

ENGINEERING COMPUTER GRAPHICS IN GAS TURBINE ENGINE DESIGN,  
ANALYSIS AND MANUFACTURE

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ABSTRACT

This paper serves as an overview of a time-sharing and computer graphics facility designed to provide effective interactive tools to a large number of engineering users with varied requirements. The evolution of applied interactive graphics at Pratt & Whitney Aircraft will be traced as it occurred within the engineering environment. The application of computer graphics displays at several levels of hardware complexity and capability will be discussed; with examples of graphics systems tracing gas turbine product development, beginning with preliminary design through manufacture. Highlights of an operating system stylized for interactive engineering graphics will be described. P&WA problems and solutions in supplying cost effective, timely, and easily usable graphic tools to a wide spectrum of engineering users provide insight for others supplying or about to apply interactive graphics in similar environments.

BACKGROUND

Prototype interactive graphics work began at P&WA in the mid 60's on a UNIVAC 1556 display located at the United Aircraft Research Laboratories. Using an AED based, high level graphics language and a roll in/roll out modification to the operating system, several practical applications of interactive graphics were demonstrated to management. These applications could be categorized as enhancing analytical tasks in the design process by graphical visualization of input/output, by editing of key input parameters and by monitoring and modifying iterative processes to optimize solutions. The potential of interactive graphics and computing was evident by these first attempts despite operational, hardware, and organizational handicaps. A decision was made in 1968 to install an IBM 360/67 with three 2250-3 displays and 15 conventional typewriter terminals for time sharing. Application system and graphics program development was begun 6 months prior to delivery on a 360/50 supporting a 2250-1 display.

Impetus for the first integrated design system at P&WA came from a requirement to reduce design and analysis flow time in turbine blade and vane durability analysis. The Turbine Airfoil Development System, TADSYS, was implemented under CP/OS and introduced key concepts of dynamic module selection and execution from a CRT plus an online data base facilitating communication between application modules within the system (figure 1). After one year, results from using TADSYS proved that engineering analysis time could be reduced by a factor of 6, and that the decision-making capabilities of the engineer were expanded to achieve better designs through more detailed analyses. The success of TADSYS soon prompted development of a similar system for compressor aerodynamics (COMP) completed in mid 1970 and achieving similar results.

The introduction of interactive graphics provided many challenges to the computing team. A transitional period was necessary when compatibility with

batch methods was maintained. A modular programming approach allowed portions of the integrated system to be used early in development. Inexperience in graphics and human factors engineering were evident until the system support matured and graphic programs showed the logic stability and display quality necessary in interactive graphic applications.

As computer graphics was developing at P&WA, the computing support organization was also taking form. Computer graphics programming was begun, and experience developed, in a small task group, but is now a standard programming tool for the entire application programming section. A factor affecting the impact of computer graphics at P&WA is a single, complete computing organization working closely together, and including operations, systems analysis, machine systems, and all application programming. This group of approximately 300 people has a sole objective to service the needs of P&WA Engineering. Its success is measured in terms of its impact on engineering projects. Programming, done by "professionals" in the application programming group, has grown in complexity not only in computer graphics but in data management and systems integration. Programming is recognized as a discipline requiring a full-time trained specialist in order to best use state-of-the-art computer hardware and software.

Projects are established and funded on an individual basis. The need for, and basic approach to, a task is determined by a user-programmer team. Development is a joint effort with an end-user representative playing a major part in task specifications, including graphic frame content and final program verification. This environment appears particularly conducive to development of interactive graphics, which requires not only proficiency in computer programming, but also a clear understanding of human factors and detailed user needs.

#### COMPUTER GRAPHICS FACILITY

Main support for engineering at P&WA consists of two IBM S/370-168s. One computer is devoted entirely to time-sharing including computer graphics during normal working hours and is operated under VM/CMS. The other machine operates under OS/VS2 and supports scientific batch and engineering commercial applications. Communication between the two 168s is an integral part of the interactive facility.

As stated previously, productive use of interactive graphics started with IBM 2250 displays. Widespread implementation of graphics at P&WA continued with the introduction of low-cost storage tube displays. Total analysis and design systems previously developed in their entirety for refreshed displays were re-analyzed, decomposed, and graphics modules implemented where most effective. Many passive or limited interactive graphics modules are run as effectively on storage tube displays and at a 10 to 1 cost differential in terminal costs. Storage tube displays are located directly in engineering work areas and provide, as needed, hands-on flexibility -- not possible with the limited number of more expensive devices requiring days-ahead scheduling for individual use. For example, a general object breakup program, GOB, has been implemented at both the refreshed display and storage tube level. Initial finite-element modeling for structural and thermodynamic analyses is completed at a

2250 display using the full picture update and light pen interaction capabilities of a refreshed display. Component trade studies requiring shape modifications, boundary condition application, banding optimization, and the overall first model verification are completed. Generally, follow-on engineering iterations necessary during component analysis require less geometric viewing and modification, and are processed on the storage tube using the same online files generated from the 2250 display.

This philosophy of a hierarchy of terminal capabilities has been extended to many areas of engineering application including preliminary design specification and engine simulations (SOAPP), component and engine test data reduction (MDR), and component design and analysis (DERVA, VIBRA). Presently, in support of these application systems, there are over 80 addressable ports, available under VM/CMS. Most are alphanumeric CRTs or edit typewriter terminals but over 30 graphic devices are supported. At present 24 Tektronix 4010s, 8 Tektronix 4014s, 3 IBM 2250s and one E&S Picture System (manufactured by the Evans and Sutherland Computer Corporation) complete the terminal complement. Offline plotting facilities including Calcomp drum plotters, and a Gerber flatbed model. Current plans include installation of a Computervision 3D-IDS system for generating detail drawings and a minicomputer-based engine part hardware measuring inspection device for online digitizing and comparisons with nominal design coordinates.

An important aspect of a computer graphics facility is software support -- particularly at the systems and graphics processing levels. Considerable effort at P&WA is directed toward making the time-sharing and graphic systems usable by noncomputer experts and engineers, without the assistance of programmers or computing technicians. Much of this software uses VM/CMS as a base. CP/CMS, its forerunner on the 360/67, was developed by IBM initially as an aid in operating system development. However, the command language flexibility and simplicity, virtual machine structure and time-sharing supervisor provide a ready foundation for an engineering-oriented time-sharing network (reference 1). The total system can be viewed as having five major software operating levels -- system supervisor, virtual machines, subsystem interfaces, exec procedures, and application modules (figure 2).

#### System Supervisor

At the systems supervisor level, graphics performance has been improved by modifications to the paging algorithm, shared pages, locking high activity pages, and by a special interrupt handler geared to P&WA's mix of compute bound and interactive requirements. This tuning has been critical to the success of time-sharing at P&WA because totally integrated engineering tasks, composed of interaction and CPU processing, are typically completed during a terminal session.

#### Virtual Machines

The virtual machine structure under VM affords the graphics user functions which enhance the usability of the terminal hardware. The virtual machine principle, stated simply, is one in which each user of the system has access to all components of a real computer; i.e., console terminal, memory, disc, and unit

record devices. The Control Program (CP) manages all requests and usage of real devices in the system. From the view of the terminal user he is using a (virtual) computer devoted entirely to his task. He is, in one respect, the computer operator. The command set allows him to start and stop tasks, attach discs, and access I/O devices at will. The P&WA conversion of the Graphics Access Method (GAM) to operate under CMS has given the 2250 user all the advantages of CMS. Prior to 1972, GSP/GAM was supported by an OS/PCP virtual machine running under CP and the engineer user was obliged to act as an OS machine operator. The user of a virtual machine is able to access and update data files, invoke language processors (APT, FORTRAN, COBOL, SCRIPT, SNOBOL) and run complete applications directly in his pre-assigned virtual machine.

Virtual machines also provide additional support functions which affect user productivity. Once a virtual machine is logged-on, the terminal console device may be disconnected, leaving the virtual machine operational but unattended. In this mode, certain communication functions are handled and special output is produced. Hard copy plotting mainly on offline Calcomps is generated by transferring output plot data directly from one user virtual machine to the virtual reader of a special disconnected plot virtual machine. Machine operations personnel transfer (dump) this plot data to magnetic tape when spool activity dictates. By this means, hard copy plot documentation is returned, in a timely fashion, to the terminal user with little inconvenience or effort on his part. Similar procedures exist for providing punch tapes for numerical control machine tools and computer output on microfiche (COM).

Disconnect virtual machines also serve a performance monitor function and are an integral part of a Central Data Base facility, to be covered later in this paper.

### Subsystems

Virtual machines serve as communicators for subsystems (figure 3). Remote job entry (RJE) and cross machine communications are handled with disconnected virtual machines. Extensions to the CMS command set provide establishment of OS job streams and allow for submissions to the batch S/370-168 during a terminal session. The full command set of a HASP RJE station is available from any virtual machine and is regularly used to query status of individual jobs within the batch computer.

Approximately 300 jobs/day are being processed via this link during normal periods. Communication with the PDP-11 based Picture System is currently supported at the virtual RJE level; a higher level FORTRAN-callable (SEND/RECV) protocol has been defined, and will be implemented shortly. This facility will provide much needed software support, whereby the CPU power and file management capability of the 168 can be combined with the picture quality and dynamics of a high performance graphic display, and exercised concurrently, during a Picture System terminal session. In general, off-the-shelf minicomputer operating systems do not address themselves to man-machine human factors encountered in a CAD/CAM application. Communications with S/370-168 need to be completed before the full potential at P&WA for this high performance display is realized.

## Exec Procedures

Supported within VM/CMS is a (exec) procedure generation capability, which allows basic CP and CMS commands to be grouped together and thereby generate a macro level command (reference 2). This exec facility contains looping commands, argument lists, and stack procedures which are extremely useful in creating end-user task procedures; which make transparent to end-users many of the basic machine system commands required for computer communication. Exec writing has become an important level of application programming in P&WA design systems. They are used to control program selection and execution in integrated design systems; they establish I/O protocols with system resources, as well as with user online files throughout the system. Designers and engineers, for the most part, communicate with the computer via these execs and see few of the basic CMS command set.

## Program Modules

Application modules are written almost exclusively in FORTRAN and complete the system. A library of approximately 500 distinct modules is operational on the time-sharing system. These programs are used throughout the design process and in many areas of manufacturing. Figure 4 depicts the areas using the interactive facility and illustrates the availability of a shared data base for interchange of engineering design data from discipline to discipline. This integration of the entire computerized design process is an underlying objective of systems development and is proceeding in an evolutionary manner. The basic computer concepts involved will be presented later. P&WA's experience has been primarily in design areas. Figure 5 shows those portions of gas turbine engine design which utilize interactive graphics for design analysis support within an integrated design system.

In many cases, the application graphics codes include use of many special purpose routines which have been developed to supplement vendor supplied software. In particular, routines to perform some functions in the non-intelligent 2250 display processor have reduced the number of interrupts to the mainframe. Faster response in light pen tracking, scaling, and some real-time object translations have enhanced graphic interaction.

## TURBINE AIRFOIL DEVELOPMENT SYSTEM

An example of an integrated design system, which serves to illustrate more concretely the significance of the total system environment, is the Turbine Airfoil Development System, TADSYS. A description with emphasis on engineering content and application can be found in a paper by K. Thomas and J. Piendel (reference 3). A more encompassing description of the turbine CAD/CAM system was presented by E. Nilson at the USA-Japan Design Automation Symposium '75 (reference 4). The major objective of the system, as it exists today, is to support rapid design and analysis of the turbine component in a gas turbine engine. Figure 6 shows the major steps in the process. Many of them contain several computer programs which are described at some length in reference 3.

Stepping through the process helps to show how computer graphics plays a role in this system.

The system begins with a one dimensional gas dynamic analysis of the entire turbine followed by a streamline determination and gas loading analysis. This is accomplished at the storage tube level. Graphic output of the flowpath and velocity vectors is possible (figure 7). The storage tube was selected because the input to these modules is mainly alphanumeric. However, passive graphical output is valuable in the iterative process of establishing a flow-path. Data resulting from these studies is deposited in a data base for input to individual airfoil aerodynamic design. This data together with parametric models of airfoil profiles is used to compute proposed airfoil contours (figure 8). The contour cannot be established until studies of the subsonic and transonic pressure distributions and boundary-layer effects are completed. Again the device is the storage tube display. A significant computation requirement exists at this step along with interactive graphics design needs. This dual requirement of heavy CPU load and interactive response is a difficult one to meet. In TADSYS, a background virtual machine processes computations while the designer is preparing new cases or examining previous results. This is one of the few areas in P&WA's design process that has needed this unique procedure.

After completion of the aerodynamic design, the terminal used for graphics becomes the 2250 refreshed display. An internal cooling scheme is synthesized at the display using the external shape as a starting point. A flow topology, representing all the internal flow paths, is determined and becomes the model for a detailed flow balance of the 3D flow network (figure 9). Conceptually, this has been one of the most difficult graphics processors we have had to develop. The graphics processor we use today has the ability to represent several path types including film holes, channels, orifices, pedestals and expansion-contractions. The designer interacts with the design shape on the CRT and the program computes automatically all characteristics of the flow path from the stored geometric model. Results of this analysis are stored as boundary conditions for subsequent steps in the process.

A finite-element model is needed for the heat transfer and stress studies which follow in the process. A family of interactive breakup programs, designed for turbine airfoil shapes, is available. The principle in all of them is identical. Given the outline of the cross section to be analyzed, the designer interactively selects flag points on the surfaces which determine major areas in the model where the coarseness of the model will be specified (figure 10). The grid (number of rows and columns) in each of these regions is then indicated. The modeling program computes the fine grid model and all properties required for thermal and stress analyses. The result is displayed on the CRT followed by key properties of the model (figure 11).

Both steady-state and transient thermal analyses are possible within the system. The designer supplies additional thermal inputs at the display and the computation begins. Output is displayed in isotherm form (figure 12) with interrogation methods provided interactively. Slices through the airfoil can be requested and temperatures at the neighboring nodes are displayed. Results of the following stress analyses use isoplot methods for stresses and strains

(figure 13). Scaling options and the ability to compute additional isolines on the fly enhance the effectiveness of these packages.

TADSYS is designed for simultaneous multi-terminal operation. Other graphic modules and many nongraphic interactive steps are part of the system. The advancing engineering technology of turbine design now requires frequent use of full 3D aerodynamic, thermodynamic, and structural analyses. Several current designs have utilized upgraded analyses and the data base has been used to extract these models.

#### CENTRAL DATA BASE

Systems like TADSYS have the ability to communicate with a Central Data Base, which is geared to assist in engineering data flow from discipline to discipline in the design and manufacturing process. This file management system relies on the virtual machine facility to handle data both in a preliminary design mode and in a final design sense (figure 14). A considerable amount of the data is geometric and represents component designs synthesized and analyzed at interactive graphic terminals. Part definition can migrate from preliminary design to manufacturing where process planners, tool designers, and numerical control part programmers use information of value to them.

The Central Data Base currently supports design systems at the file management level only. Data bases (as in TADSYS) address data at the record and word level. When data is transferred to Central, header and control information at the beginning of every file is stored in directories. Directories can be integrated by the user via search/sort utilities. Files are managed by an application system data base administrator whose responsibilities are to maintain data integrity and to monitor the proper balance of online and tape archival data.

The need for a technical data management system is crucial to any large-scale integration of interactive computing systems. VM/CMS - PWA Graphics does not totally meet this need. Systems to handle very large engineering/manufacturing data bases are under study. Preliminary work suggests that it will be possible to expand the present system, possibly using a Virtual Data Access Manager (VDAM) approach (reference 5) together with a direct communication support between active virtual machines.

#### HIGH PERFORMANCE GRAPHICS

The spectrum of computer graphics at P&WA has been upgraded to encompass a high performance intelligent display, namely the E&S Picture System. A requirement exists in design and manufacture for high resolution, real-time dynamics of 3D objects and distributed processing to support fast response in user interaction. Applications include pre- and post-processing of 3D structural, thermal and aerodynamic data, representation of hardware test rig results, geometry

synthesis of complex turbine blades and vanes and NC data generation and verification. Potential for advanced technology graphics at P&WA is highest in areas where costly and time consuming model making and trial part manufacture can be eliminated by computer models.

Figure 15 is a photograph from the CRT display showing the core of a turbine blade and an inserted tube partially removed. A simulation of the removal process is required to assure that the component can be manufactured. Twist and curvature of the part combined with tight tolerances in the tube operating position make this verification non-trivial. The high performance display's hardware clipping has been used as a plane slicer and linear interpolator such that displays of any section of the object in various orientations can be generated. The data structure within the computer is such that the pierce points can be reconnected and redisplayed in real time. This dynamic slicing has been valuable in this application as well as others. Figure 16 is a photograph from the CRT of a numerical control cutter path of approximately 5000 lines. This display has proved useful in determining errors in NC part generation, particularly for complex surfaces. The Picture System display program communicates with the main APT support under CMS. Storage tube graphics is also utilized in NC applications. Acknowledgement is given to L. C. Knapp from E&S for his onsite software development and system support in this Picture System effort.

#### SUMMARY

This paper presents an overview of a total system environment conducive to engineering use of computer graphics. The growth in computer graphics as illustrated in Figure 17 is some indication of the success of this effort. Records show that over 600 engineers and technicians per month use the VM/CMS - PWA Graphics facility -- nearly 900 have received formal training. What has evolved at P&WA is a result of many major contributions by people with special skills and talents working in an atmosphere which has made the user transitions to new computer technology and computer graphics viable.

## REFERENCES

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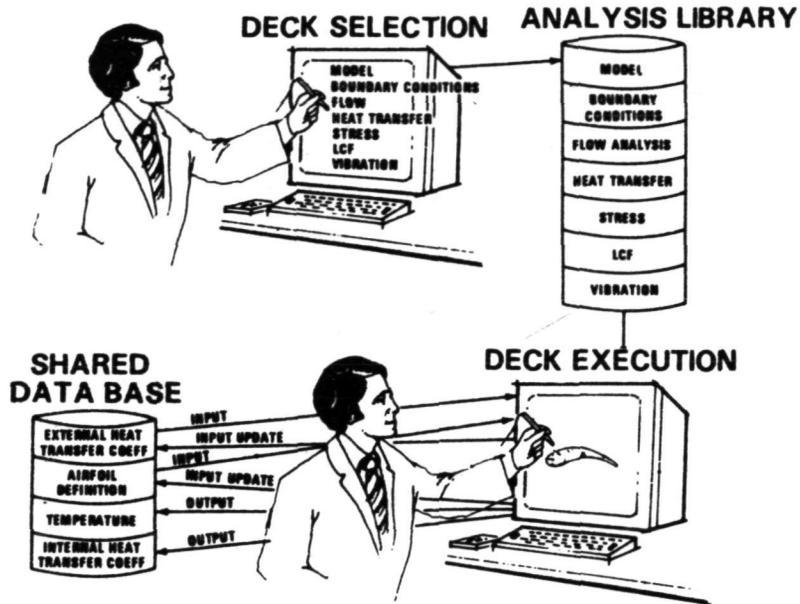


Figure 1.- Interactive design system operation.

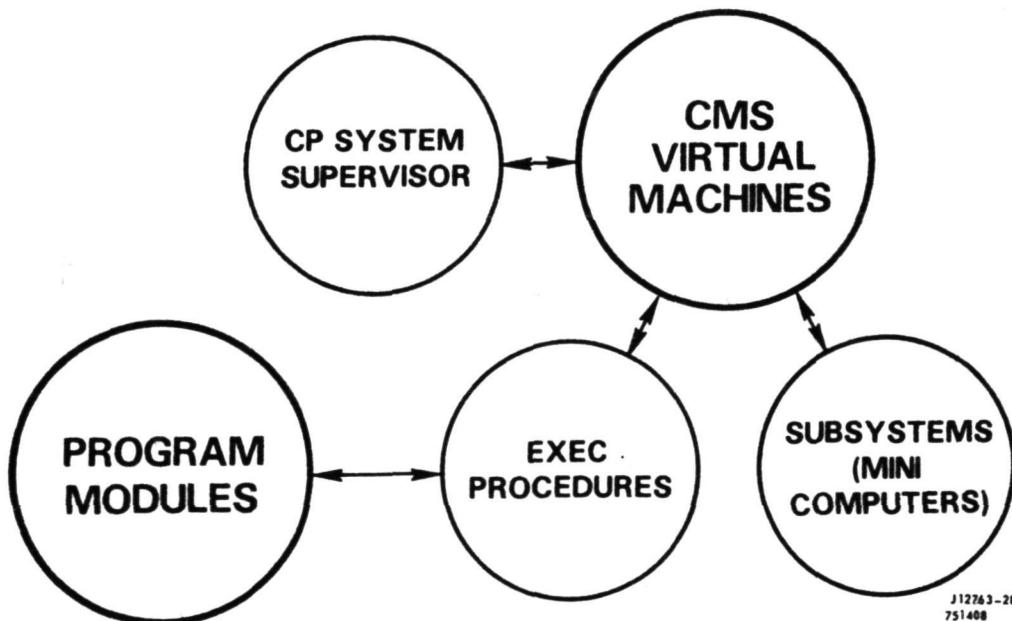
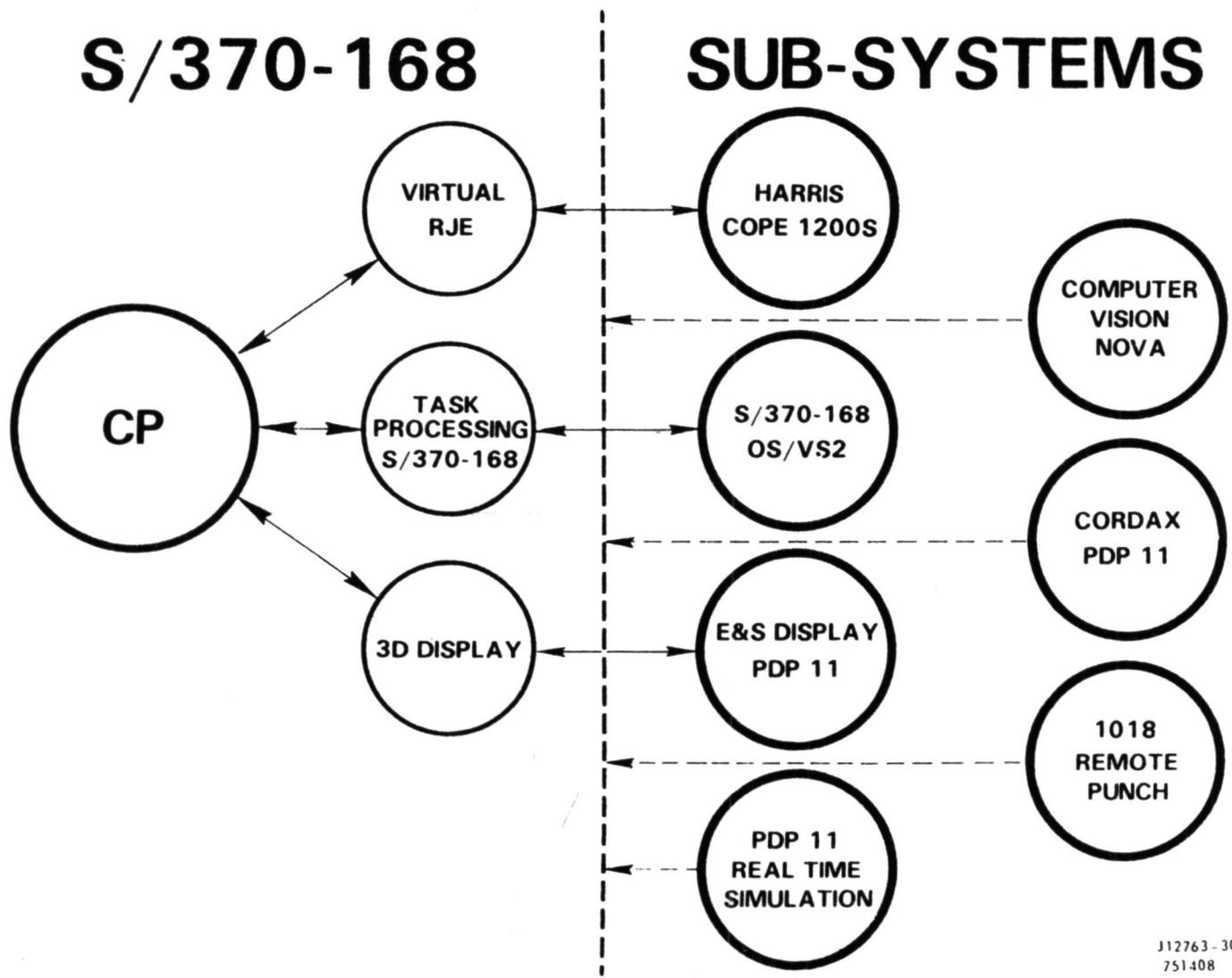


Figure 2.- VM/CMS P&WA graphics overview.



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Figure 3.- Subsystems.

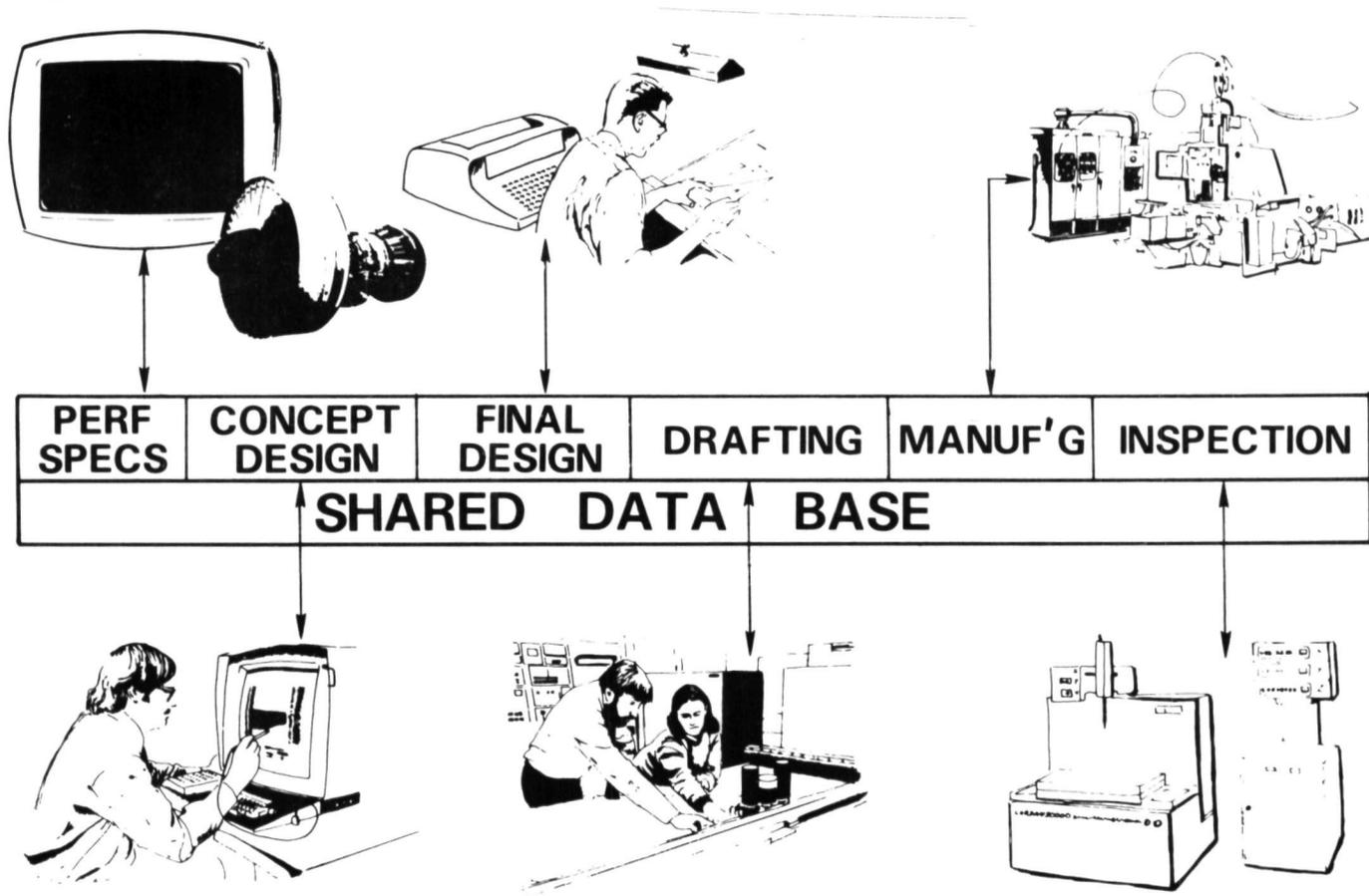
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Figure 4.- CAD/CAM shared data base.

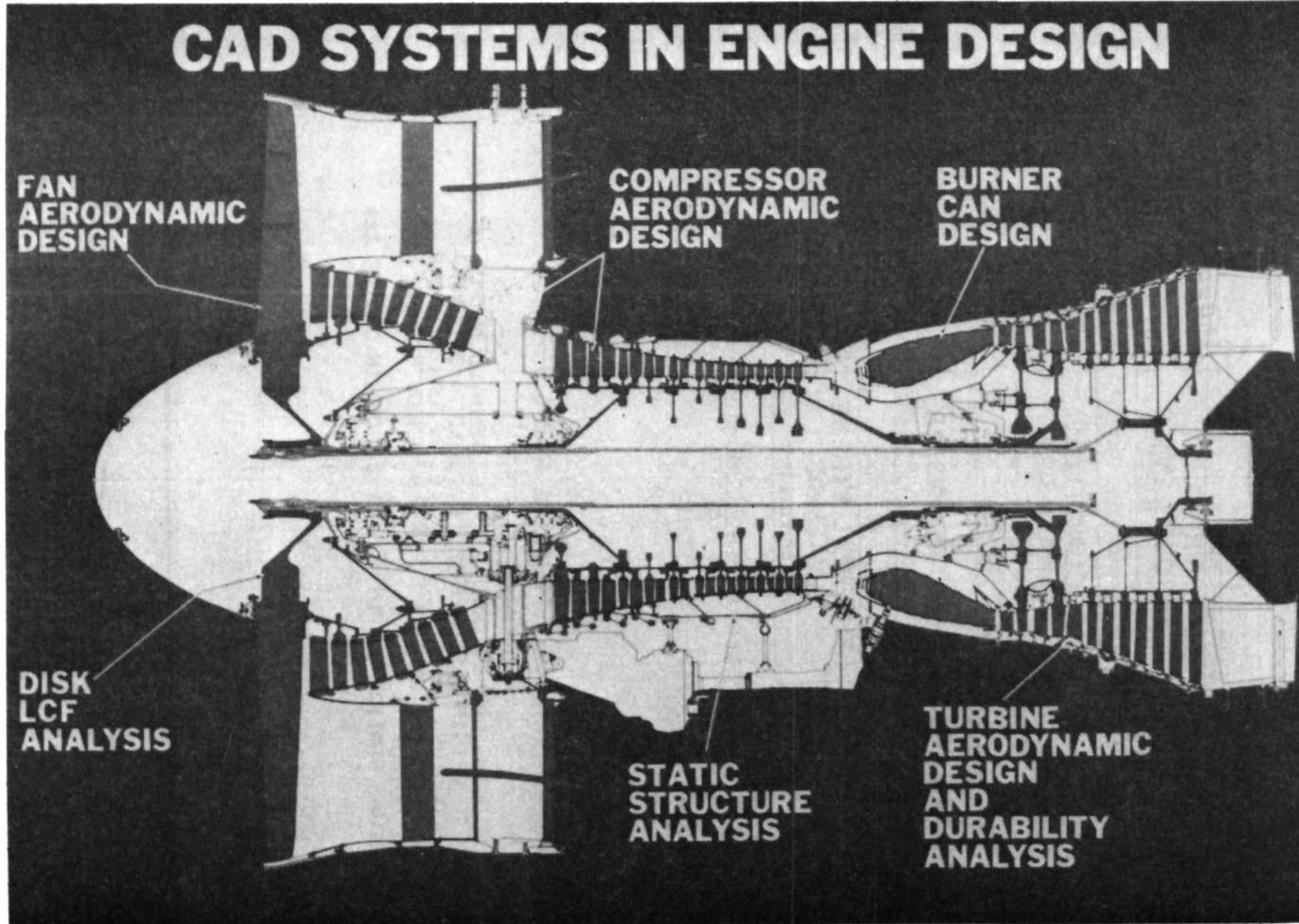
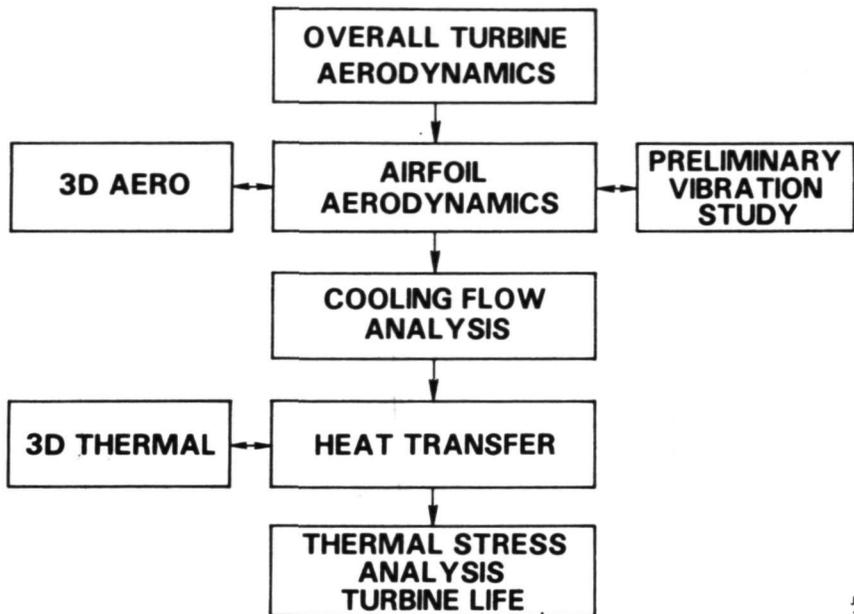


Figure 5.- Computer-aided design systems.



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Figure 6.- Turbine airfoil development system.

W677 STREAMLINE ANALYSIS  
CONVERGED FLOWPATH  
OPTIONS:

- |   |                          |
|---|--------------------------|
| 0 BLOW UP USING CROSSHAIRS                      | 6 PRINTED OUTPUT OF CASE |
| 1 RETURN TO ORIGINAL FLOWPATH<br>(NOT BLOWN UP) | 7 DELTA OPTION           |
| 2 RETURN TO OUTPUT CONTROL                      | 8 RETURN TO INPUT        |
| 3 OVERALL OUTPUT                                | 9 EXECUTE CASE           |
| 5 INDIVIDUAL STATION OUTPUT                     |                          |
- \*\*\* TYPE IN CHOICE \*\*\*

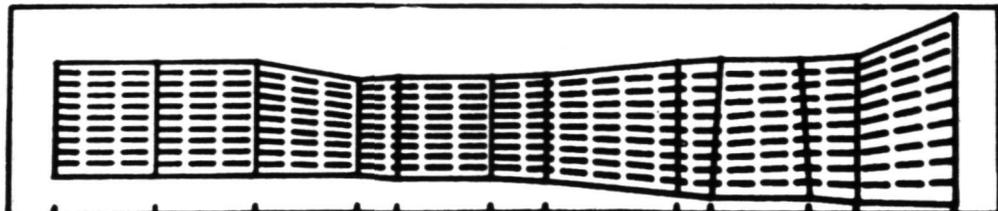


Figure 7.- Overall aerodynamics. Storage tube.

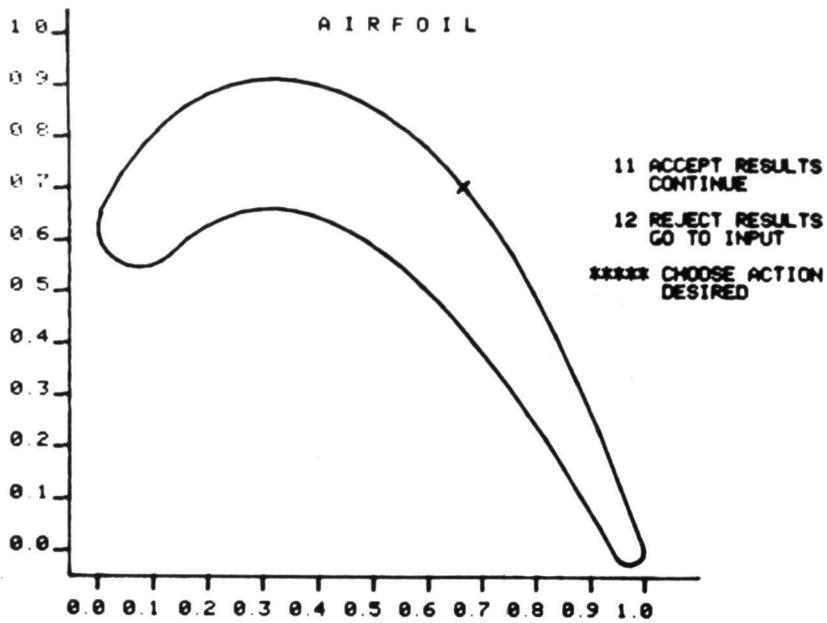


Figure 8.- Airfoil profile. Storage tube.

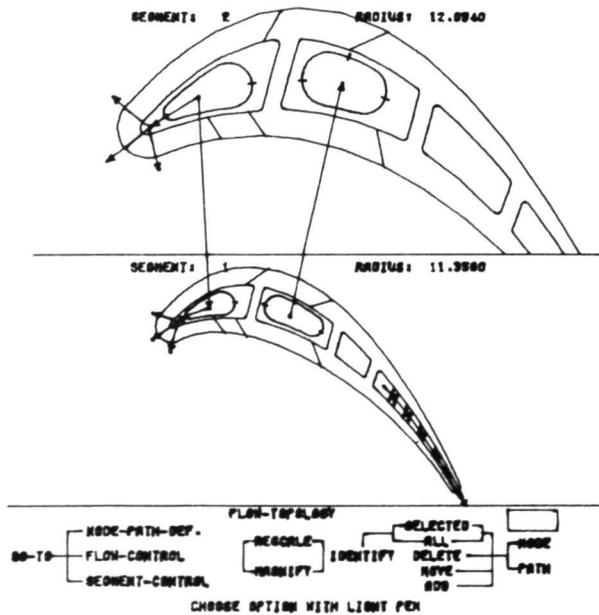
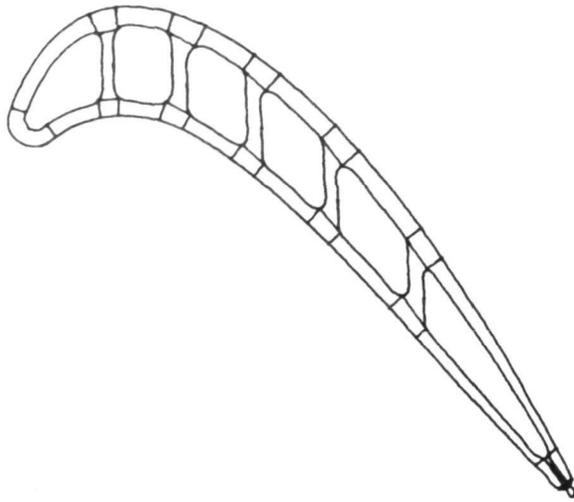


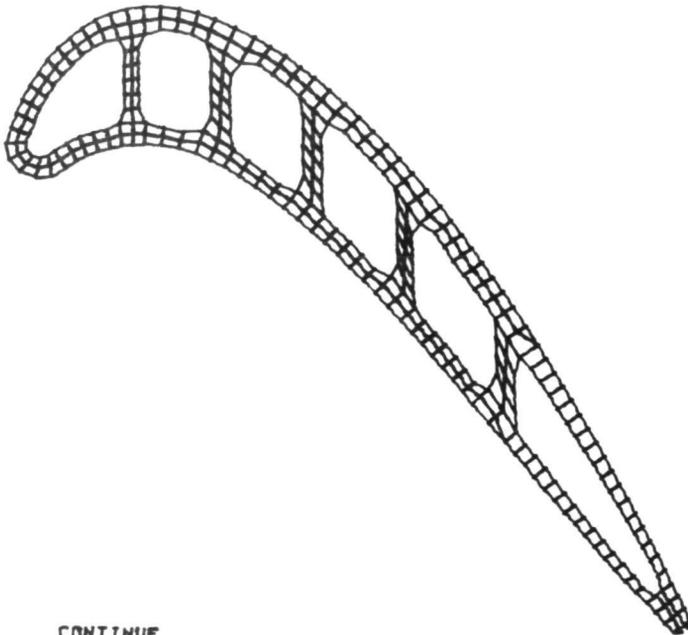
Figure 9.- Internal flow topology. Refreshed display.



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Figure 10.- Flag point description. Refreshed display.



**CONTINUE**

Figure 11.- Finite-element model. Refreshed display.

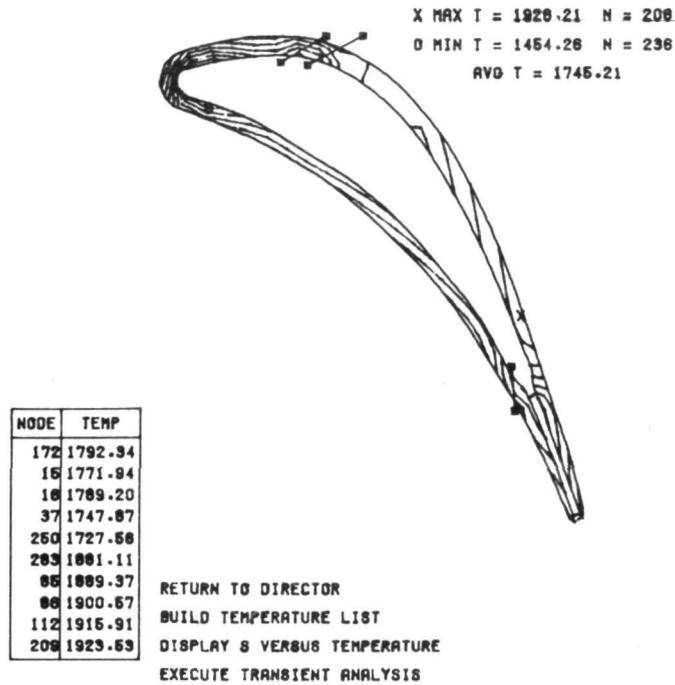


Figure 12.- Isotherm display. Refreshed display.

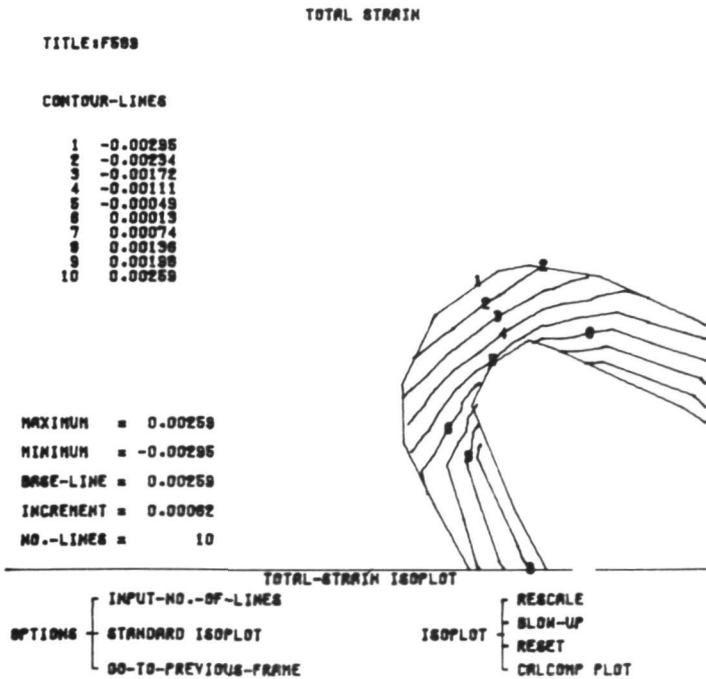


Figure 13.- Isostrain display. Refreshed display.

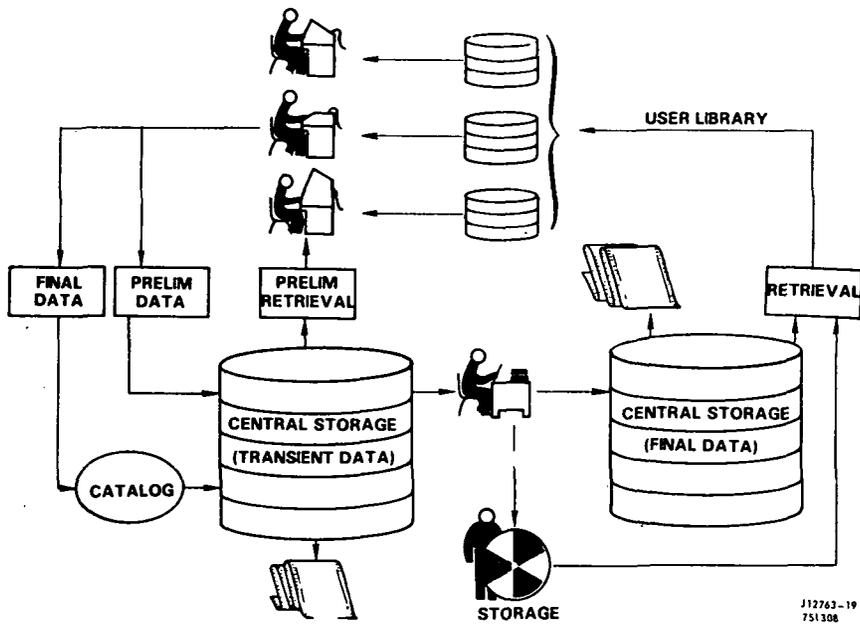


Figure 14.- Engineering data flow for computer-aided design and manufacture.

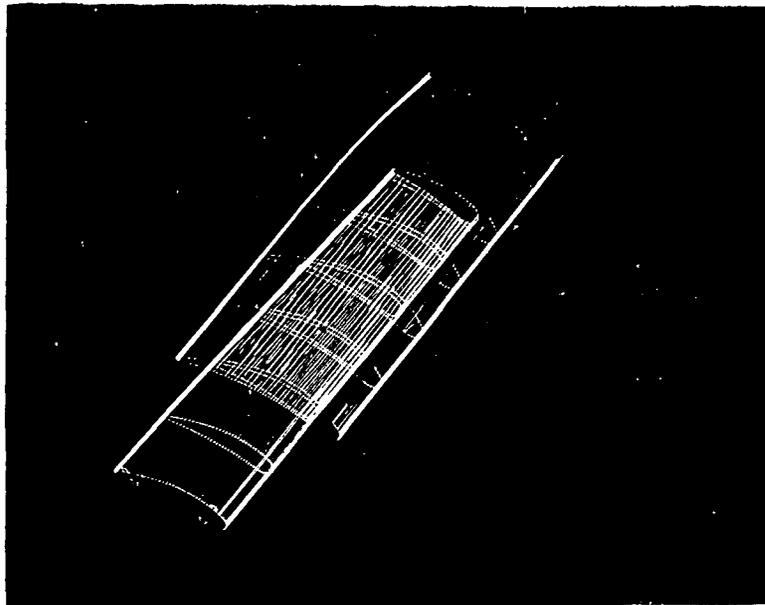


Figure 15.- Turbine core with tube partially extended. High performance display.

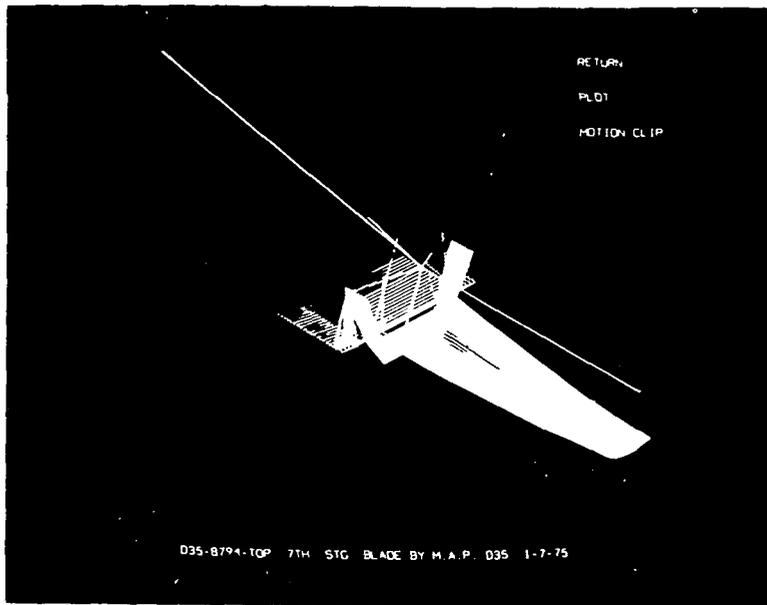
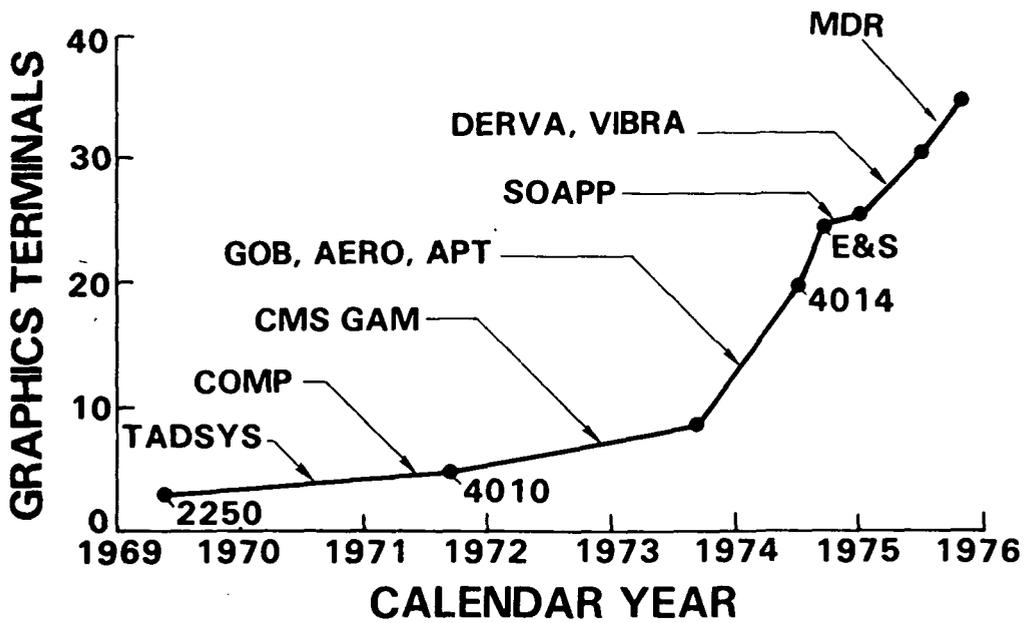


Figure 16.- Numerical control cutter path.  
High performance display.



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Figure 17.- Interactive graphics growth.