 7 IPAD Geometry
	Vol. 8 User View of IPAD
	Vol. 9 IPAD Level II Design
D6-IPAD-70038-D	Manufacturing Data Management Requirements
D6-IPAD-70040-D	IPAD Requirements
D6-IPAD-70046-R	Guidelines for Management of Manufacturing Information

Appendix B: Boeing IPAD Technical Reports
(NASA Contract NAS1-14700)

Originating WBS No.	Report No.	Reporting Title and Description
3.2.1	1	"Definition of IPSR Processes." A list and associated description of services needed by IPAD tasks.
3.2.2, 3.2.3	2	"IPSR Interface Definition." Definitions of IPAD task to IPSR interfaces; for IPR functions.
3.4.1, 3.4.3	3	"Definition and Specification of Interfaces for Data Collection." Method of collection for system performance.
3.5.1	4	"Report on Study of Existing Network Communication Protocols." Recommendations for use of an existing protocol or designing one for IPAD.
3.5.1	5	"Recommended IPAD Network Communication Protocols." A preliminary protocol specification.
3.5.1	6	"Final Specification of IPAD Network Communication Protocols." A preliminary protocol specification.
3.5.2	7	"Message Interface Definition." Message transfer interface and applicability to IPAD functions.
3.5.2	8	"Connection Interface Definition." Connection interfaces by IPAD tasks and method implemented.
3.10-1	9	"An Overview of Distributed Computing in the Engineering and Manufacturing Environment." Four basic topics: objectives of distributed processing, components of distributed processing, work stations, and possible distributed processing architectures.
3.10-2	10	"Functional and Design Alternatives for Distributed Data Base Management Systems in the Engineering and Manufacturing Environment." Alternatives that should be considered in designing a distributed data base management facility.
4.2	11	"Design and Implementation of Geometry Processing in IPIP." Application of IPAD DBMS concepts to the storage and manipulation of geometric data. The features of IPIP designed to support the management of geometric data are discussed. The functional capabilitis for manipulation of geometric data are described in terms of IPIP DML commands and the schemas developed for geometry.
4.2.2	12	"Literature Search and System Survey Distributed Computing." Research and recommendations on distributed data processing.

5.2.1	13	"Interim Report on Integration of Program and Data." Results of studying the use of a data management system with engineering application programs including sample engineering scenarios.
5.2.4	14	"Protocol Specifications for Integration Programs Into IPAD." Documentation of procedures, sample programs, and scenarios showing full integration of user-written programs using IPIP.
5.4.4	15	"Interim Report - Geometry Data Management." Description of the procedures and data structures used in the RIM prototype geometry task.
5.4.5	16	"Geometry Multiple Representation." Discussion of the canonical forms used in the RIM prototype work and associated ANSI transformations for these entities."
6.1.1	17	"Report on NOS Model (EX IPIP)." Results of performance modeling analysis of IPAD prototype work and associated ANSI transformations for these entities.
6.1.1	18	"Report on IAS Model (EX IPIP)." Results of performance modeling analysis of the IPAD prototype on the DEC PDP 11/70 using IAS and recommendations for changes to the IPAD prototype, IAS or the host computer.
6.1.1	19	"Report on System Design Evaluation." The final report on the evaluation of the IPAD prototype. It will contain quantitative results of throughput, performance, and component utilization analysis. It will identify discrepancies between the system and the requirements for first-level IPAD. It will provide quantitative descriptions of the host capabilities required and make recommendations for changes to host hardware and software.

Appendix C: IPAD Prototype Software Releases

Release 0.0:
IPAD Integration Prototype System
Prototype GRTS (RG library)
Patch II display (RD library)
Patch II user interface (RU library)
IPAD integration prototype:
- AD-2000 postprocessor to RIM
- Finite-element modeler
- Preprocessor to ATLAS and SPAR
- Postprocessor to ATLAS

RIM II
GPGS
AD-2000 (PDP 11/70 - IAS, VAX/VMS)
Pascal compiler
CDC/DEC communications package
SPAR
ATLAS

Release 1.0:
Overview
Release 1.0 provides the fundamental data management capabilities and the internal communications facility for the CYBER. It can be used to demonstrate fundamental data processing capabilities of IPIP and make an assessment of the effort required to install the system software. Release 1.0 may only be used with the application that is delivered with it.
This release contains the following functional subcomponents:
- IPIP data manager, record processing
- IPEX service for data transformation between CYBER and the network standard
- IPEX CYBER host service access as required
- IPEX CYBER intrahost communications
- CYBER Pascal compiler
- GPGS
- IPIP demonstration program
- Installation program

Release 2.0
This release contains all of release 1.0 and the following functional components:

- DATA definition language compilers
- CYBER data manipulation precompiler
- Application module 7
- AD-2000, version 0.0
- ATLAS
- SPAR
- Installation instructions

Release 2.5
This release is the same as version 2.0 but with improved performance.
- Improved performance
- Record processing DML extended
- Preruntime binding
- Complete demo script-no restrictions
- Total SPRs installed since version 2.0: 159
- Updated user instructions
- Updated instruction manual

Release 3.0
This release contains all of version 2.0 plus communications and geometry to support IPIP.
- Network product
- IPIP record processing
- Multilevel schema
- Program bind
- Schema bind

Release 4.0
Version 4.0 IPAD product supersedes and replaces previous versions, supports geometry (points, lines, arcs, and objects). Performance is improved over past versions with less core required for IPIP and faster processing.
- IPIP
- IPIP compilers
- GPGS
- Installation, test and usage instructions

Release 5.0:
Software
Version 5.0 software was released in two versions: IPIP multiuser, multithread version and a single user version (DM/SU). Both versions offered improved performance over previous versions and included geometry, Interactive Query Facility (IQF) and IGES translators. Network software and test progams were also released.
- Data base manager:
  - IPIP
  - DM/SU
- Network product
- Interactive Query Facility (IQF)
- IGES translators:
  - GPGS
  - Pascal
- Application programs (test cases)
- Comprehensive CCL procedures for system control

Appendix D: Industry Technical Advisory Board (ITAB) (1984)

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Mr. George H. Kuper	National Research Council
Mr. Jeff Kurn	Hewlett Packard
Mr. Mike Kutcher	International Business Machines
Mr. Pierre Laberge (M)	Univac Corporation
Mr. Orville M. Langdahl	Boeing Computer Services Company
Mr. Richard S. Lawson	Tool and Tape
LTC Lanse M. Leach	U. S. Army
Mr. Men-Ching Lee	Brown and Root, Inc.
Mr. L. A. Lemmerman	Lockheed Corporation
Dr. Lloyd Lemn	Pentagon
Mr. Georg M. Lanz	McDonnell Aircraft Company
Dr. R. S. Levy (M)	Fairchild Republic Company
Mr. C. R. Lewis	General Motors Corp.
Mr. John Lewolt (M)	Lockheed Corporation
Dr. David Loendorf	Duke University
Mr. Henry Loshigian (M)	Grumman Aerospace Corporation
Mr. R. H. Lovdahl	Todd Pacific Shipyards Corp.
Mr. Seaforth Lyle	Banyan Systems Incorporated
Mr. F. Y. Lyon	Rockwell International
Mr. Ken Mannin	Decoto Aircraft Inc.
Dr. James W. Mar	Massachusetts Institute of Tech.
Mr. Alan T. Matsumoto	Boeing Computer Services Company
Mr. H. G. McComb	NASA
Dr. R. R. McCready	Vought Corporation
Mr. John W. McInnis	U. S. Navy
Mr. Donald R. McMorrow, Jr.	Ford Aerospace & Comm. Corp.
Mr. Donald D. Meyer	Boeing Comm. Airplane Co., IPAD Staff, Ret'd.
Mr. J. C. Mitchell (M)	Rockwell International
Mr. Wendell D. Mock	Rockwell International
Mr. W. T. Moody (M)	Cessna Aircraft Company
Mr. R. C. Moore	Newport News Shipbuilding
Mr. Milton Mortan	Auto-Trol Technology Corp.
Mr. Charles P. Moshier	Boeing Computer Services Company
Mr. R. L. Motard	Washington University
Ms. Pat Mullin	Robert Sayles Associates, Inc.

NAME: (M)=Member	Company
Mr. Bob Mullings	Northrop Corporation
Mr. Ray Neal	Vought Corporation
Mr. Phil Ness	Boeing Aerospace Company
Mr. R. K. Neumann	Garrett Turbine Engine Co.
Mr. E. North	Circuit Tools Inc.
Mr. Bryan Noton	Battelle Columbus Laboratories
Mr. David A. O'Keefe	Lockheed Corporation
Mr. Robert H. Page	Texas A&M University
Dr. John H. Painter	Texas A&M University
Mr. Curt Parks	General Dynamics
Mr. Melvin Platt	Northern Research & Eng. Corp.
Dr. O. R. Plummer	University of Missouri
Mr. J. Presti	Boeing Computer Services Company
Mr. Michael Propen	AVCO Lycoming Division
Mr. Harry E. Richter (M)	International Businness Machines
Mr. Derek Robb	Cray Research, Inc.
Mr. Tom Rogers	Hewlett Packard
Mr. Tom Rooney	Northrop Corporation
Mr. Richard M. Russell	Cray Research, Inc.
Mr. F. R. Saenger	U. S. Navy
Mr. George C. Salley	NASA
Mr. Arnold J. Savitt	GTE Products Corp.
Mr. Dennis Schibonski (M)	Network Systems Corp.
Mr. Brimmer R. Sherman	Control Data Corp.
Mr. Juris Skujins	Control Data Corp.
Mr. Carl O. Smarling	Amdahl Corporation
Mr. W. G. Smiley	Hughes Aircraft Company
Mr. Maurice Smith	Bendix Corporation, Kansas City Div.
Mr. Michael E. Smith (M)	Northrop Corporation
Mr. Wendell Stephens	NASA
Mr. Robert J. Stewart	Gulfstream Aerospace Corp.
Mr. Warren A. Stewart	Technology Development of Cal.
Mr. W. J. Stone	Lockheed Corporation
Mr. Marvin Sussman	Borg-Warner Corporation
Mr. Warren E. Swanson (Chm)	Rockwell International-Retired
Dr. Richard E. Thomas	Texas A&M University

NAME: (M)=Member	Company
Mr. Arthur R. Thomson	Cleveland State University
Mr. Don Toombs	Boeing Military Airplane Co.
Mr. Timothy Towey	Amdahl Corporation
Ms. Tuyet-Lan Tran	Jet Propulsion Lab.
Mr. R. E. Vassau	The Aerospace Corporation
Mr. Sam L. Venneri	NASA-Headquarters, OAST
Dr. C. Visser	Westinghouse Research
Mr. R. E. Wallace	Boeing Commercial Airplane Company
Mr. Robert J. Wallace	Research Triangle Institute
Mr. Everette Webb (M)	Boeing Commercial Airplane Company
Mr. Jerry A. Weiss	McDonnell Douglas Corporation
Mr. Carey K. Westbrook (M)	Vought Corporation
Ms. Margaret L. White	Lockheed Corporation
Mr. Don E. Wilson	Lockheed Corporation
Mr. Michael J. Wozny	Rensselaer Polytechnic Institute
Mr. Kinji Yamasaka	Circuit Tools Inc.
Mr. John Zimmerman	Bendix Corporation, Kansas City Div.
Dr. Burt A. Zolotar	Technology Development of Cal.

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Table 1: IPAD Assessment Survey

HOW HELPED COMPANY?	RESULTS FOUND USEFUL?	USE MADE OF PRODUCTS?	ITAB EFFECTIVENESS?	NO. STAFF CONTACTS w/IPAD	OTHER COMMENTS
Forum for key issues. Lent credence to integration issues. Candid sharing of other company activities. Visible national focus for research on data base management for engineering and manufacturing. Methodology for defining engr. problem solving process and reqts. for computing system to support process. Concepts of an integrated environment. "Boeing, NASA, ITAB were invaluable sources of knowledge." "Management is now more knowledgeable in CAD/CAM and data mgt. issues." Mgt. would not have begun data base mgt. efforts without IPAD. Insight regarding distributed data management. "Encouraging commercial products by CDC & IBM."	Insight into: -Integration issues -Engin. data bases -Product data bases -Distributed DBM -Networking. IPAD documents excellent. Documentation of engineering process. Requirements of data base mgt. system. Documentation of engr/mfg. interface. Exchange of information among NASA and industry. "Requirements document which has been used broadly." Greatly accelerated IGES. Helped computer companies define their positions to meet user requirements. Insight into relational data bases for engr/mfg.	"RIM widely used." "MICRORIM" "BCS RIM successful product commercially." "RIM used extensively." "RIM and its commercial derivative BCS RIM." RIM used for prototype material properties data base. Documents. Research reports. Network software. IPIP assessed only in cursory fashion due to code complexities.	"Extremely effective." "Uniquely effective management tool." "Key to IPAD success." Most rewarding experience of whole program. Candid discussions. Unique for govt/industry activities. "Remarkably effective in guiding development in direction to support industry." "ITAB involvement a professionally rich experience." Brought together knowledgeable people from aerospace, computer automotive, govt., etc. "ITAB was an enjoyable and educational experience." "Was the most important IPAD contribution."	"Hundreds," just within engineering. Results distributed to 3000 technical staff. 30 in the "core IPAD group." 50-100 in multiple divisions. 150 worked on project, many still in company. Approx. 30 engr., mfg., comp. sci. 25 key mgt., middle mgt., and senior engr. personnel.	"No question IPAD significantly altered the collective opinions of a surprising number of decision makers." "Excellent program for its time." "Took long time to find a final direction." "No real, hard useable products." "The major deficiency was lack of adequate funding." "Program had excellent management (NASA/Boeing), excellent team members, and excellent advisory board." IPAD failed to project its image as "leading edge data management research effort;" was viewed incorrectly by many as a development effort with an end product. "Sorry to see momentum halted when industry clearly expressed need for data management research." "Insufficient attention to: -"IGES standard" adaptation -"workstations" -"mfg. data mgt. reqts." -"finite element/solid geom. DRM" -distributed data base mgt. Program too dependent on single module IPIP. Failure to forcefully demonstrate integrated CAD/E environment. Shortcomings of program: -Funding inadequate for timely development of IPIP -Inadequate engineering applications -Too slow in addressing heterogeneous software prototype.

Table 1: ITAB Assessment Survey

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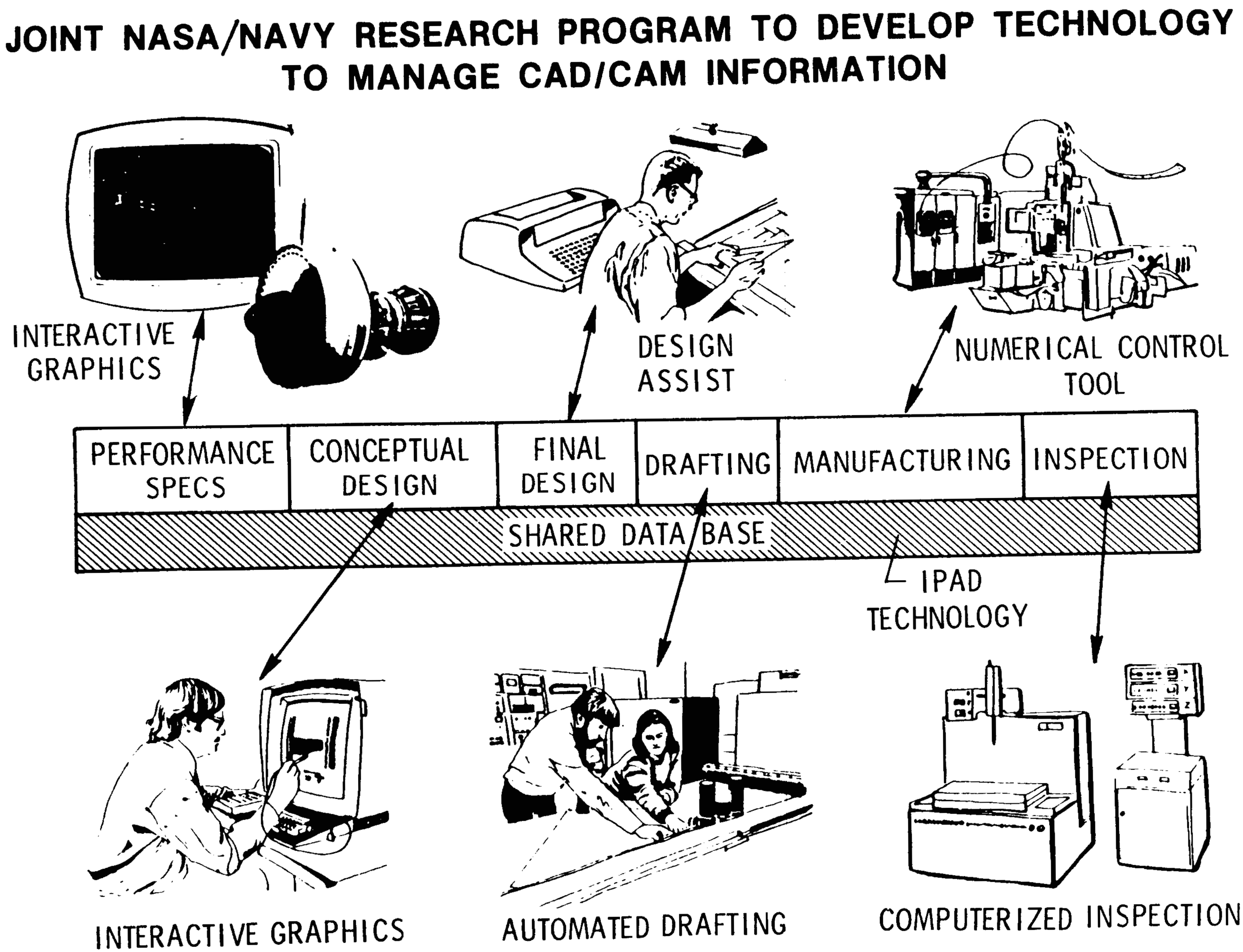

Figure 1. - Joint government/industry research program to develop technology to manage CAD/CAM information

IPAD INDUSTRY TECHNICAL ADVISORY BOARD (ITAB)

ITAB MEMBERSHIP

W. E. SWANSON
CHAIRMAN

EXECUTIVE OFFICER/INTERFACE MANAGER
D. E. TAYLOR (BOEING)

● MEMBERS

AEROSPACE INDUSTRY
- BOEING
- CESSNA
- FAIRCHILD
- GENERAL DYNAMICS
- GRUMMAN
- LOCKHEED
- MARTIN-MARIETTA
- McDONNELL-DOUGLAS
- NORTHROP
- ROCKWELL INTL
- VOUGHT

ENGINE MANUFACTURERS
- GENERAL ELECTRIC
- PRATT AND WHITNEY

COMPUTER MANUFACTURERS
- IBM
- CDC
- DEC
- UNIVAC

● OBSERVERS (100 +)

- • ADVANCE MARINE ENTERPRISES
- • AVCO - LYCOMING
- • BATTELLE
- BELL HELICOPTER
- • COMPUTERVISION
- • DENELCOR
- FORD
- • GTE
- GENERAL MOTORS
- • GERBER SCIENTIFIC INSTRUMENT
- • GULFSTREAM AMERICAN
- • HIGHER ORDER SOFTWARE
- • HUGHES AIRCRAFT
- • MacNEAL SCHWENDLER
- MANUFACTURING AND CONSULTING SERVICES
- • NATIONAL BUREAU OF STANDARDS
- • NAVAL AIR SYSTEMS COMMAND
- NASA
- • NETWORK SYSTEMS
- • PIPER AIRCRAFT
- • PRIME COMPUTER
- • RENSSELAER POLYTECHNIC INSTITUTE
- • RESEARCH TRIANGLE INSTITUTE
- • ROYAL GRAPHICS
- • SOFTECH
- • STRUCTURAL DYNAMICS RESEARCH
- • TEKTRONIX
- • TEXAS A & M
- • TRW
- • UNIVERSITY OF MISSOURI - ROLLA
- • VIRGINIA POLY. INST. AND STATE U.
- • WESTINGHOUSE
- AIR FORCE - ICAM PROGRAM
- • JOHN DEERE
- • NSRDC
- • AIR FORCE - FLIGHT DYNAMICS LAB
- AIR FORCE - MATERIALS LAB
- ⋮

• ADDED SINCE 1979

ITAB ACTIVITIES

GUIDE DEVELOPMENT TO MEET INDUSTRY NEEDS

REVIEW/CRITIQUE ONGOING WORK

EVALUATE PROTOTYPE SOFTWARE

USE IPAD TECHNOLOGY AND PRODUCTS TO SPUR IN-HOUSE PLANNING AND DEVELOPMENT

Figure 2. - IPAD Industry Technical Advisory Board (ITAB)

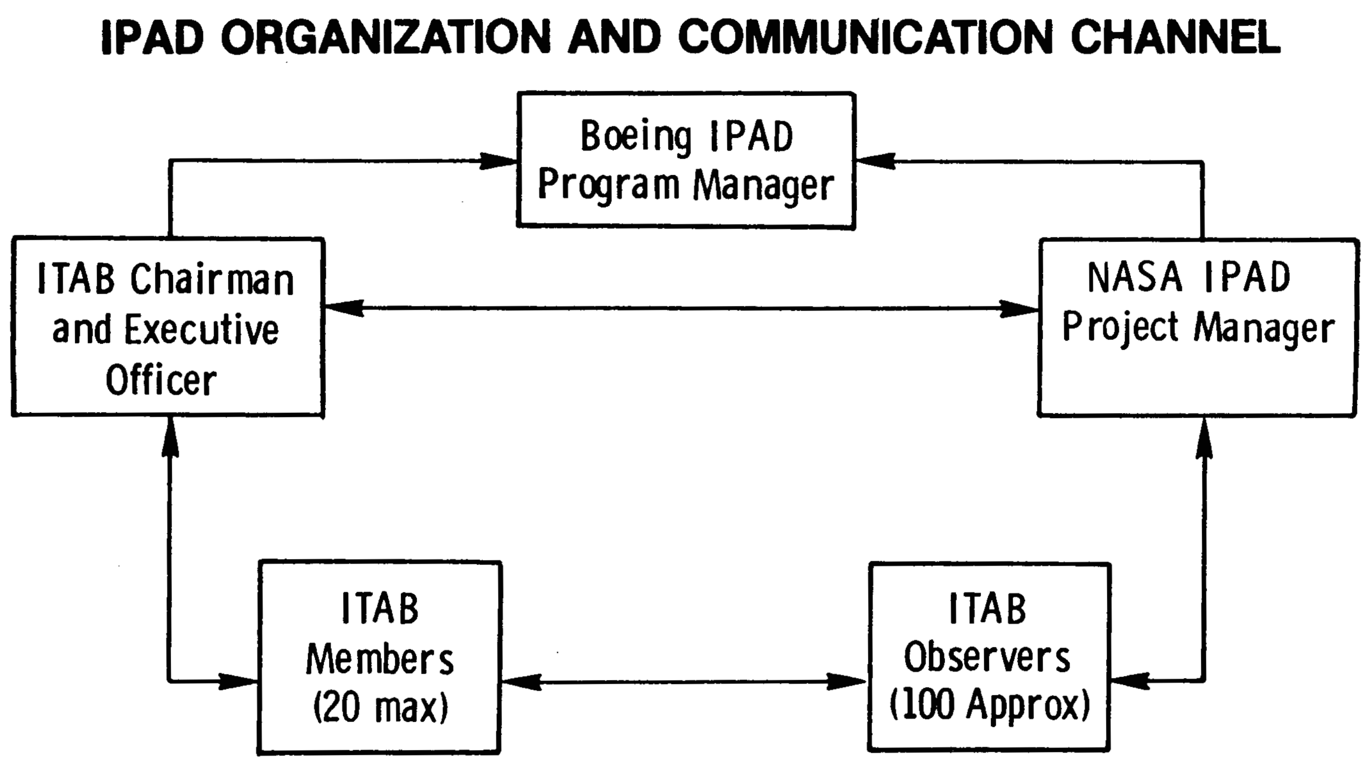

Figure 3: IPAD Organization and Communication Channel

TYPICAL IPAD AGENDA

Opening	ITAB Chairman
Welcome	Host Company
IPAD Programmatic Status	NASA/Navy
Technical Status Report	Boeing and Subcontractors
Report of Other Related Program Activities	ICAM, Industry, Other NASA Programs, Etc.
Assessment of Specific Technical Work	ITAB Audit Committees
Open Discussion of Key Issues	ITAB
Proposed Recommendations to Contractors	ITAB Control Board
Finalization of Recommendations and Review of Status of Outstanding Recommendations	ITAB
Plans for Next Meeting	ITAB Chairman and Executive Officers
Closing Comments	ITAB Chairman/Boeing/NASA/Navy

Figure 4: Typical ITAB Meeting Agenda

INDUSTRY COOPERATIVE EFFORTS

ITAB Meeting Activities

- Host Meetings (All)
- Review Documents, Support Technical Visits and Exchanges (All)
- Participate in Technical Audits
- Sponsor Two IPAD Symposiums and a Data Management Workshop (All)

Evaluate First Release Software (All)

Extend RIM Capabilities (All)

Provide On-Site Staff and/or Review Teams
(CDC: DEC, IBM, UNIVAC, Boeing)

Provide Company Hardware/Software Products (CDC, DEC, IBM)

Cooperate in Special Demonstrations (GD)

Host IPAD Technical Briefings for Inhouse Staff (All)

Figure 5: Industry Cooperative Efforts on IPAD Project (Participating ITAB Members Shown Parenthetically)

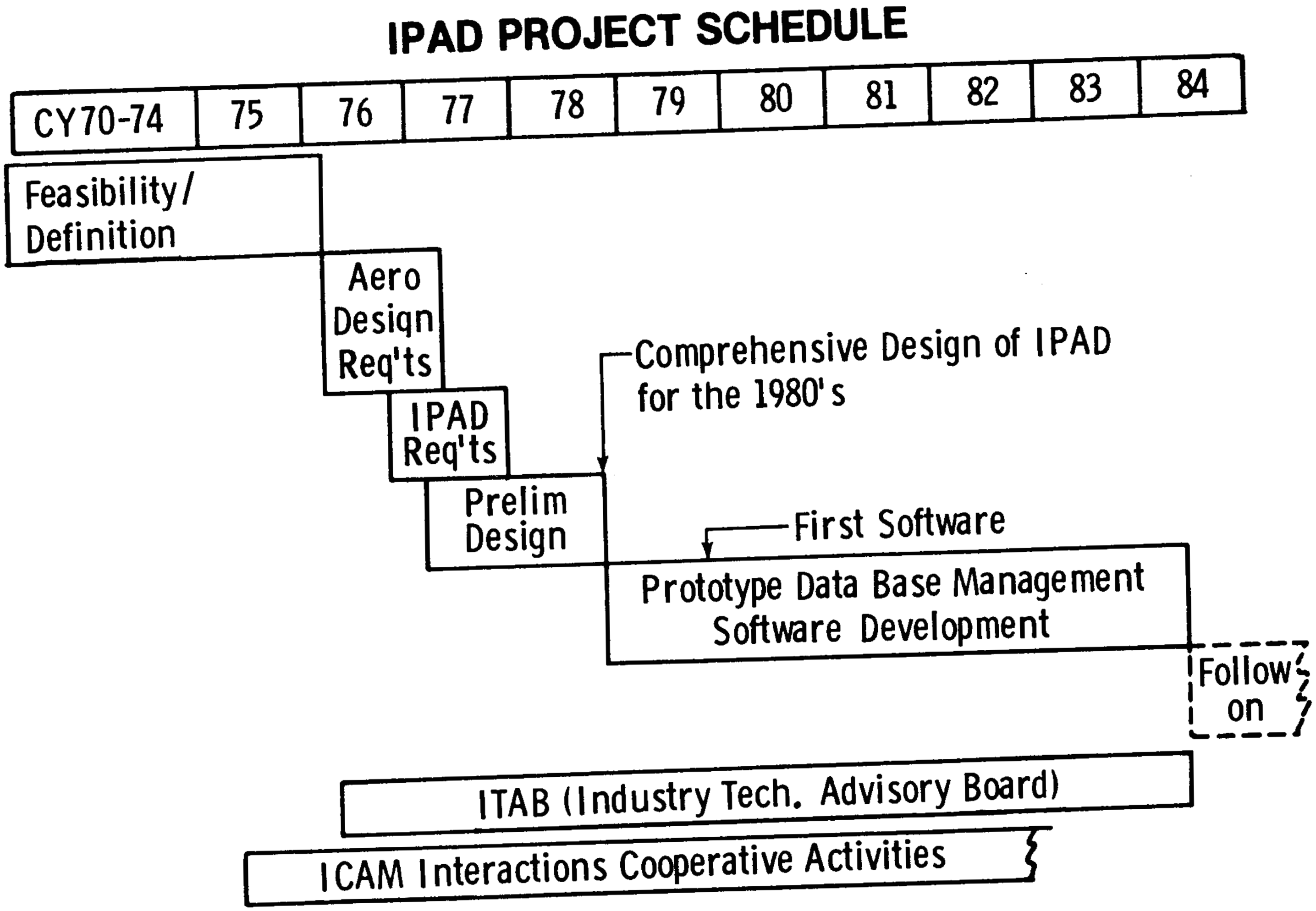

Figure 6: IPAD Project Schedule

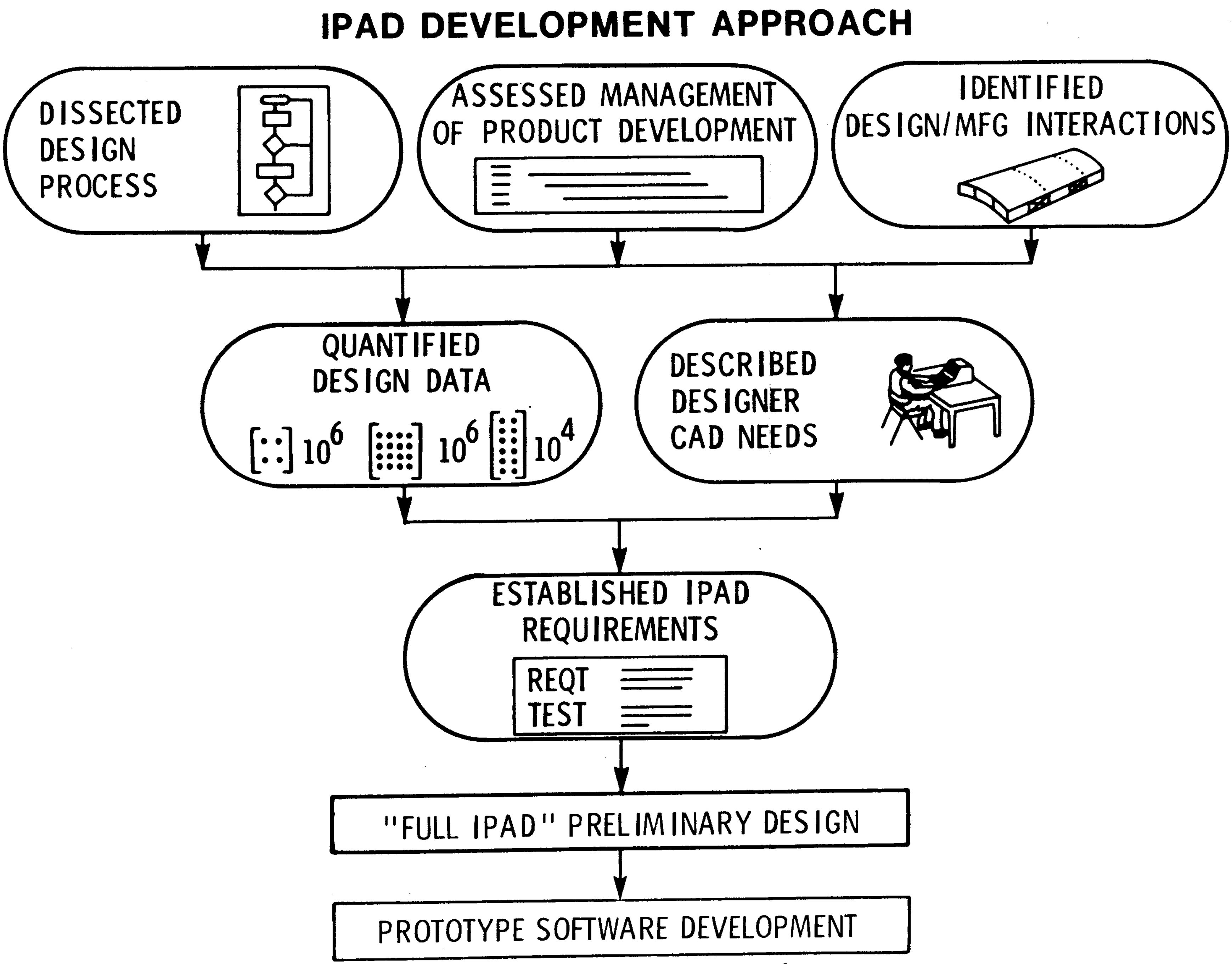

Figure 7. - IPAD Development Approach

INITIAL FEASIBILITY/DEFINITION STUDIES

BOEING COMMERCIAL AIRPLANE COMPANY
GENERAL DYNAMICS/CONVAIR AEROSPACE DIVISION
17 MONTHS, $611 K

- Dissected Design Process
- Examined Designer Needs
- Defined Software Elements
- Assessed Computer Requirements
- Assessed IPAD Feasibility/Benefits

Figure 8: Initial IPAD Feasibility/Definition Studies

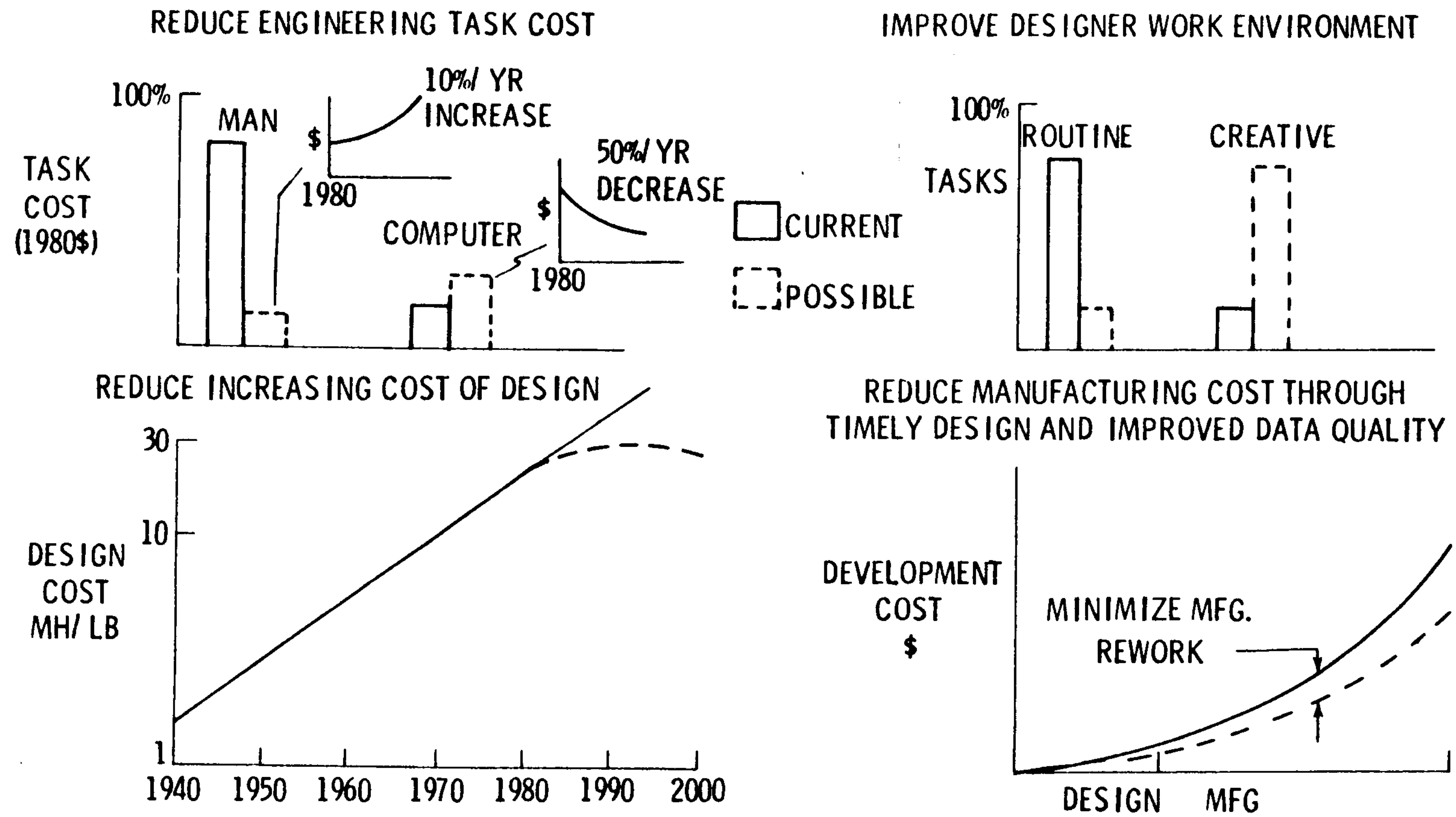

Figure 9. - Benefits from CAD/CAM technology

WHY IPAD

Bring the Computer Revolution into the Design Office

Integrate Activities of Large Design Teams

Improve Management of Engineering Data

Provide Fast, Accurate Communication Among Design Disciplines

Increase Designer Productivity

Improve Interface Between Design and Manufacturing

Reduce Cost and Time to Design a Better Product

WHY NASA

Government/Involvement Needed to Accelerate Development of Needed CAD/CAM Technology

- High Risk Long-Term Development Out - Normal Aerospace Company Product Line
- High Risk Development for a Small Computer Company Market
- Requires Unnatural Cooperation Among Computer Vendors
- Utilizes Scarce Resources More Effectively

Provides Basic Technology Needed for DOD CAD/CAM Programs

Benefit NASA Missions and Products

Figure 10: Reasons for NASA Development of IPAD Technology

INDUSTRY SCRUTINY

- Four Oral Reports of Study Contract Results (74-187 Attendees)
- Aerospace Management Review (Jan. 30-31, 1974)
  NASA, ASD, AFFDL, Boeing, Grumman, MDAC, DAC, P+W, RI, Lockheed, Vought
- Funded Technical Critiques (Oct. 19, 1973 - March 19, 1974)
  MDAC, Lockheed, Grumman, RI, CDC, IBM, UNIVAC
- Numerous Informal Visits and Meeting Presentations
- Prospectus and Survey of 41 Aerospace Executives (Feb. 1975)
  Sought Commitment to:
  - Become Member of ITAB
  - Evaluate IPAD Software
  - If IPAD is Useful, Support User Organization for Maintenance/Improvement

Figure 11: Industry Scrutiny of IPAD Feasibility Definition Studies

INDUSTRY COMMENTS ON FEASIBILITY STUDIES

- IPAD DEVELOPMENT <u>SHOULD</u> PROCEED
- GOVERNMENT DEVELOP CORE - LEAVE TECHNICAL MODULES TO INDUSTRY
- PROVIDE EARLY USER INVOLVEMENT
- COST ESTIMATES PROBABLY LOW
- AIM TOWARD 'WORKING PROTOTYPE' SYSTEM

Figure 12: Industry Advice from IPAD Critiques

DISSECTION OF THE DESIGN PROCESS

CTOL, SST, HYDROFOIL VEHICLES

DESIGN LEVELS

PART OF STRUCTURAL DETAIL DESIGN NETWORK

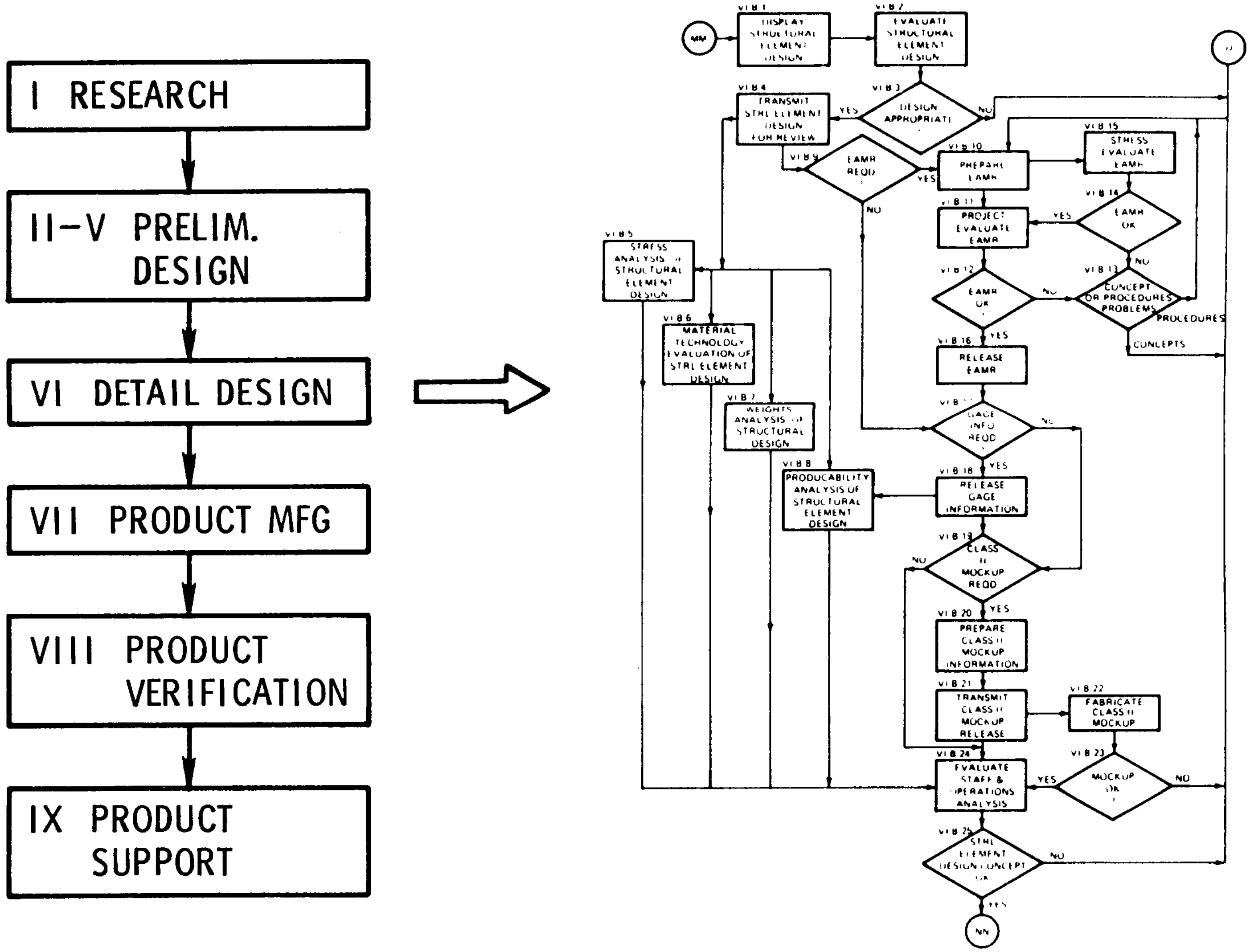

Figure 13: Detail Dissection of Design Process for Representative Vehicles

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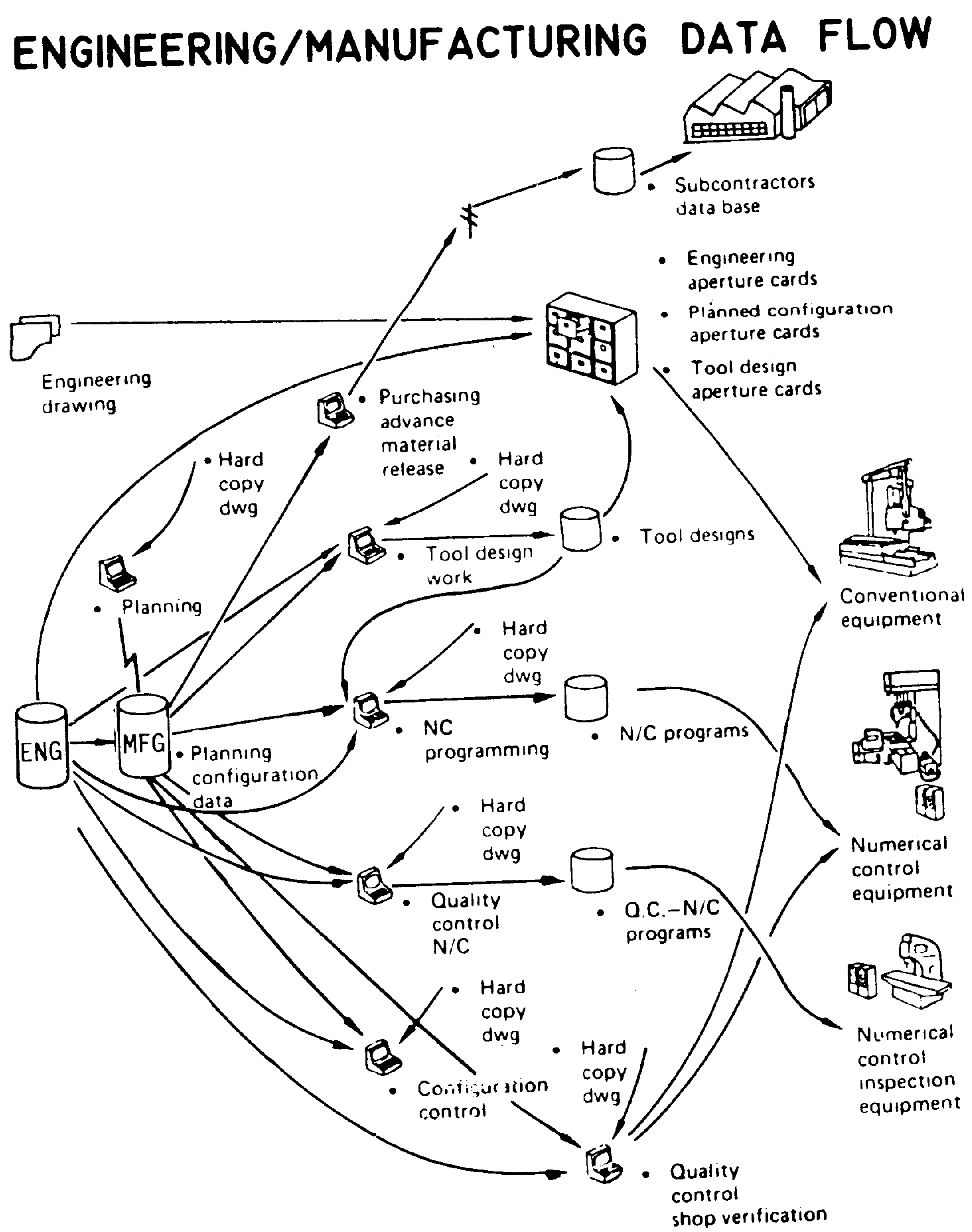

Figure 14: Flow of Data from Engineering to Manufacturing

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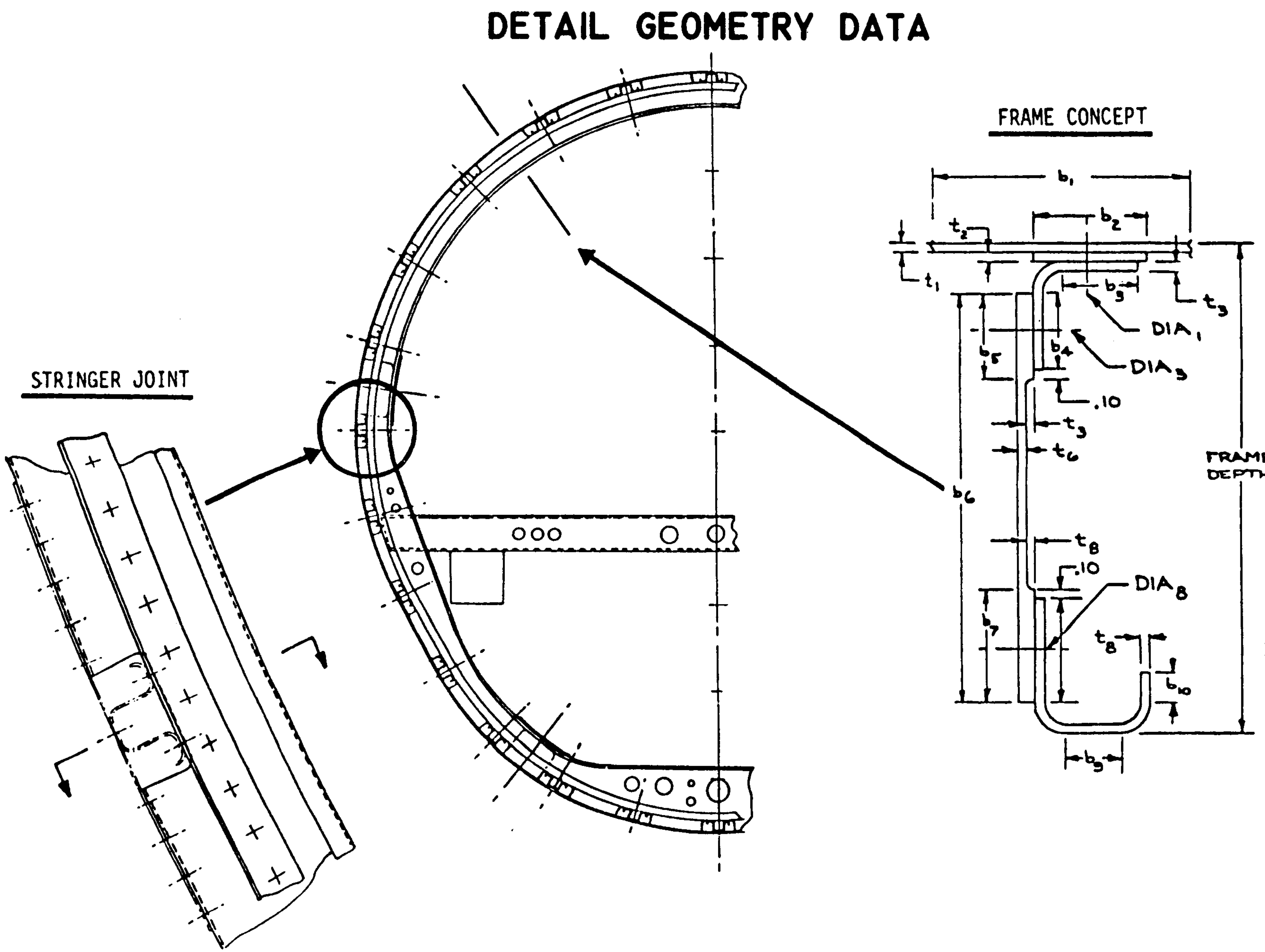
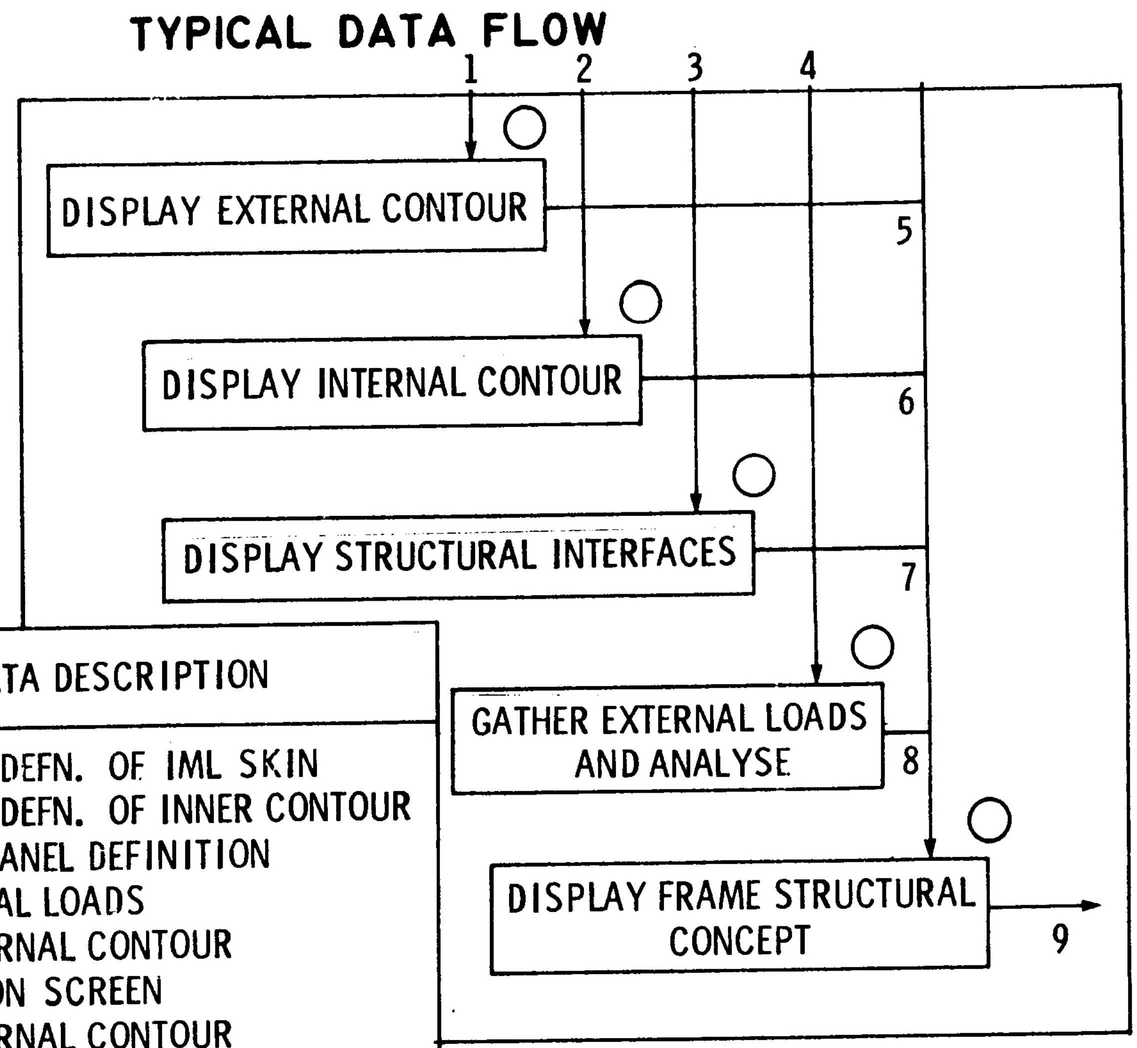


Figure 15: Detail Geometry Data for Aircraft Fuselage Frame



DATA I. D.	DATA DESCRIPTION
1	LEVEL V GEOM. DEFN. OF IML SKIN
2	LEVEL V GEOM. DEFN. OF INNER CONTOUR
3	LEVEL V SKIN PANEL DEFINITION
4	LEVEL V EXTERNAL LOADS
5	MAINTAIN EXTERNAL CONTOUR DISPLAY ON SCREEN
6	MAINTAIN EXTERNAL CONTOUR DISPLAY ON SCREEN
7	MAINTAIN SKIN PANEL DISPLAY ON SCREEN
8	SIZING INFORMATION
9	STORE FRAME STRUCTURAL CONCEPT IN DATA BASE

Figure 16: Typical Data Flow for Preliminary Design of Aircraft Fuselage Frame

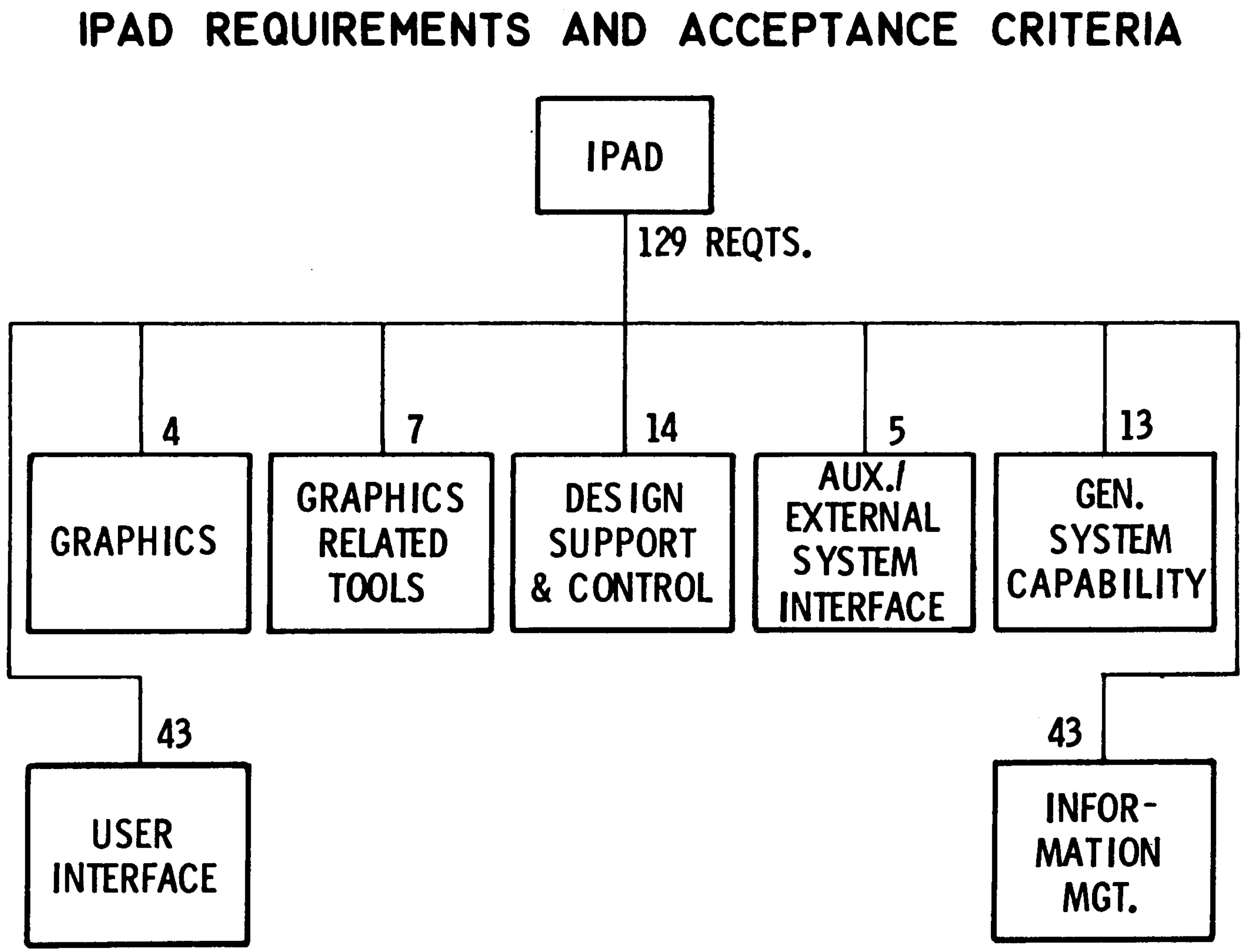


Figure 17: IPAD Requirements in Various Categories

CAD/CAM DATA MANAGEMENT SYSTEM REQUIREMENTS

- ACCOMMODATE MULTIPLE VIEWS OF DATA
- ALLOW MULTIPLE LEVELS OF DATA DESCRIPTION
- PERMIT CHANGES AND EXTENSIONS IN DATA DEFINITION
- DISTRIBUTE DATA OVER COMPUTER NETWORKS
- MANAGE GEOMETRY DATA
- PROVIDE CONFIGURATION MANAGEMENT CAPABILITIES
- MANAGE INFORMATION ABOUT DATA

Figure 18. - CAD/CAM data management systems requirements

KEY REQUIREMENTS FOR FULL IPAD

500 - 1000 SIMULTANEOUS USER TERMINALS

LARGE, RAPID ACCESS DATA VOLUMES TO SUPPORT VEHICLE DESIGN

	ON LINE DATA 10^9 WORDS	10 MINUTE AVAILABILITY 10^9 WORDS
10 PRELIMINARY DESIGNS	1.7	-
10 SUSTAINING DESIGNS	7.8	15.7
2 DETAIL DESIGNS	2.5	3.2
	12.0	18.9

Figure 19: Key IPAD Performance Requirements Driving Software Package

FULL IPAD COMPONENTS

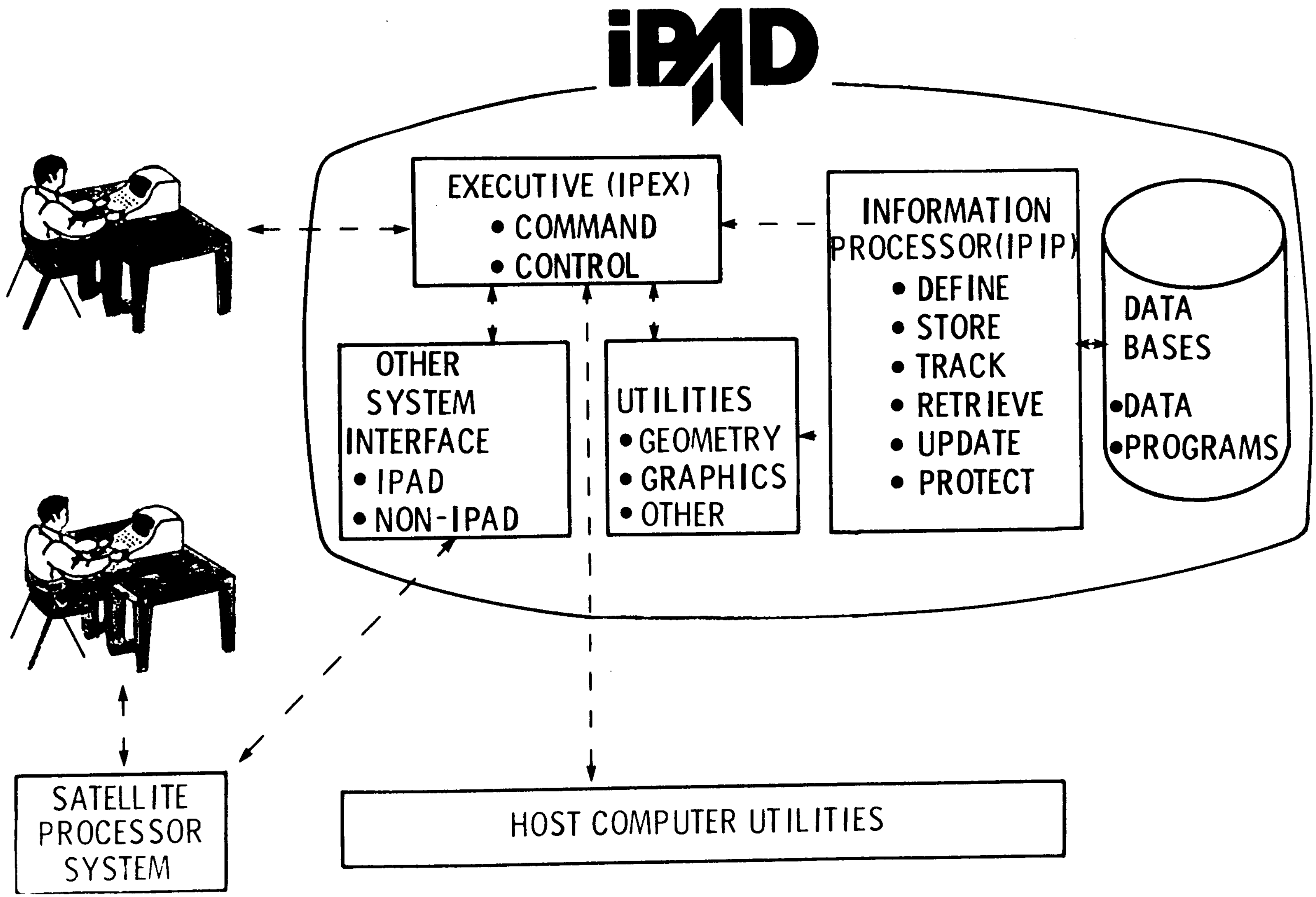


Figure 20: Key Software Components of a Full IPAD System

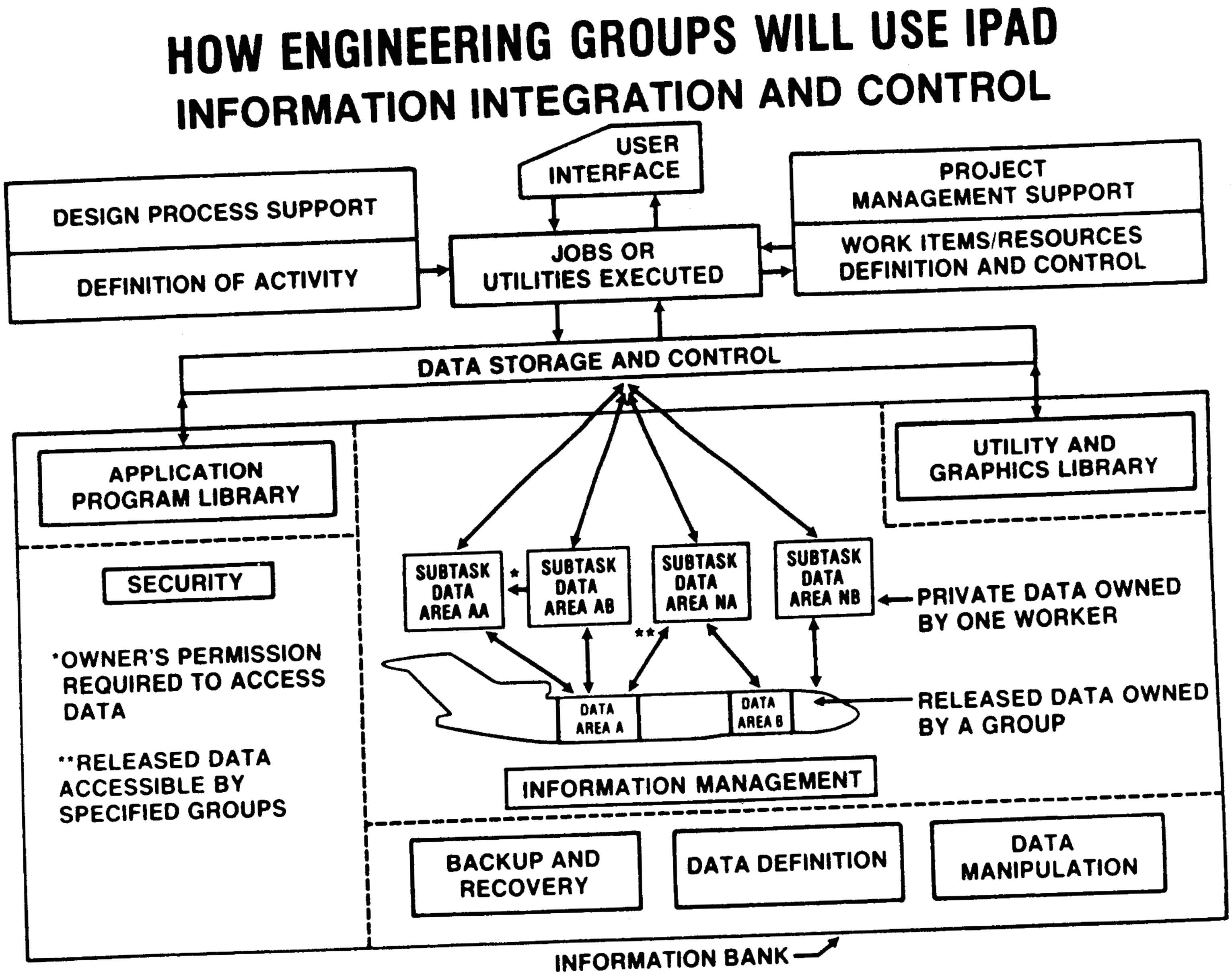


Figure 21: Engineering Use of Integrated CAD/CAM Data Management System

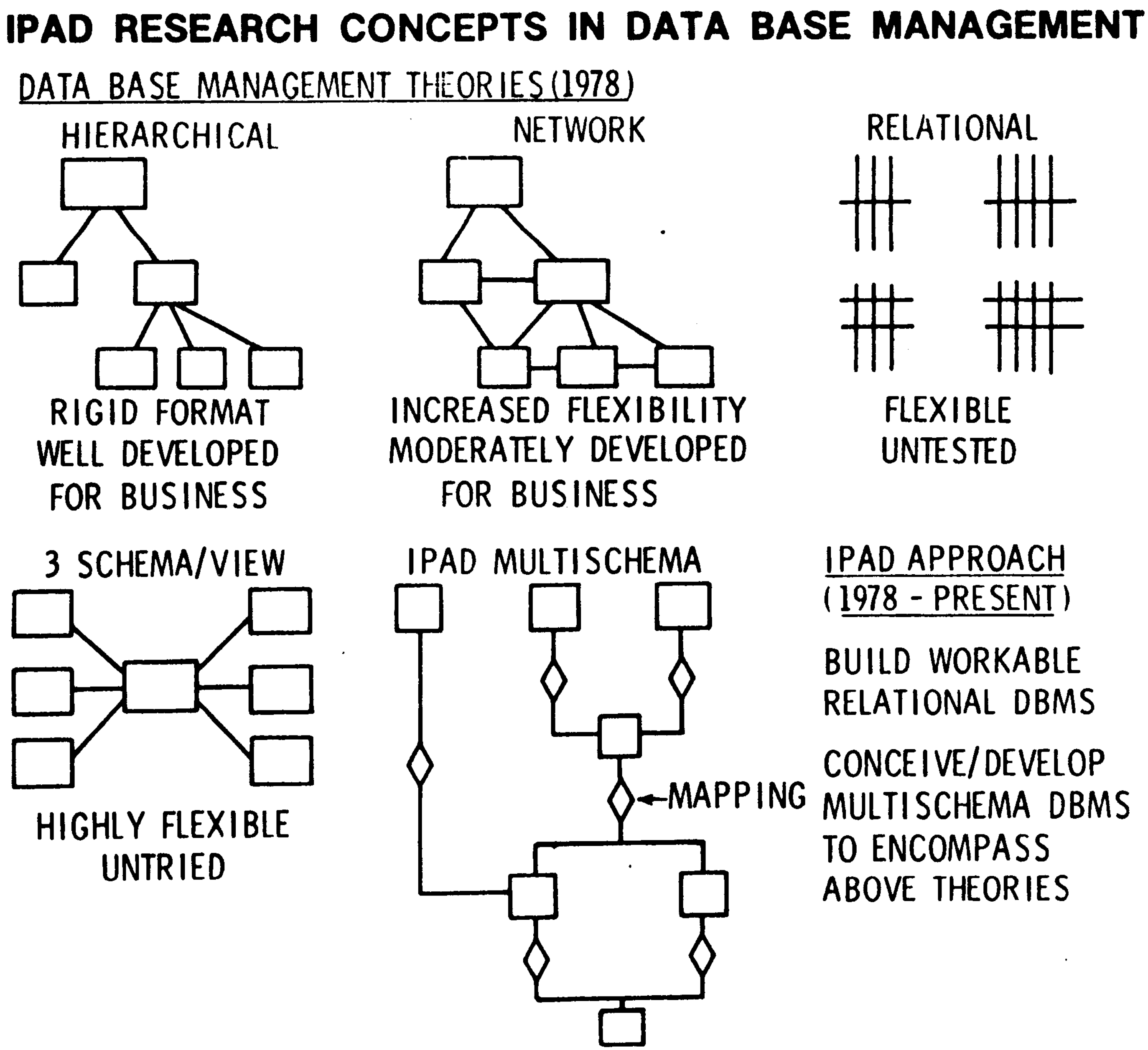


Figure 22: Alternate Data Base Management Models Considered by IPAD

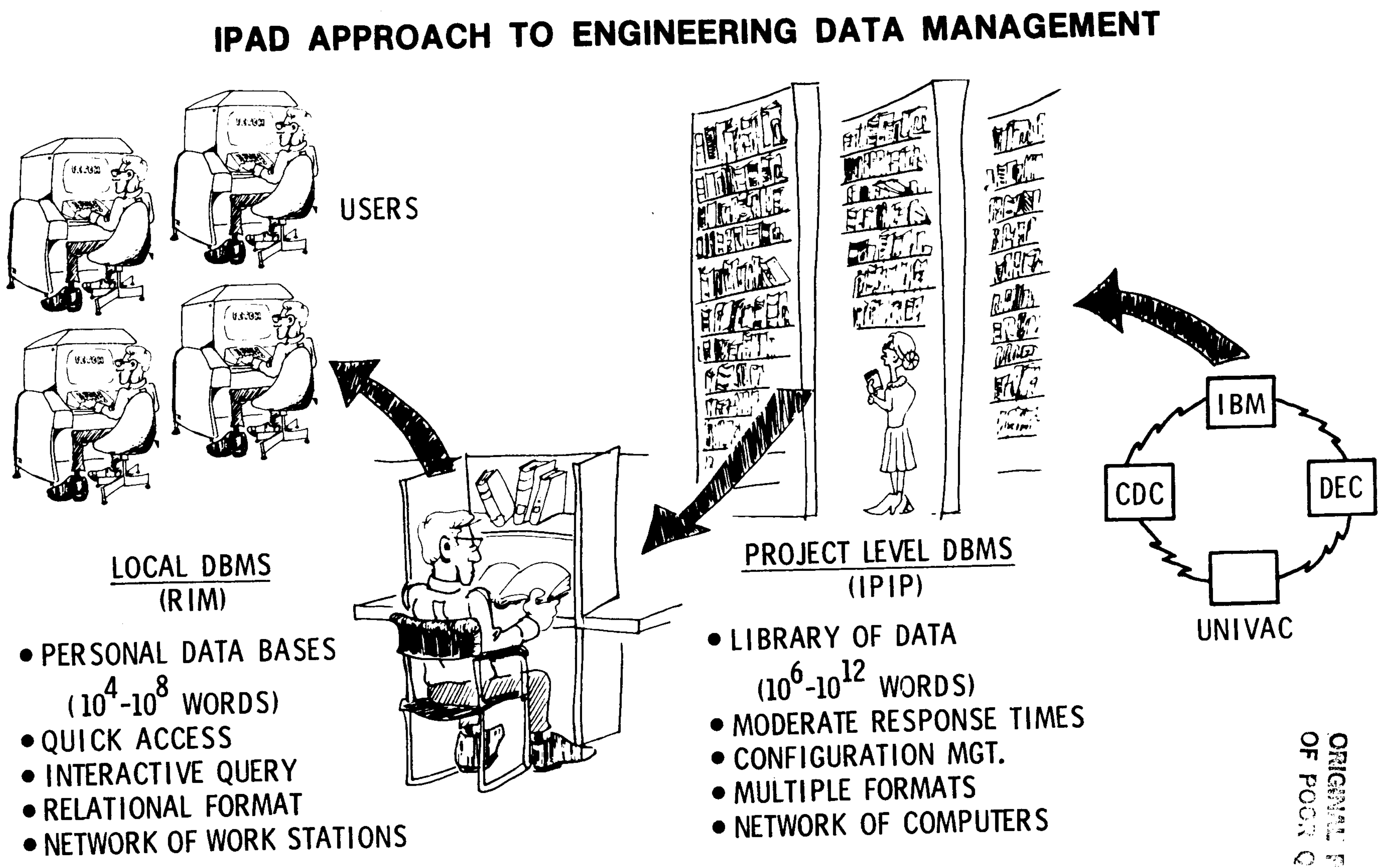


Figure 23: IPAD Multilevel Approach to Engineering Data Base Management

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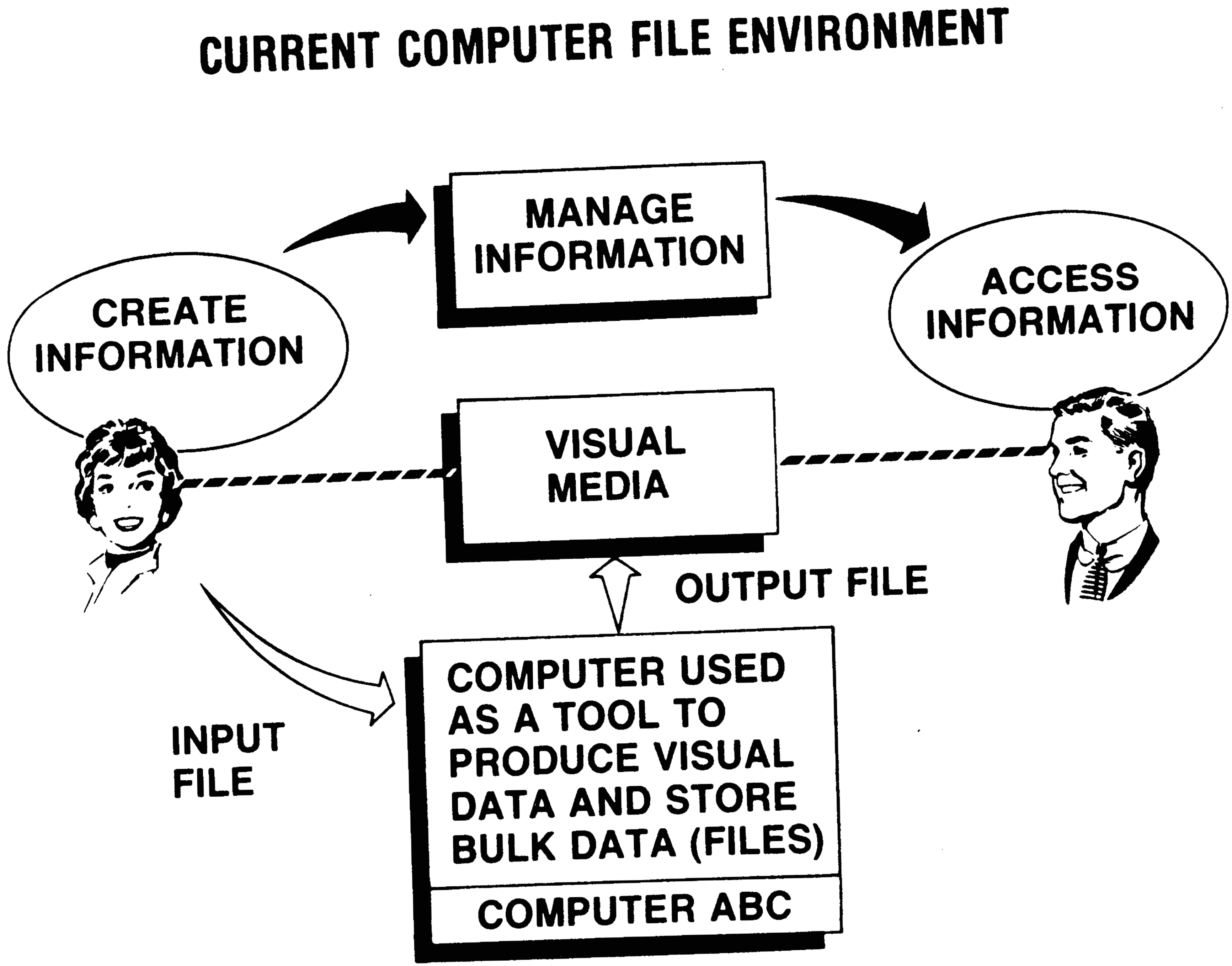

Figure 24: Current File-Oriented Approach for CAD/CAM Information

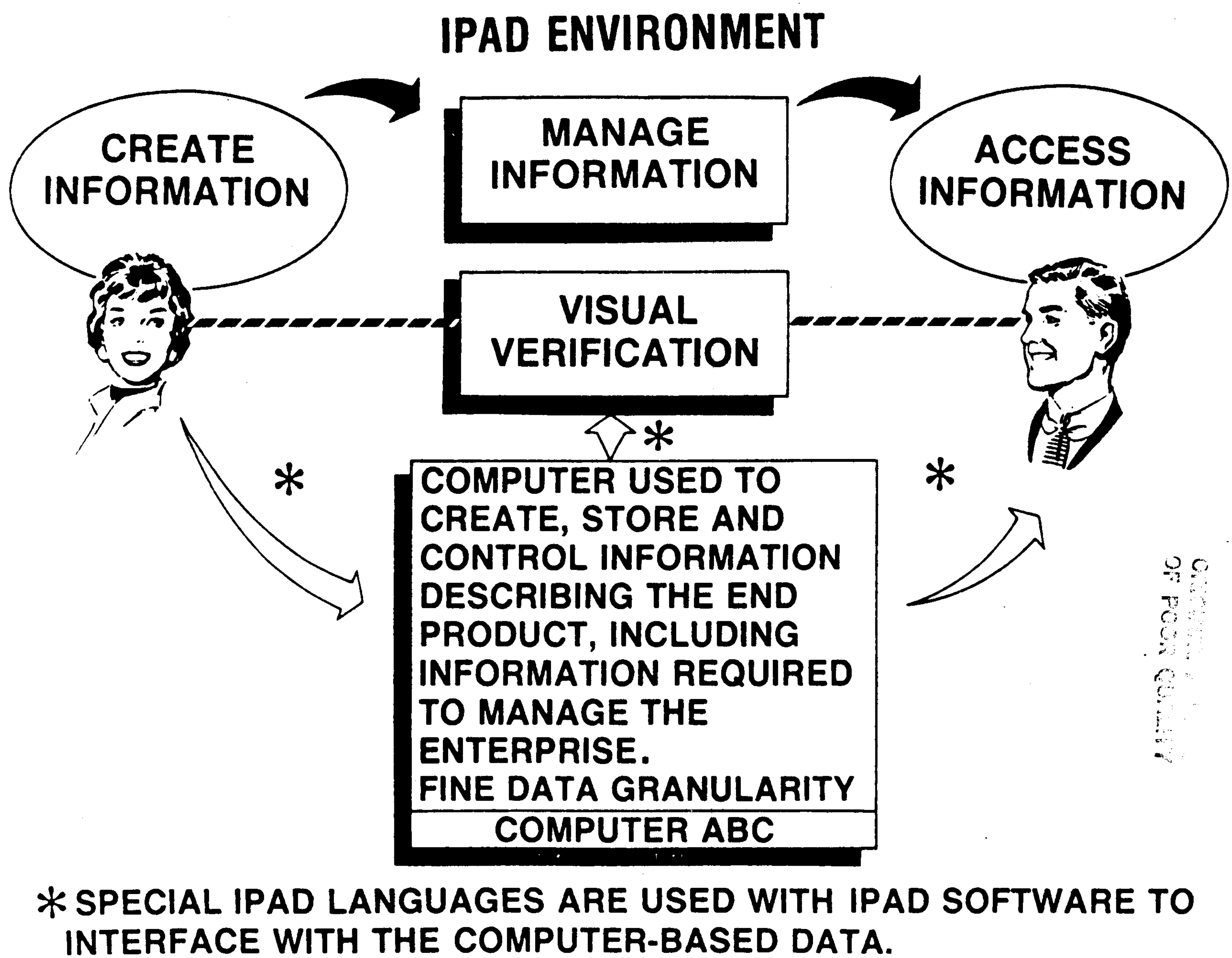

Figure 25: Future Data Base Management Approach for CAD/CAM Information

RIM STATUS

- WRITTEN IN FORTRAN
- CODE HIGHLY PORTABLE (CDC, VAX, PRIME, IBM, UNIVAC, CRAY, MICROS, ETC.)
- BASED ON RELATIONAL ALGEBRA
- FLEXIBLE QUERY LANGUAGE
- APPLICATION PROGRAM INTERFACE CAPABILITIES
- RIM TO RIM COMMUNICATIONS FILE
- SCHEMA CAN BE MODIFIED AS NEEDED
- VARIABLE LENGTH ATTRIBUTES
- COMMERCIAL VENDORS SUPPORTING/EXPANDING RIM

Figure 26. - Features of RIM Relational Information Management System

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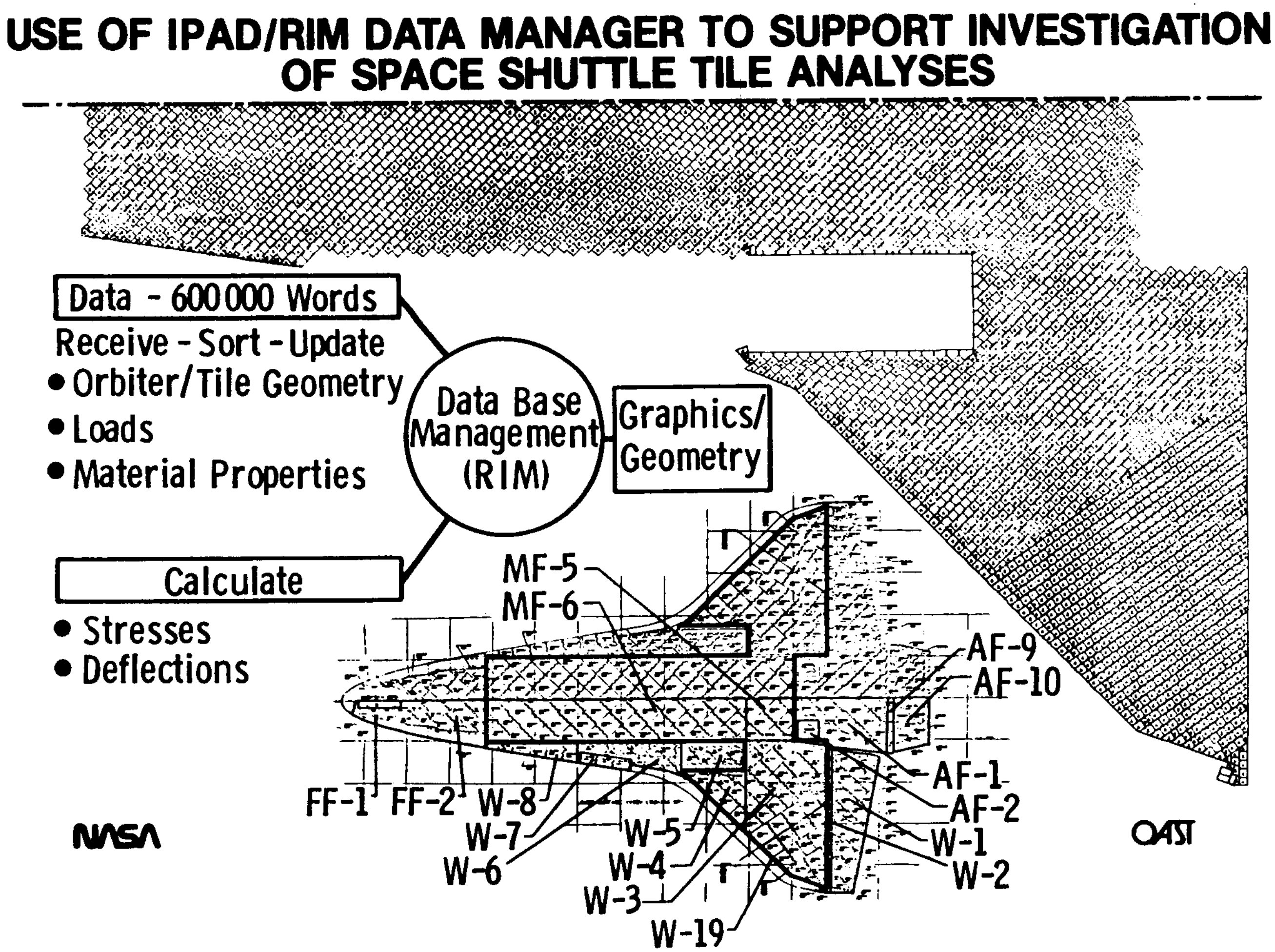
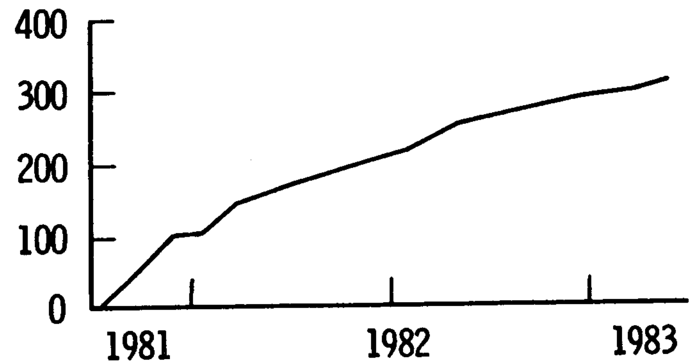


Figure 27: Use of IPAD/RIM Data Manager to Support Investigation of Space Shuttle Tile Analyses

DISTRIBUTION OF RIM SOFTWARE AS OF APRIL 1, 1983



IBM	46
Cyber/Nos	37
Dec Vax	161
Prime	35
Cyber Nos/BE	13
Univac	11

Figure 28: Distribution of RIM Software as of April 1, 1983

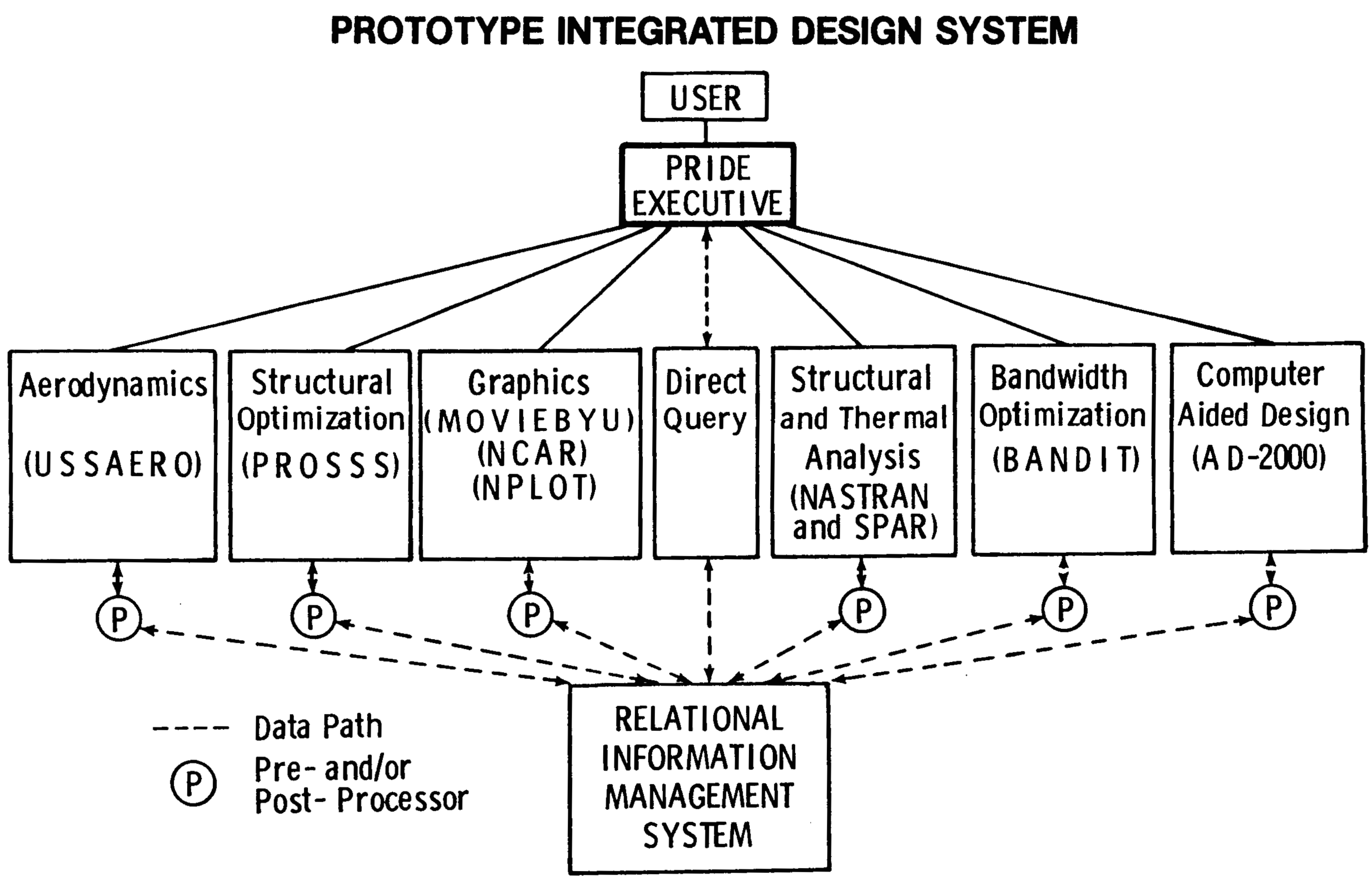


Figure 29: Organization of PRIDE Prototype Integrated Design System

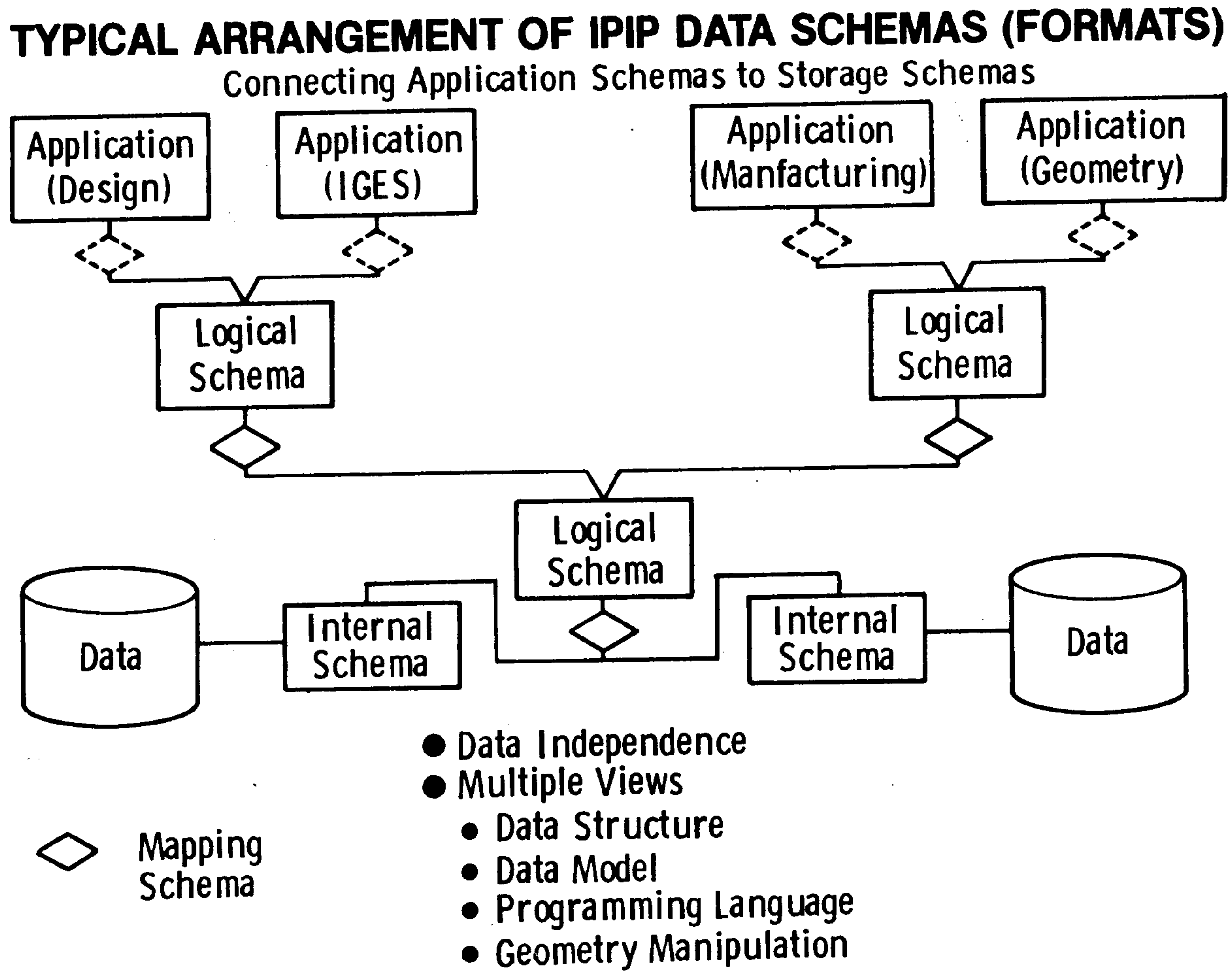
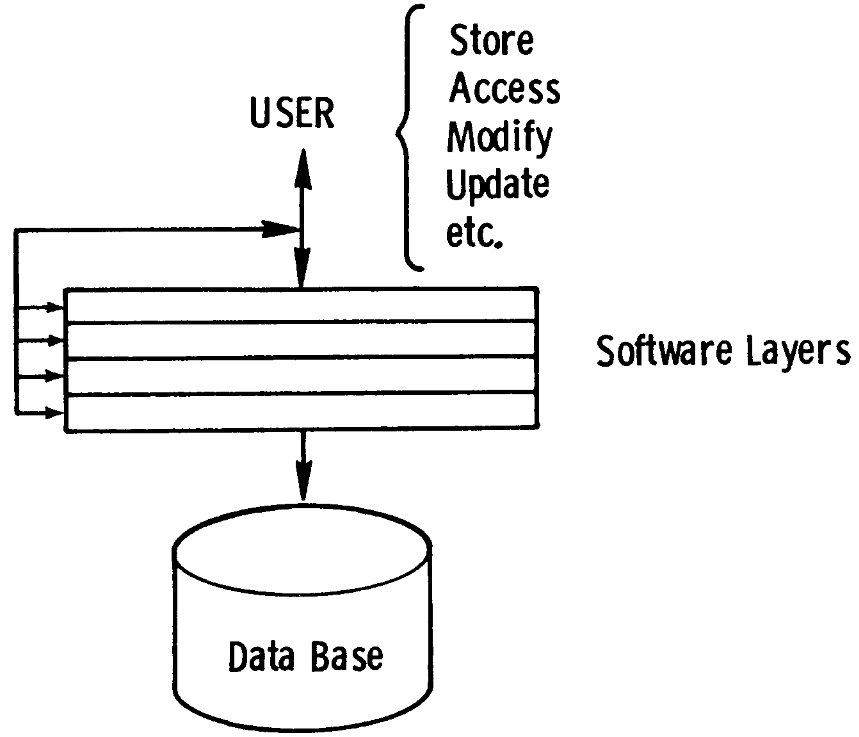


Figure 30: Typical Arrangement of IPIP Data Schemata (Formats) to Connect Application Schemata to Storage Schemata

TYPICAL APPLICATIONS OF IPIP MULTISCHEMA CAPABILITY



Generalized Information Structure Processing

Figure 31: Typical Applications of IPIP Multischema Capability

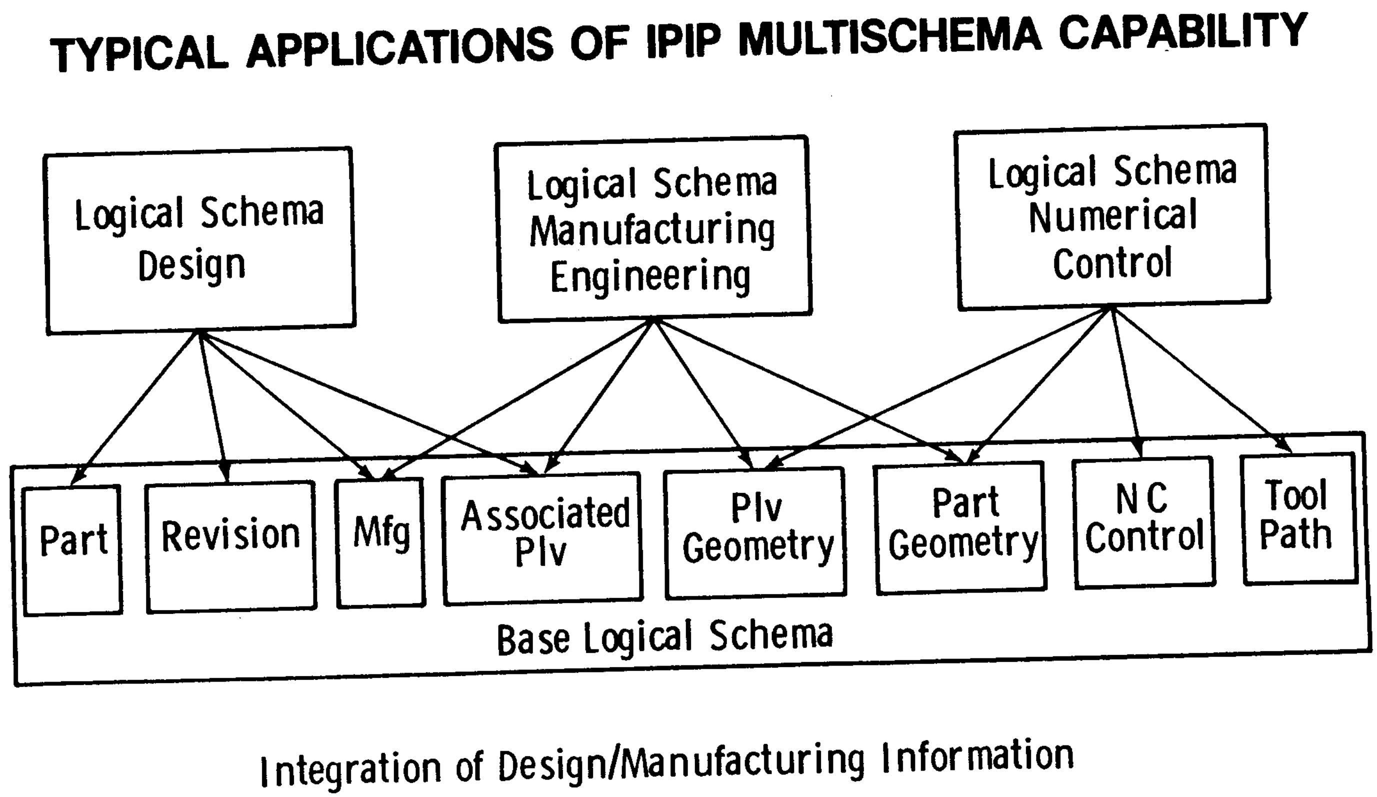


Figure 32: Typical Applications of IPIP Multischema Capability

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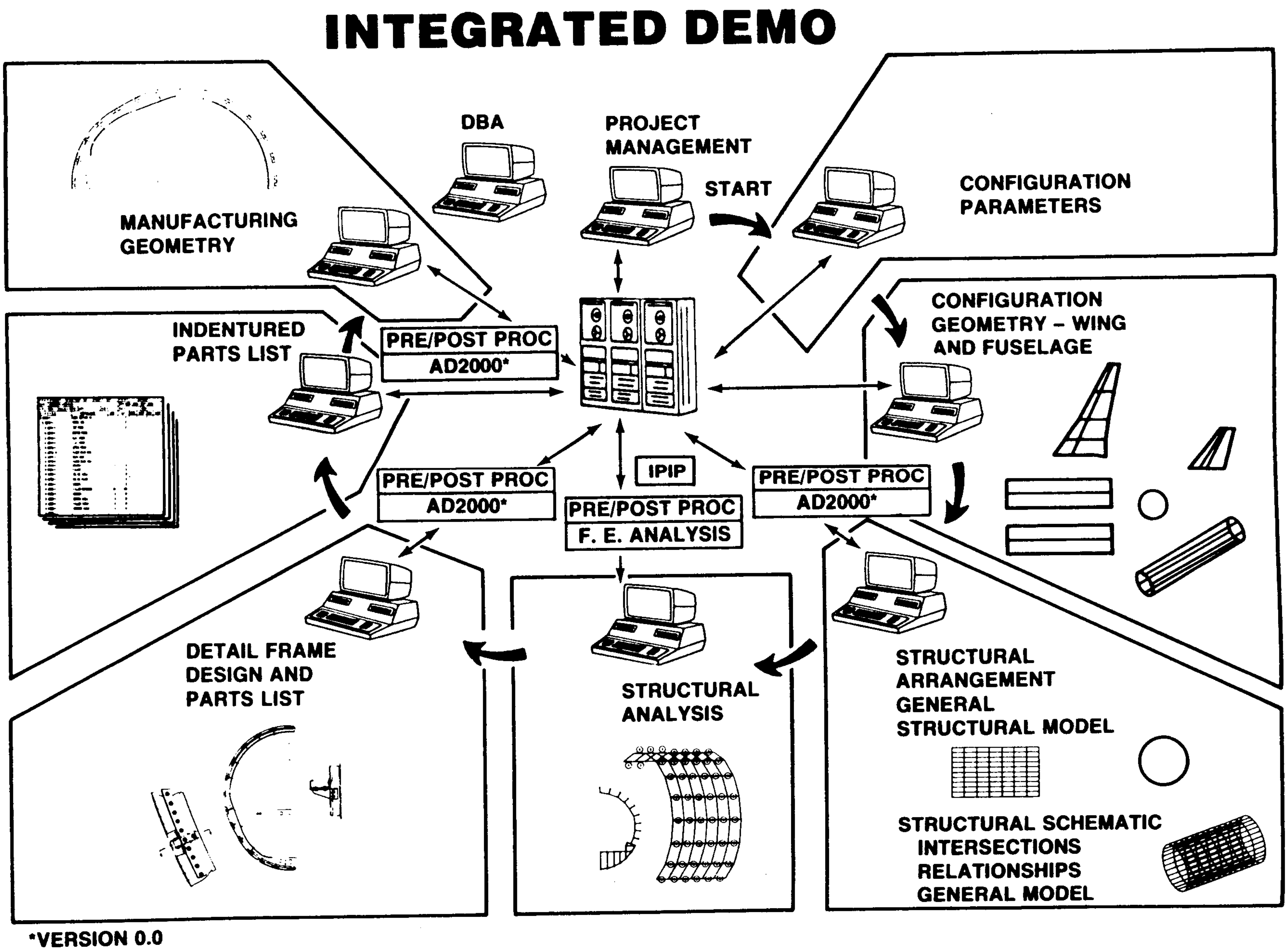

Figure 33: Planned Test Demonstrations to Evaluate IPAD/IPIP for CAD/CAM Use

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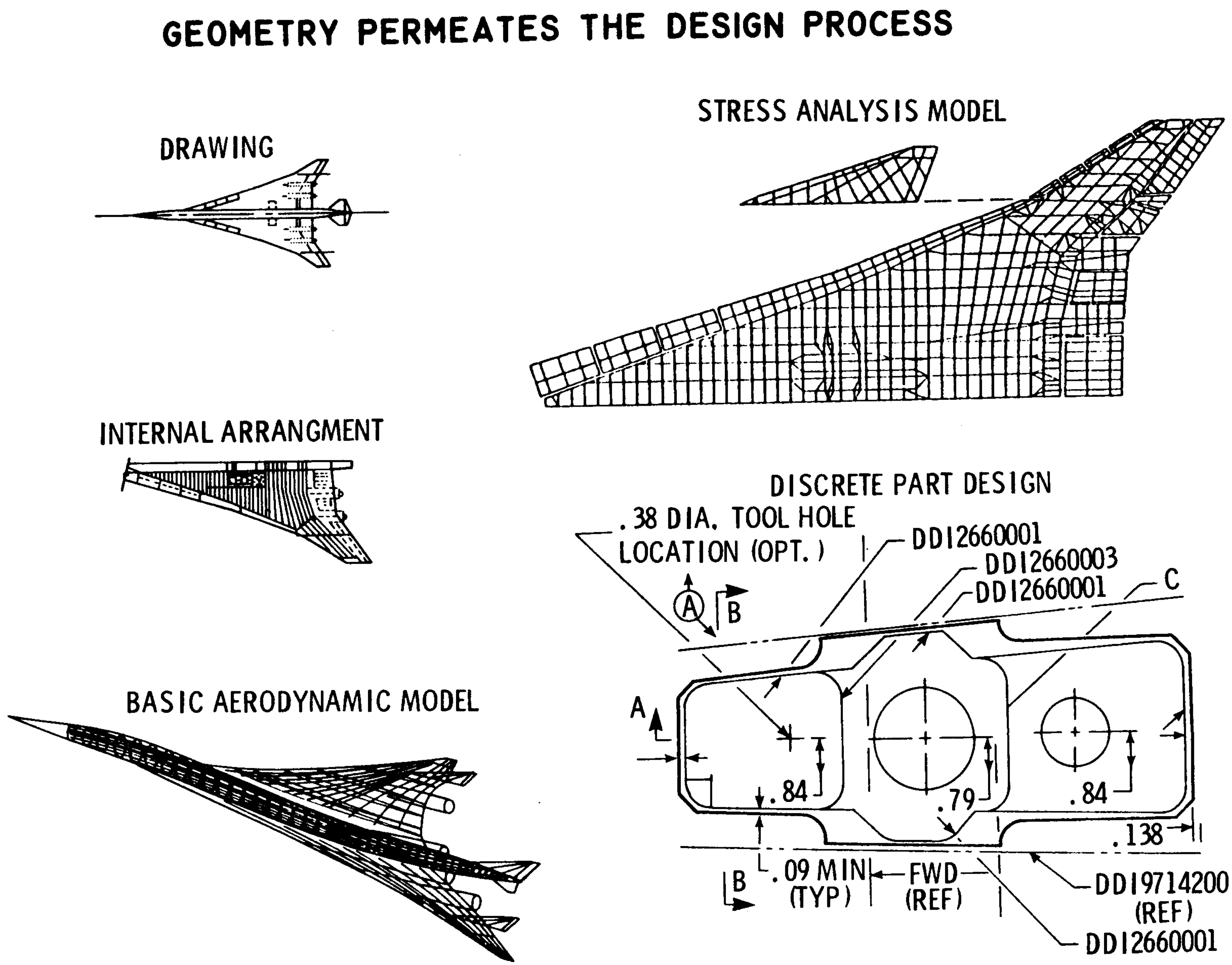

Figure 34: Critical Role of Geometry Information to CAD/CAM

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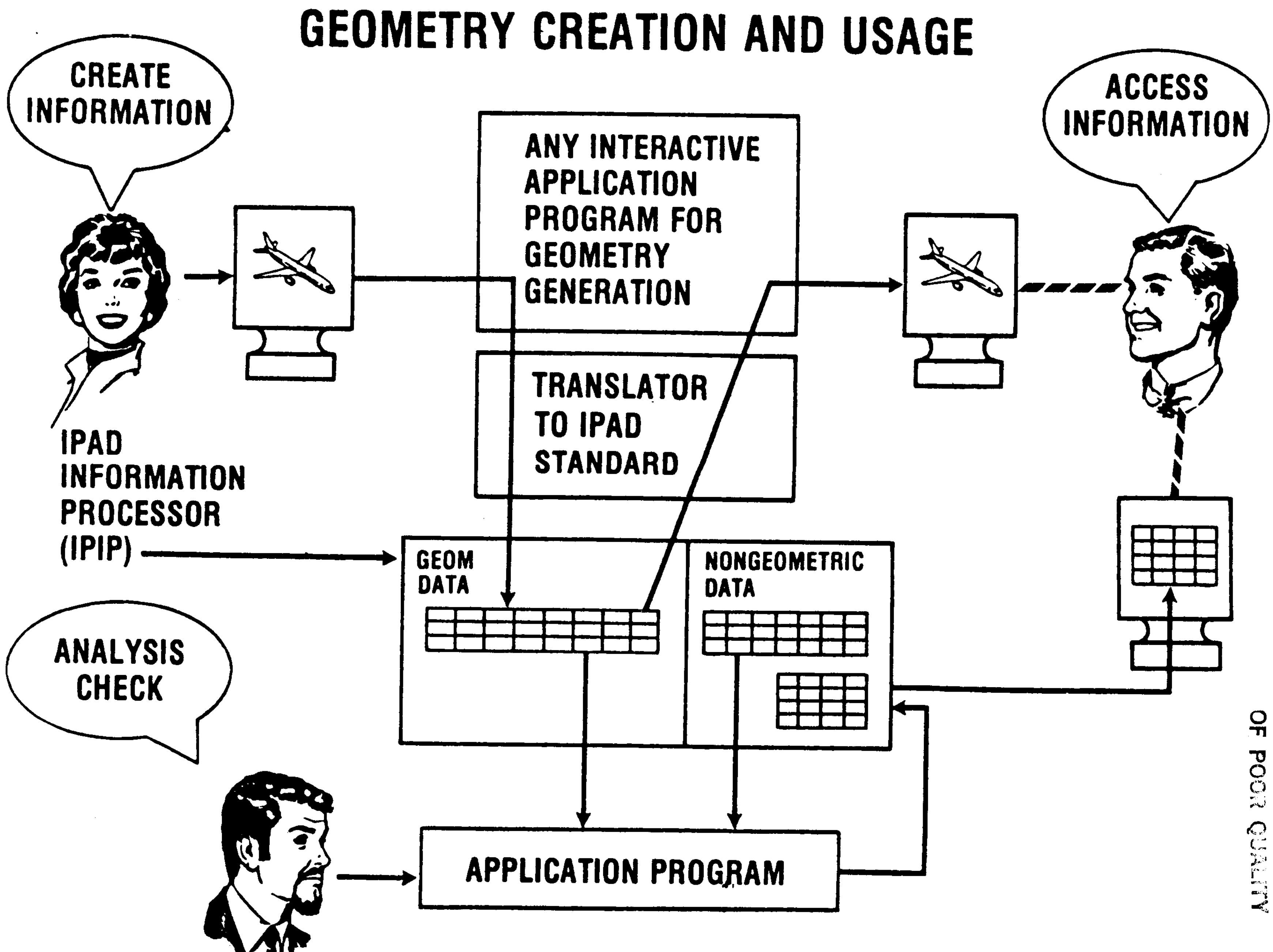

Figure 35: IPAD Approach to Unified Management of Combined Geometry and Non-Geometric CAD/CAM Data

APPROACH TO DEFINING INITIAL CAM DATA MANAGEMENT REQUIREMENTS

Detailed Trail of Sheet Metal Information

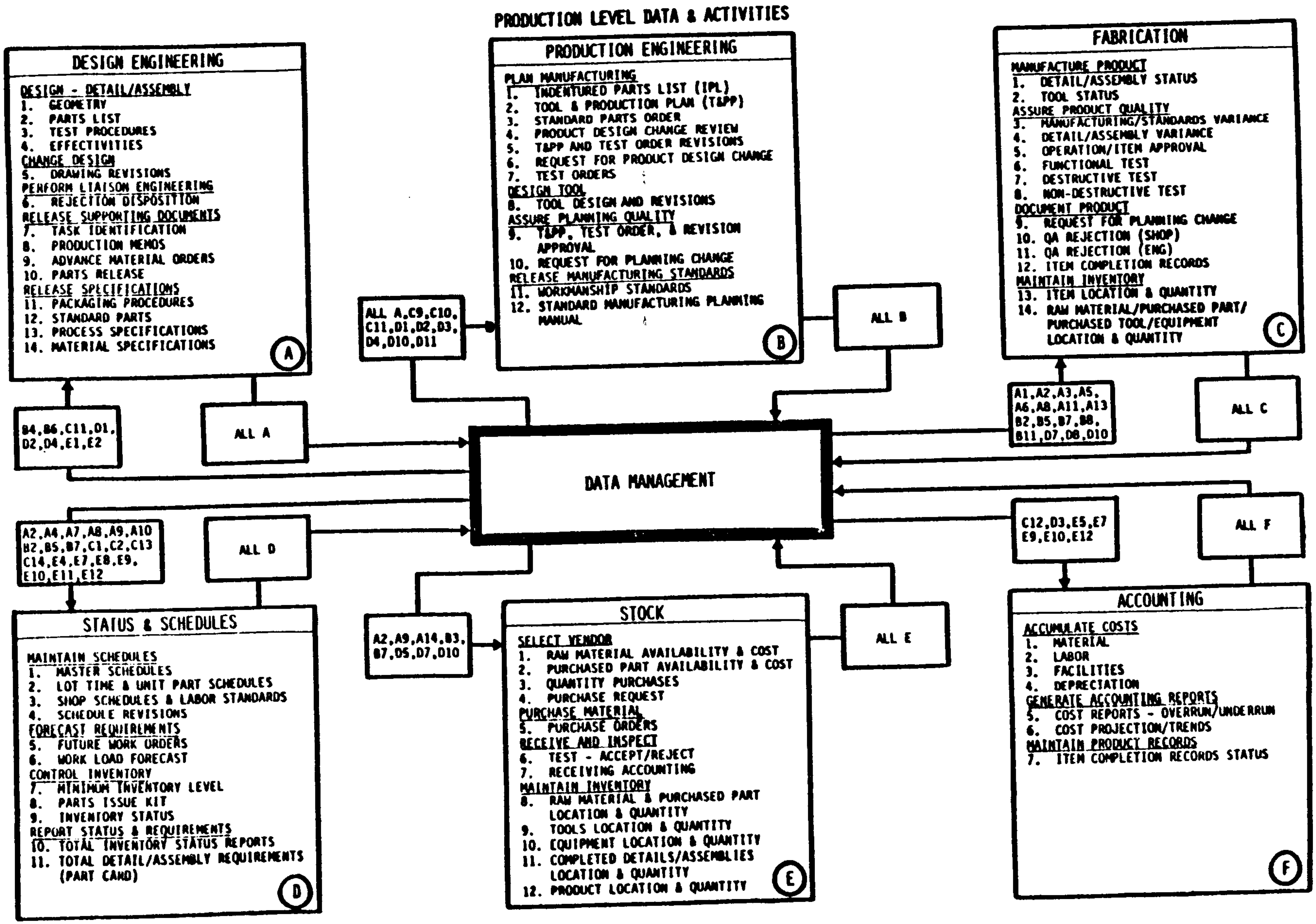

Figure 36. - Approach to Defining Initial CAM Data Management Requirements

C-2

FUNCTIONS NEEDED IN A CAM INFORMATION MANAGEMENT CAPABILITY

Data integration across heterogeneous computer systems

Transaction processing data

Real time interactions

Distributed processing and data

Multiple views of data

Levels of security, data integrity

Multiuser networks across dispersed work environment

Local - global data distribution

Geometry management

Versioning

Backup and recovery

Good user interface and knowledge base support

Integrated manufacturing and material management control

Quality assurance integration

Configuration control

3d electronic product definition data

Incremental implementation, organized to evolve, expandable

Figure 37: Functions Needed in a CAM Information Management Capability

IPAD PRODUCTS

Technology Reports (13000 Documents)
- Requirements and Design of Integrated CAD/CAM System
- Data Management, Geometry, Networking
- Data Communications Standards

Prototype Software (600 Software Packages to 325 Organizations)
- Data Management
- Networking
- Graphic Design/Drafting (Purchased)

CAD/CAM Coordination Mechanism (60 ITAB Meetings/Workshops/ Working Groups/Seminars/Symposiums)
- Information Exchange
- Concept and Software Evaluation
- Technology Guidance
- Focus Technology Attention

Figure 38: IPAD Products

C-2

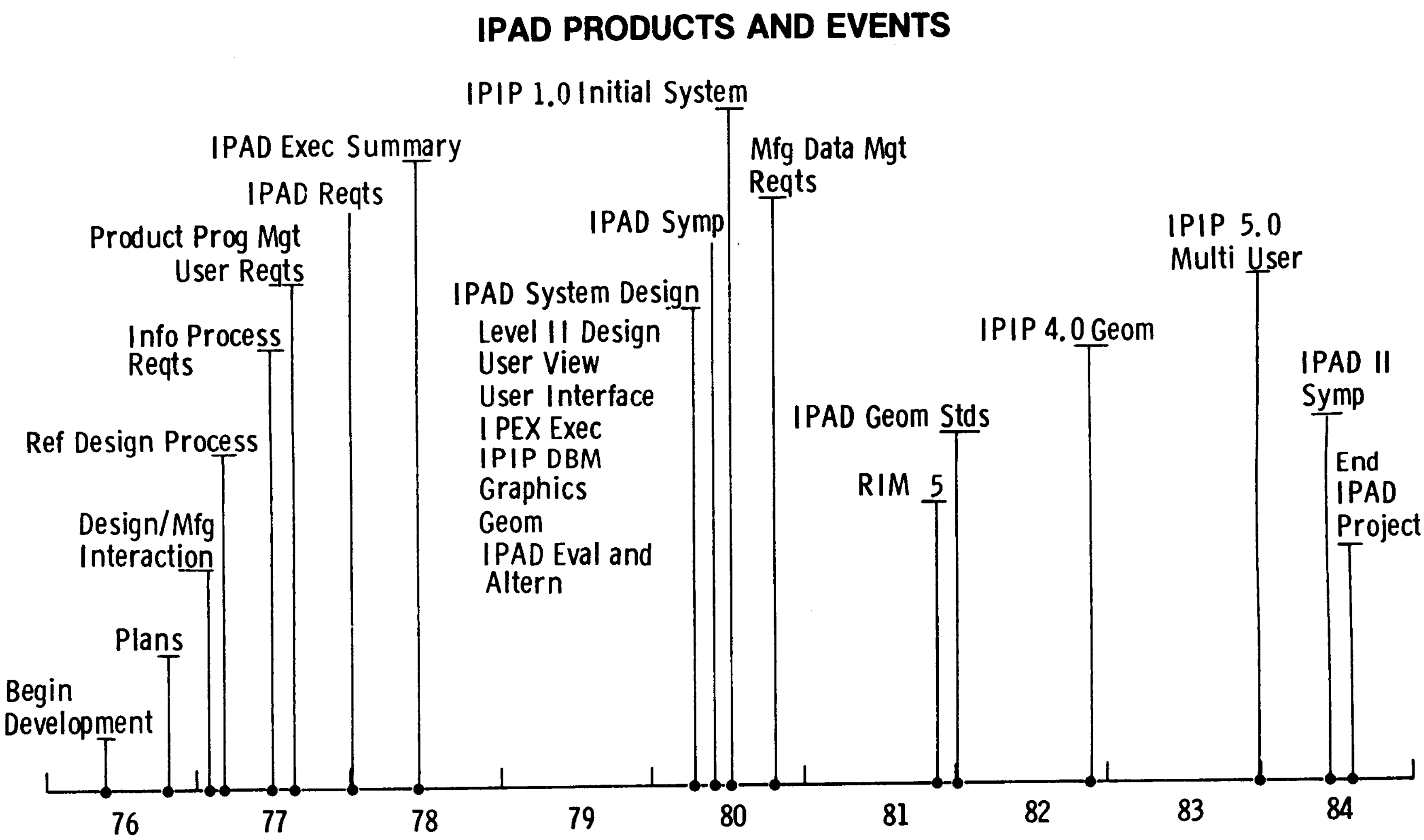

Figure 39: IPAD Products and Events

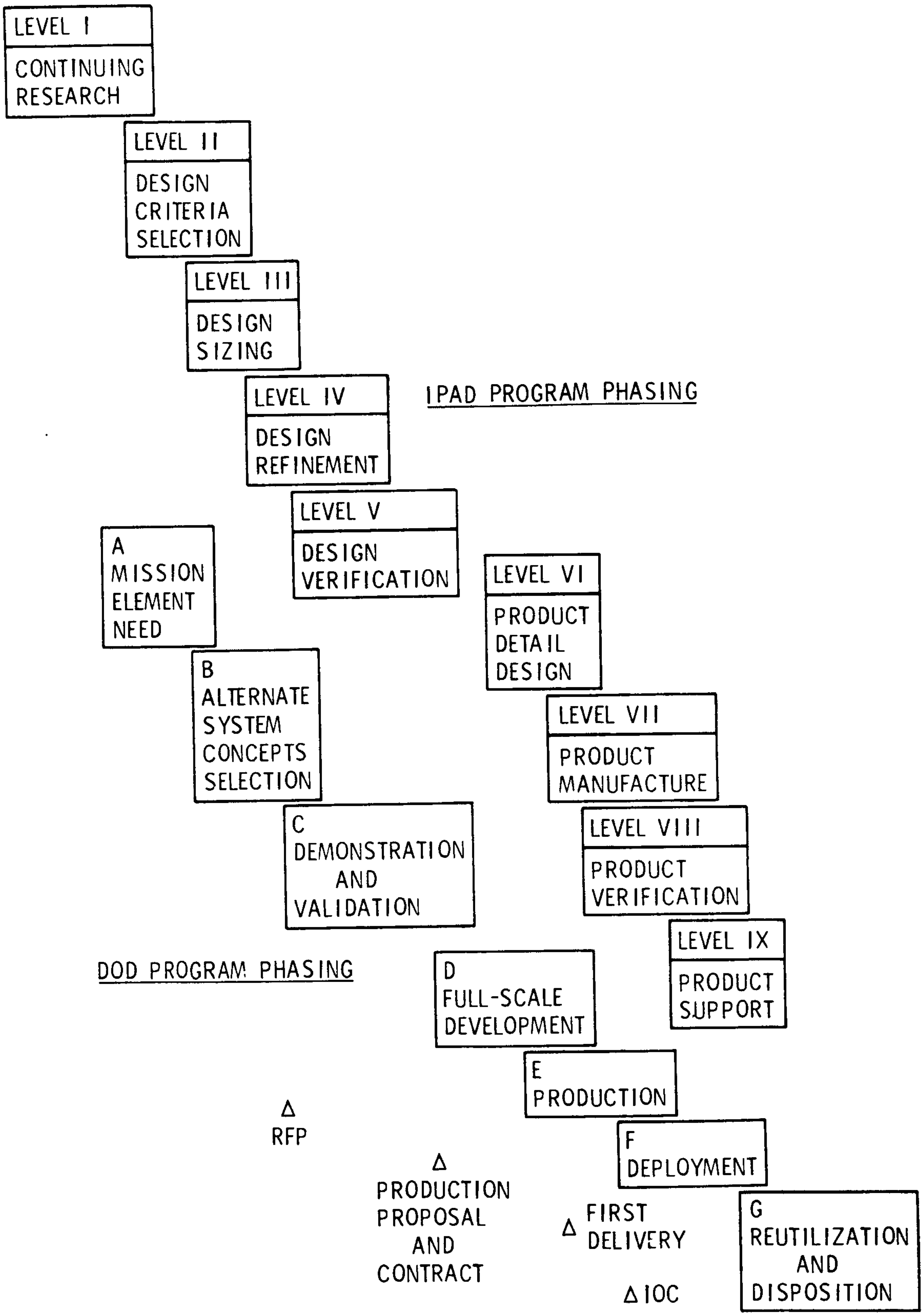

Figure 40: Commercial vs. Military Program Phasing
(courtesy of Lockheed Georgia)

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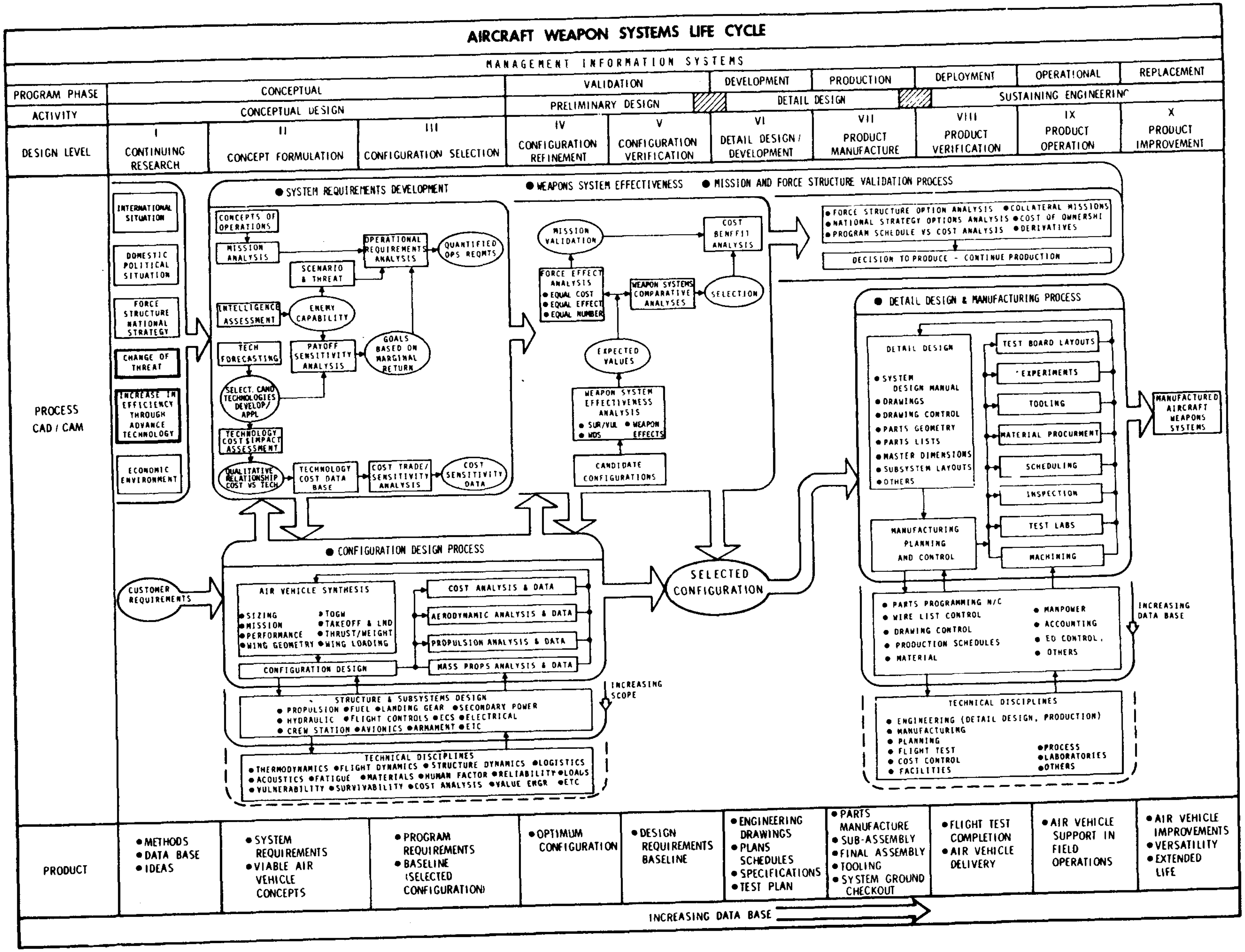

Figure 41: Aircraft Systems Life Cycle (courtesy Rockwell International)

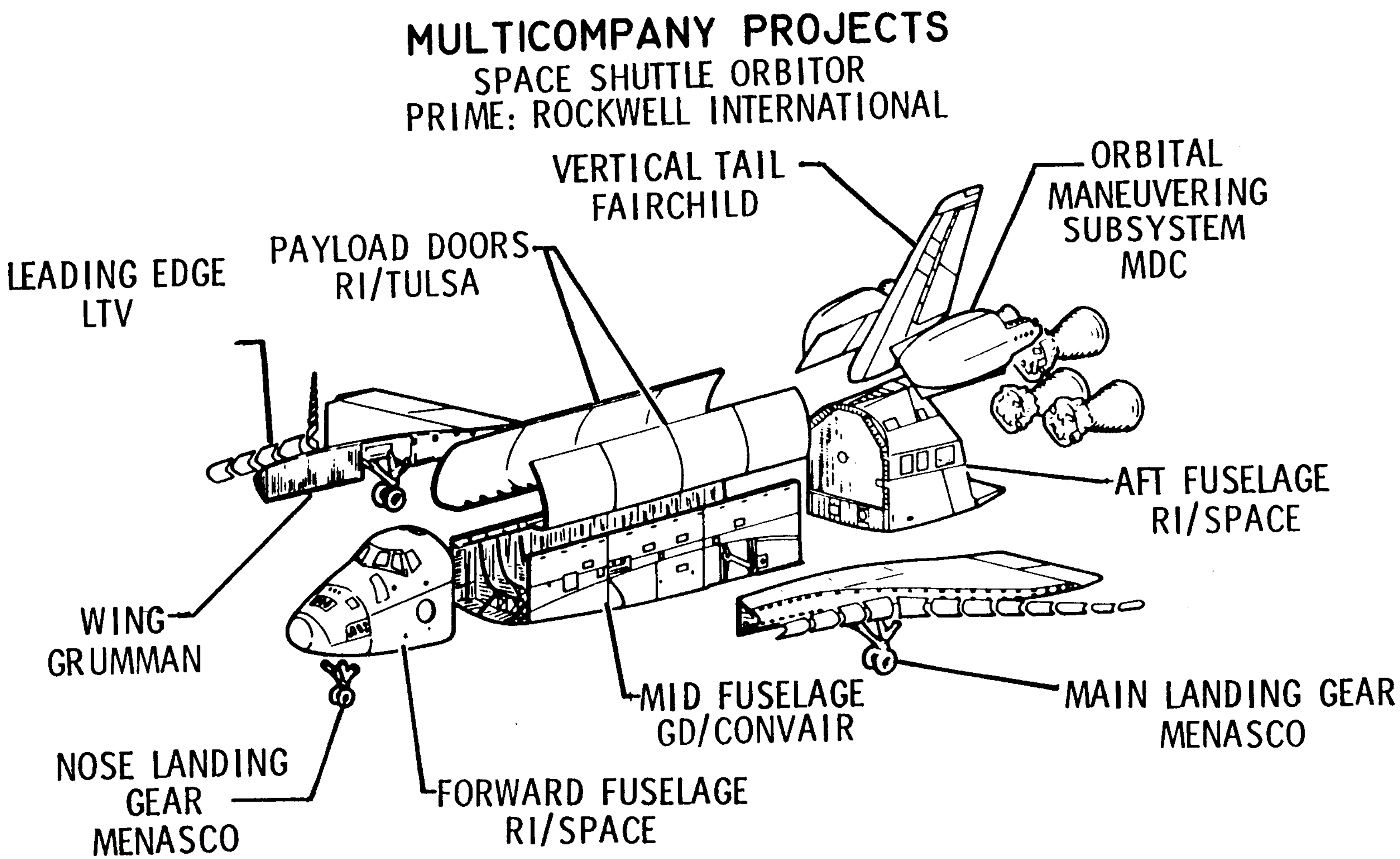

Figure 42: Typical Multi-Company Development Approach for Aerospace Products

MAJOR AVIONICS SUPPLIERS FOR ADVANCED NAVY AIRCRAFT E2C

COURTESY GRUMMAN AEROSPACE CO.

	MAJOR SUPPLIER
RADAR	GENERAL ELECTRIC
PASSIVE DETECTION SYS.	LITTON AMERCOM
COMPUTER PROGRAMMER	LITTON DSD
ROTODOME	RANDTRON
CONTROL INDICATOR GROUP	HAZELTINE
COMMUNICATION	COLLINS
IFF DETECTOR PROCESSOR	HAZELTINE
EQUIPMENT COOLING	GARRETT

EQUIPMENT LOCATIONS

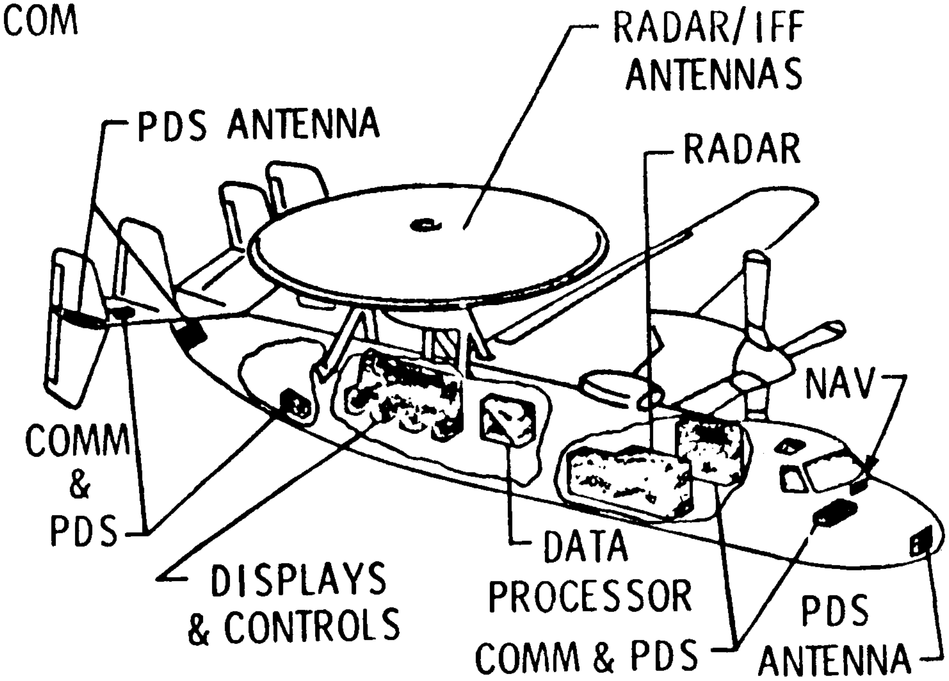

Figure 43. - Major avionics suppliers for advanced Navy aircraft E2C (courtesy Grumman Aerospace Co.)

INITIAL CAD/CAM DISTRIBUTED DATA MANAGEMENT APPROACH

DATA BASE FILE TRANSFER ENVIRONMENT

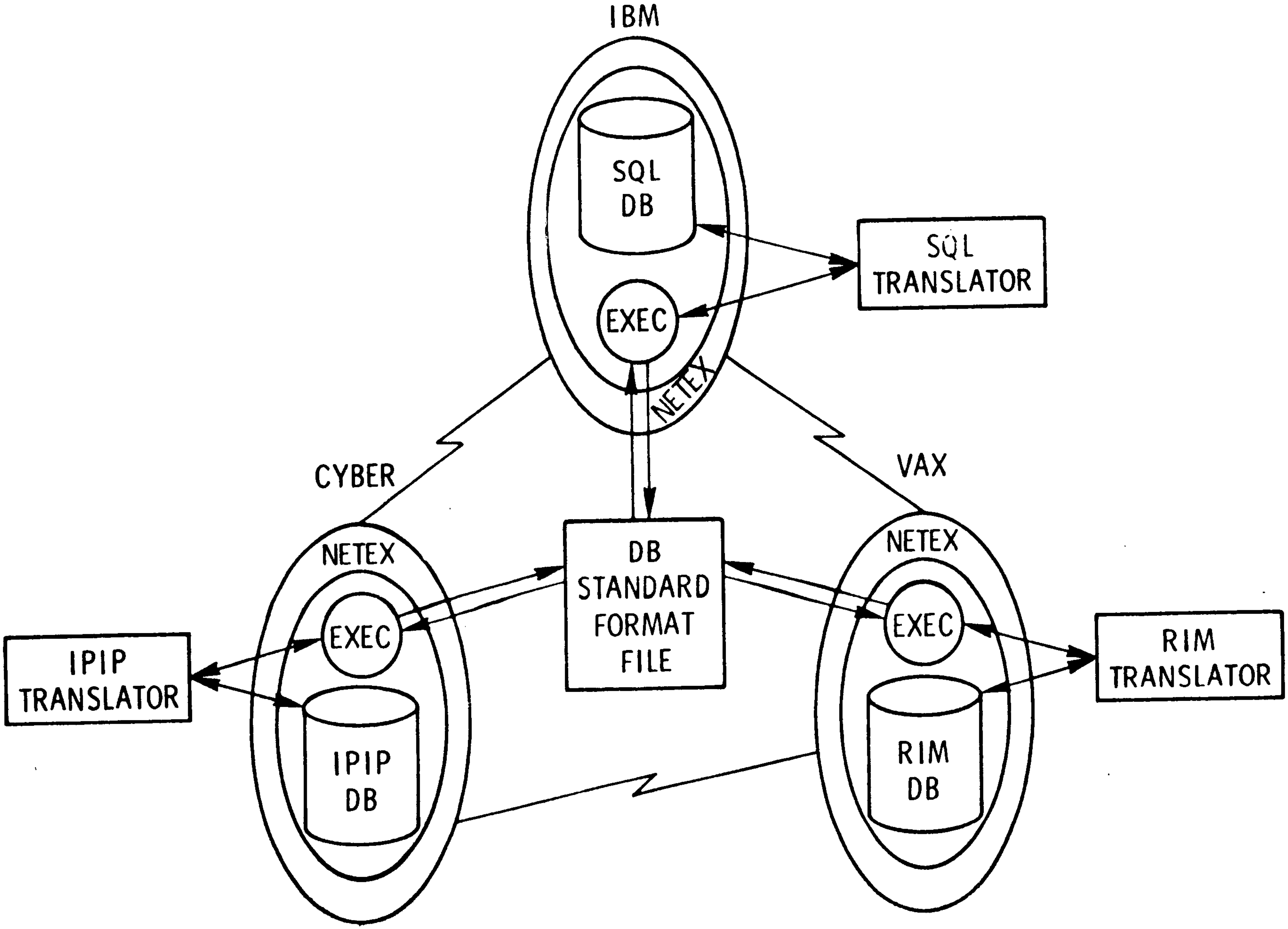

Figure 44. - Initial CAD/CAM distributed data management approach

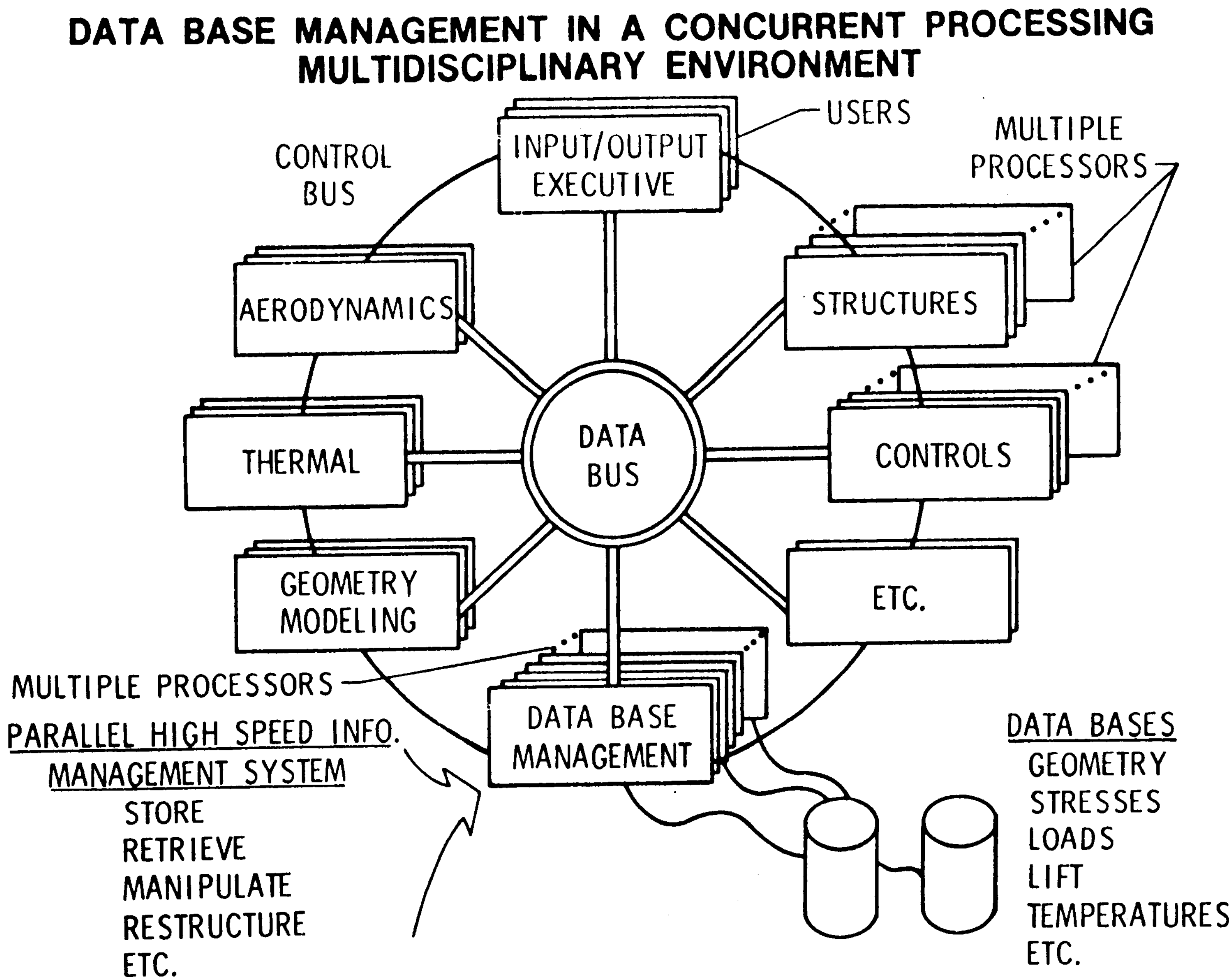

Figure 45. - Data base management in a concurrent processing multidisciplinary environment

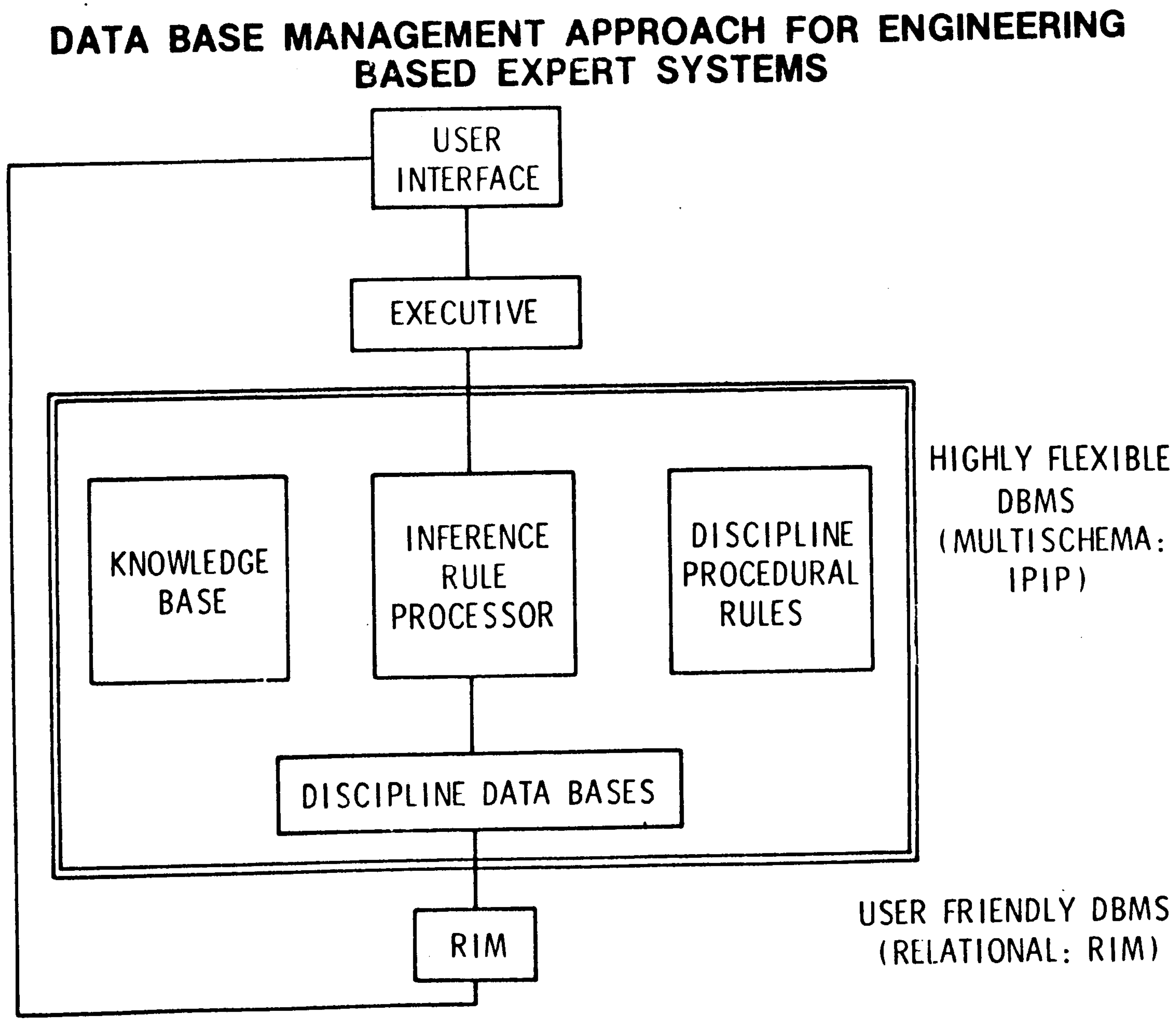

Figure 46 - Data base management approach for engineering-based expert systems

IPAD TECHNOLOGY TRANSFER CONTENT

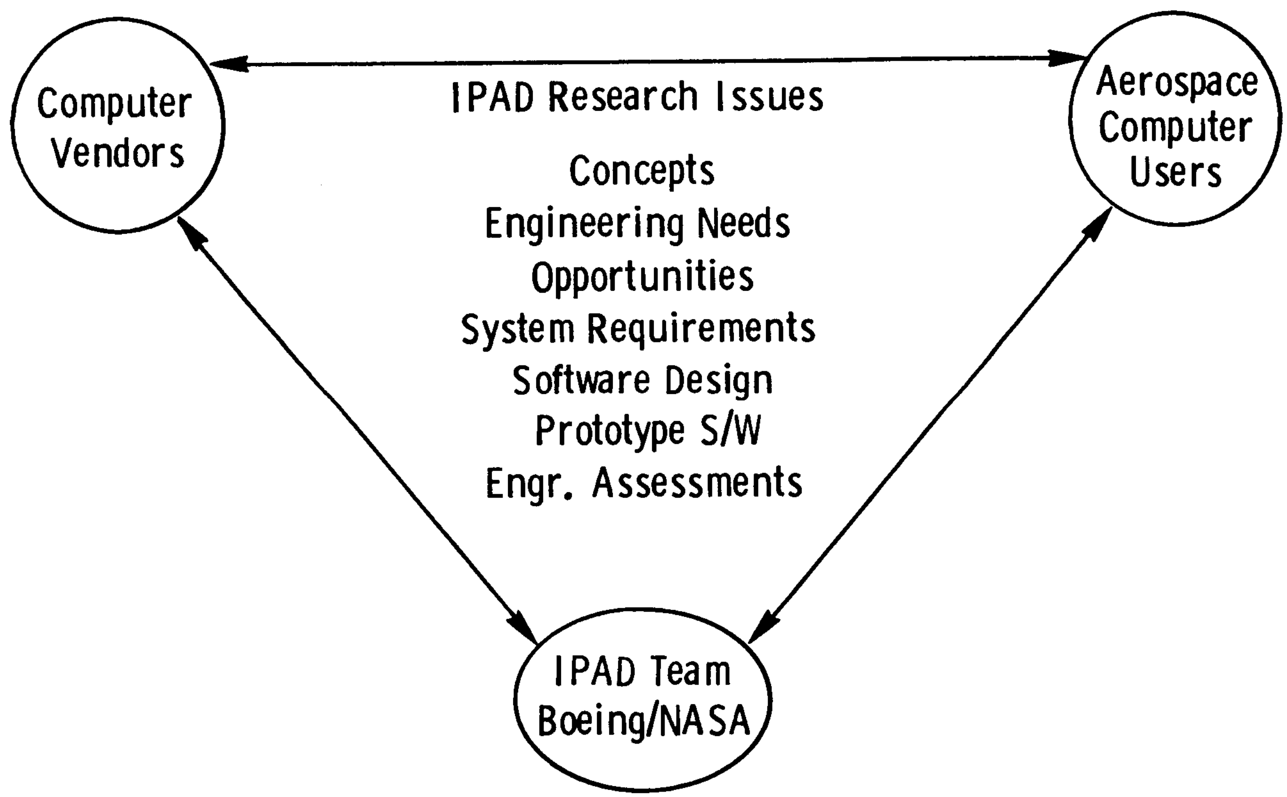

Figure 47: IPAD Technology Transfer Content

APPROACH TO TRANSITION OF IPAD PRODUCTS TO INDUSTRY

- ITAB Meetings/Technical Teams Critique Concepts, Recommend Actions, Coordinate Industry Efforts, Exchange Information
- ITAB Members Evaluate Products, Report Results
- ITAB Members Assign on Site Technical Staff to Participate in Development
- ITAB Sponsors Major Workshops to Summarize Status and Focus Technology Attention
- Prime Contractor Distributes Reports and Software to Prime ITAB Members/ Observers/ Others (150 Organizations)
- IPAD Project Encourages, But Does Not Support, Development of Commercial Ventures or User Groups for Software Maintenance, Support, Enhancements

Figure 48: Approach to Transition of IPAD Products to Industry

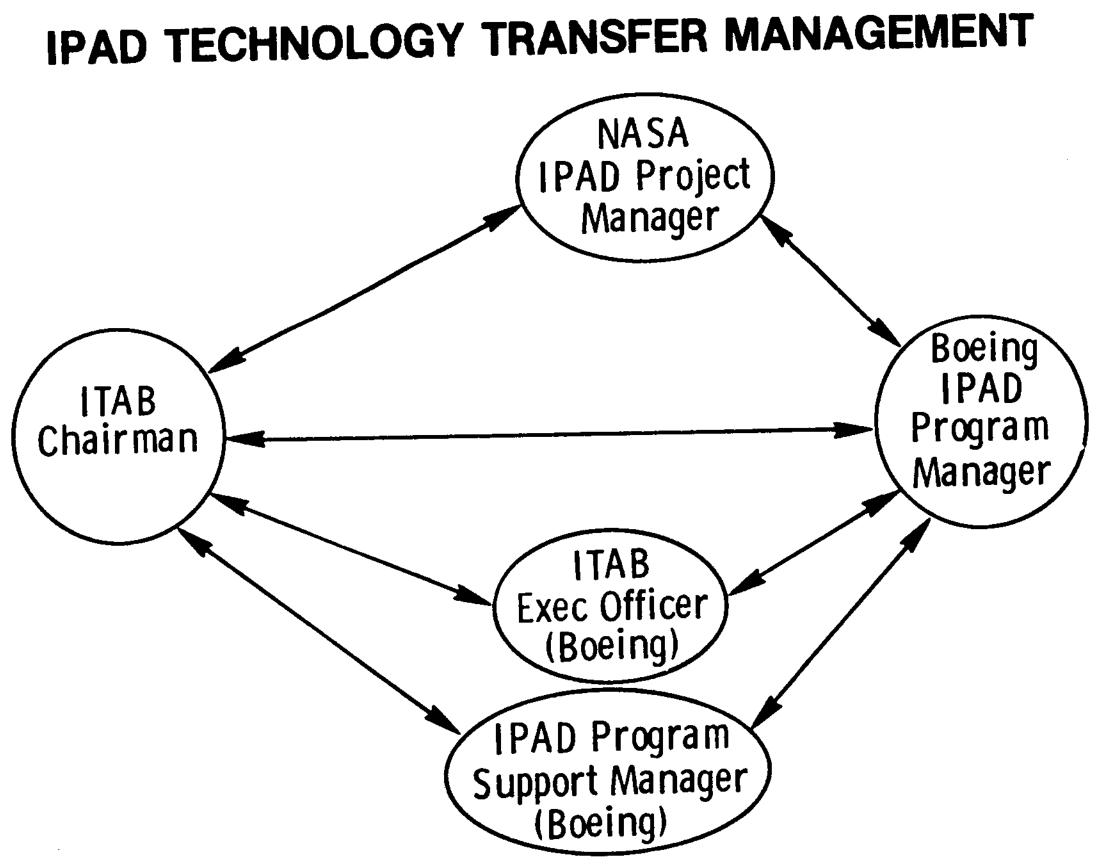

Figure 49: IPAD Technology Transfer Management

IPAD PROGRAMMATIC MILESTONES

1970 - 1973	IPAD concept studied in house at NASA Langley
Mar 72 - Aug 73	IPAD feasibility/definition studies
Oct 73 - Mar 74	Assess IPAD applicability to missile design (MDAC-W)
Oct 73 - Mar 74	Assess non aerospace spinoff (Battelle)
1973	Preliminary project plan
Jan 74	Aerospace management review (MIT)
Feb 75 - Apr 75	Industry review of IPAD prospectus
May 75	Release RFP for IPAD development
Dec 75	Select development contractor (Boeing)
Apr 76	Begin IPAD project to develop integrated design system, establish ITAB
1978	Program redirected to advance engineering data management technology
1980	IPAD relational data management system (RIM) applied to shuttle tile problem
1980	IPAD symposium, Denver, Colorado
1981	Multischema data management system operational (IPIP)
1982	Initial geometry DBMS Operational (IPIP)
1983	Begin Navy co-sponsorship, expand effort to CAM requirements
1984	IPAD II symposium on distributed CAD/CAM MGT technology, Denver, Colorado
June 1984	Close IPAD project, begin restructured program

Figure 50: IPAD Programmatic Milestones

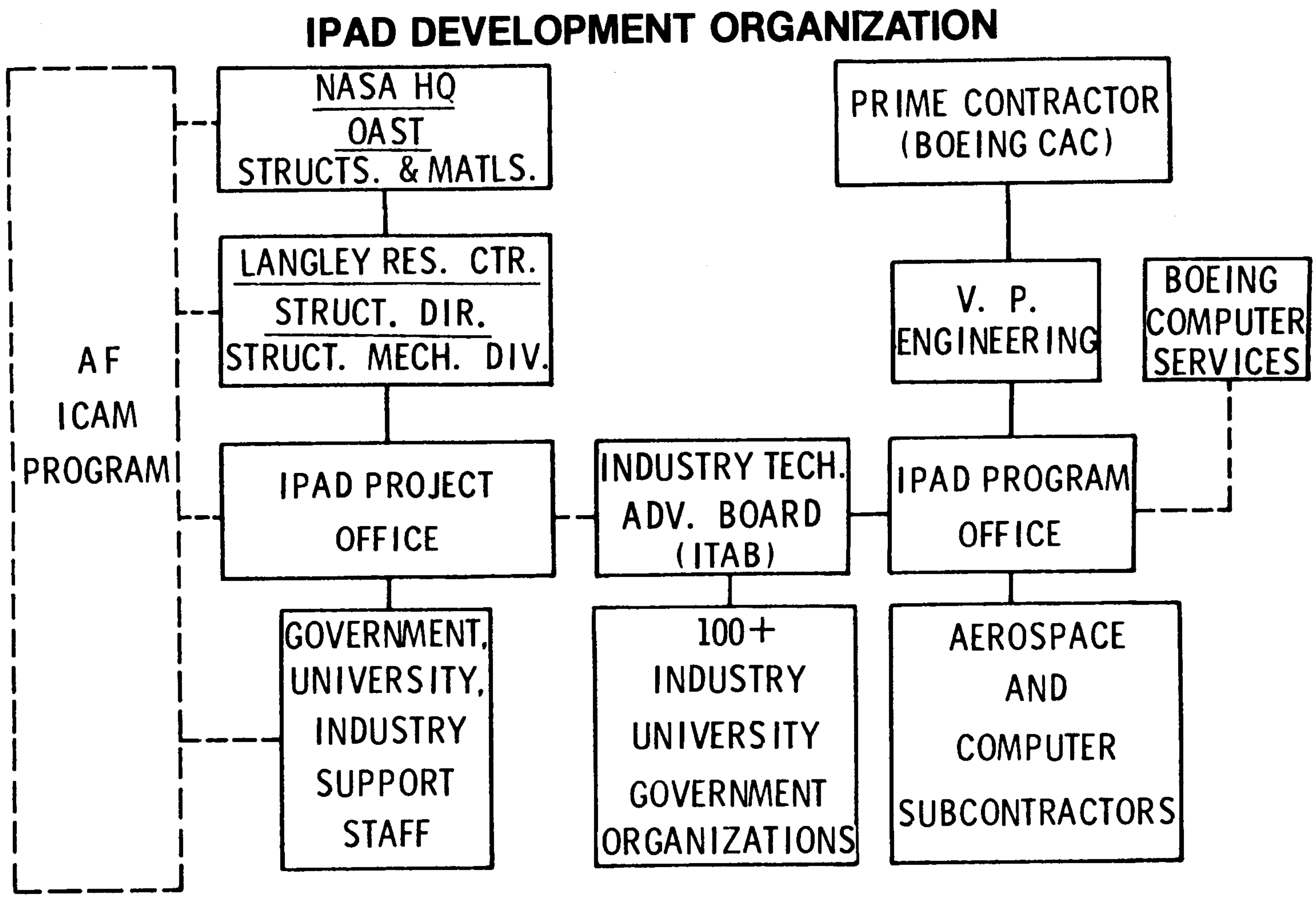

Figure 51: IPAD Development Organization

IPAD DEVELOPMENT PLAN

1970 - 84

Feasibility/Definition Studies and Industry's Critiques

Long Term R and D Prime Contract
- Establish Industry Technical Advisory Board (ITAB)
- Preliminary Design of Comprehensive Full IPAD System for 1980's
- Develop Prototype Software
  - Design, Code, Test Engineering Data Management Software
  - Distribute Incrementally, Seek User Feedback

Integrate Major CAD/CAM Functions

Independent Software Evaluation

Initiate Follow on Development

Figure 52: IPAD Development Plan (1970-84)

IPAD/ICAM COOPERATIVE ACTIVITIES

- Integrate Program Planning
- Provide Continuing Technical Liason
- Cooperate in Technical Conferences/Symposiums
- Collaborate in Tasks on Design/Mfg Interaction
- Planning S/W Integration and Joint CAD/CAM Demonstrations

Figure 53: IPAD/ICAM Cooperative Activities

NASA/NAVY CAD/CAM MANAGEMENT RESEARCH STRATEGY

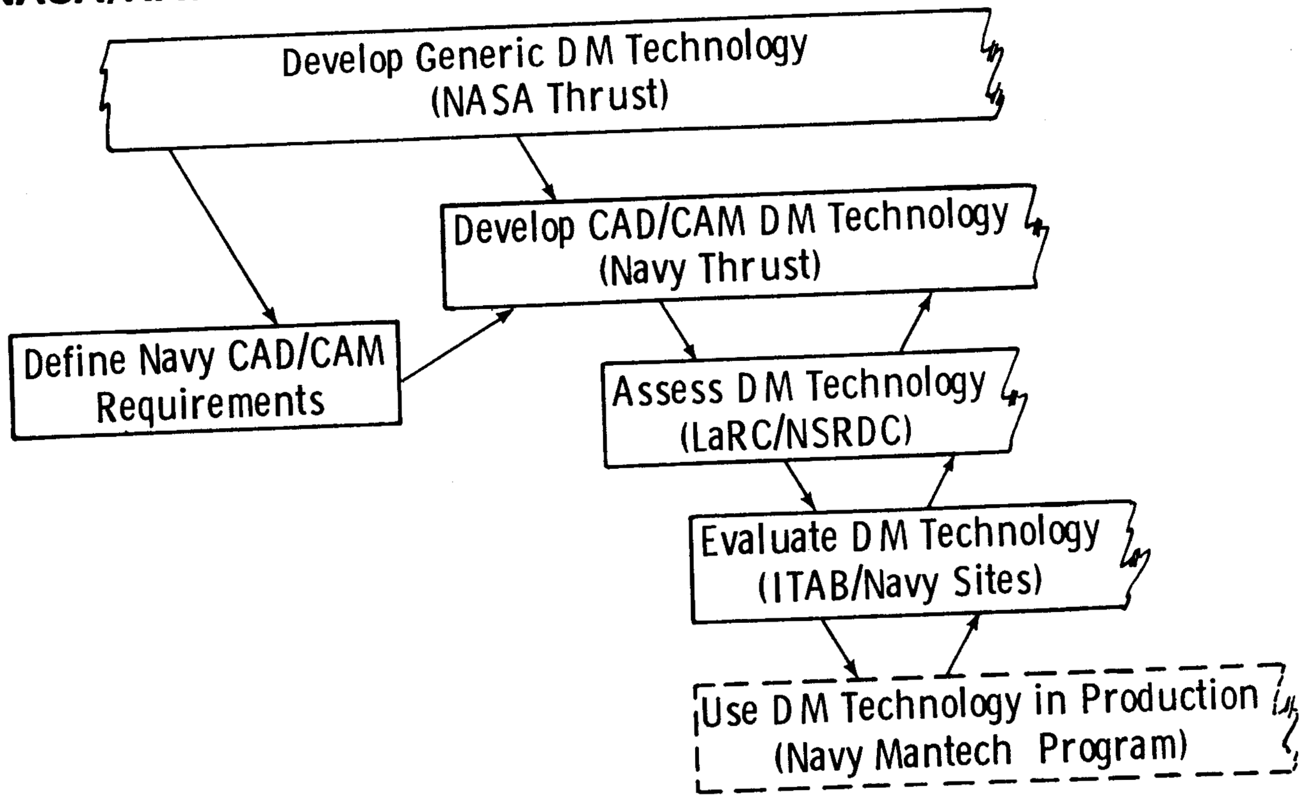

Figure 54: NASA/NAVY CAD/CAM Data Management Research Plan

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15. Supplementary Notes

Robert E. Fulton, George Washington University, Joint Institute for Advancement of Flight Sciences, NASA Langley Research Center, Hampton, Virginia.
George C. Salley, NASA Langley Research Center, Hampton, Virginia.

16. Abstract

A key element to improved industry productivity is effective management of CAD/CAM information. To stimulate advancements in this area, a unique joint government/industry project designated Integrated Programs for Aerospace-Vehicle Design (IPAD) was carried out from 1971-1984. The goal was to raise aerospace industry productivity through advancement of computer based technology to integrate and manage information involved in the design and manufacturing process. IPAD research was guided by an Industry Technical Advisory Board (ITAB) composed of over 100 representatives from aerospace and computer companies. The project complemented traditional NASA/DOD research to develop aerospace design technology and the Air Force's Integrated Computer-Aided Manufacturing (ICAM) program to advance CAM technology. IPAD had unprecedented industry support and involvement and served as a unique approach to government/industry cooperation in the development and transfer of advanced technology. This paper summarizes the IPAD project background, approach, accomplishments, industry involvement, technology transfer mechanisms and lessons learned from the project.

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