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The Numerical Propulsion System Simulation: An Overview

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THE NUMERICAL PROPULSION SYSTEM SIMULATION: AN OVERVIEW

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SUMMARY

Advances in computational technology and in physics-based modeling are making large-scale, detailed simulations of complex systems possible within the design environment. For example, the integration of computing, communications, and aerodynamics has reduced the time required to analyze major propulsion system components from days and weeks to minutes and hours. This breakthrough has enabled the detailed simulation of major propulsion system components to become a routine part of designing systems, providing the designer with critical information about the components early in the design process. This paper describes the development of the numerical propulsion system simulation (NPSS), a modular and extensible framework for the integration of multicomponent and multidisciplinary analysis tools using geographically distributed resources such as computing platforms, data bases, and people. The analysis is currently focused on large-scale modeling of complete aircraft engines. This will provide the product developer with a "virtual wind tunnel" that will reduce the number of hardware builds and tests required during the development of advanced aerospace propulsion systems.

INTRODUCTION

The strategic goals of the Aero-Space Technology Office at the National Aeronautics and Space Administration (NASA) are defined in terms of advancing transportation capability across the speed spectrum from subsonic for commercial applications to hypersonic for access-to-space applications. These goals are organized under the Three Pillars of Global Civil Aviation, Revolutionary Technology Leaps, and Access-to-Space (ref. 1). Within the Three Pillar goals are technical objectives that contain specific goals for revitalizing general aviation; increasing airport throughput; and reducing the aircraft accident rate, travel time, noise and emissions, aerospace product development time, and ownership cost. The accomplishment of these goals will require advanced technologies that will be prohibitively expensive to develop and insert into aerospace products without advanced design tools to reduce the number of hardware builds and tests traditionally required in engine development.

The NASA Glenn Research Center is developing the capability to increase design confidence through the use of advanced computational simulation known as the numerical propulsion system simulation (NPSS). This "virtual wind tunnel," depicted in figure 1, will permit rapid, affordable computation of stability, cost, life-time, and certification requirements. The simulation uses validated models for fluid mechanics, heat transfer, combustion, structural mechanics, materials, controls, manufacturing, and economics. It will enable accurate information about propulsion system parameters such as performance, operability, and life to be determined early in the design process before any hardware is built or tested.

The NPSS is a cooperative effort between NASA and other Government agencies, industry, and universities to integrate propulsion technologies with high-performance computing and communications technologies into a complete system for performing detailed full-engine simulations. Computing and communications technologies are essential to enable the execution of complex simulations in a timely manner and to produce information of value to the designer and analyst. A major engine manufacturer estimates that such simulations could reduce design and development time and cost by about 30 to 40 percent through fewer redesigns, retests, and rebuilds of costly hardware. This translates into a savings of \$100 million over a year of development time. For example, more accurate prediction of engine efficiency and operability would be possible if the "hot-running" geometry of the compressor rotor, blades, and casing could be predicted as a result of the integrated aerodynamic, structural, and thermal loadings. In advanced high-speed engines, because of prohibitively expensive testing, large-scale simulation may be the only viable approach for evaluating the integration of components like the inlet with the engine.

The NPSS system consists of three main elements: (1) the engineering application models, (2) the system software for the simulation environment, and (3) the high-performance computing environment. This

integrated, interdisciplinary system requires advancements in modeling techniques and data standards to couple the relevant disciplines such as aerodynamics, structures, heat transfer, combustion, acoustics, controls, and materials; modeling techniques to couple subsystems and components at appropriate levels of fidelity; object-oriented software design for a modular architecture; and portable, scalable, reliable system software for integrating large numbers of distributed, heterogeneous computing platforms for parallel processing.

The technology products from NPSS and a summary of the technology challenges and possible solutions are described in this paper. A roadmap for the development of capabilities that shows a transition from single-discipline components and subsystems to full-system simulation into multidisciplinary and dynamic simulations is shown in figure 2. The National Cycle Program is an early release of the NPSS object-oriented architecture, ADPAC represents the advanced ducted propfan analysis code, and APNASA is the average passage NASA code. Additional details on the NPSS technologies are described in reference 2. They are summarized below for completeness. The NPSS is currently supported under the NASA High Performance Computing and Communications Program.

ENGINEERING APPLICATION MODELS

The modeling capabilities are divided into three subelements: (1) component integration to achieve large subsystem and system simulations, (2) multidisciplinary coupling to capture critical interactions among the disciplines, and (3) multifidelity analysis to tailor the complexity of the analysis to the design problem under study. The current modeling is focused on aircraft turbofan engines.

Component Integration

The ability to resolve interactions between components in a gas turbine engine is currently limited to two-dimensional models. Most of the full-engine simulations are conducted at zero-dimensional or parametric levels. These models are unable to resolve the complex multidimensional and multidisciplinary flows that exist within the engine. Interactions that are driven by these complex flows are usually unresolved until hardware is built and tested. This is often late in the development process and after a significant investment has been made in the design of the engine. At this point, changes in design are very costly and time consuming.

Component integration is required to understand important interactions between the components. Traditional component design methods assume steady, uniform boundary conditions that are generally not accurate and result in operational problems that are not discovered until late in the development process or until deployment in the field. Two approaches are currently being developed to account for component interaction: the establishment of interface standards for code-to-code communication, which is being addressed in the development of the simulation environment, and the use of single-analysis codes to perform larger scale simulations. The latter requires that the appropriate physical processes be represented in one code, such as tip clearance flows, turbulence, heat transfer, and so forth, and that the code be run in parallel to reduce the overall analysis time. The current state of development involves a focus on turbomachinery and combustion models to enable the assembly of a high-fidelity, full-engine simulation.

In fiscal year 1999, the turnaround time for three-dimensional Navier-Stokes analysis of turbomachinery was reduced by a factor of 400 relative to the 1992 baseline through improvements in the average passage NASA code (APNASA). Improvements were made in the modeling approach that reduced the number of iterations across the blade rows required for convergence and in the interprocessor communication overhead. This accomplishment enables a full 21-blade-row compressor simulation in less than 15 hr and a coupled high-pressure and low-pressure turbine subsystem simulation. The later configuration represents work by Turner et al. on the 18-blade-row cooled turbine in the GE90 aircraft engine (ref. 3). This was the first time a dual-spool cooled turbine was analyzed in three dimensions. The parallel efficiency of the code was 87.3 percent using 121 processors on the NASA High Performance Computing and Communications Program (HPCCP) SGI Origin 2000 testbed. The accuracy and efficiency of the calculation allow it to be effectively used in a design environment so that the multistage and multicomponent effects can be accounted for in turbine design before hardware is built and tested.

In addition to the turbomachinery simulation, high-fidelity analysis of the combustor is also required. Rapid analysis of a combustor design requires not only short processing turnaround, but also tools to assist in pre- and postprocessing of the data. Preprocessing is aided by an unstructured grid generation to enable complete model buildup from compressor exit to turbine inlet. This includes the complex geometry associated with swirlers and injectors. Postprocessing tools are required to reduce the vast amount of data produced by three-dimensional reacting-flow computations into a few design parameters that can be used to assess

performance and make design decisions. Improvements in processing time were gained by reducing inter-processor communication overhead and kinetics modeling time through implementation of the intrinsic low-dimensional manifold method. As a result, processing turnaround time has been reduced by a factor of 200 relative to the 1992 baseline, as shown in figure 3 for the National Combustion Code (ref. 4). Additionally, aircraft engine emissions will be reduced to meet national goals.

Clear data exchange standards are necessary to develop the integrated simulation system approach proposed for NPSS. The approach taken by NPSS is to work closely with national and international standards organizations to implement existing standards within NPSS, expand standards as required, and develop new standards when necessary. The standards currently being worked on cover a broad spectrum from one-dimensional and three-dimensional engineering standards to software standards.

Multidisciplinary Coupling

The physical processes within an air-breathing gas turbine engine are inherently multidisciplinary. Consequently, the accurate simulation of these processes must properly account for the interactions between the disciplines. For example, in the high-pressure compressor, aerodynamic, structural, and thermal loadings all contribute to changes in geometry (i.e., casing, blade shape, tip clearances, etc.) that affect the efficiency and stability of the compressor. An accurate prediction of stall margin requires simulation of all these loadings.

Aerospace propulsion systems are complex assemblies of dynamically interacting disciplines. The traditional analysis approach is to handle interactions between single disciplines in a sequential manner; one discipline transfers information from its own calculation through unique, application-specific translators to make it usable by the next discipline in the sequence. This is a lengthy, tedious, and oftentimes inaccurate process because of the multiple translations taking place. Three different types of coupling are being investigated for inclusion into NPSS. These types are referred to as loosely coupled, process-coupled, and tightly coupled. A detailed description of the three processes is contained in reference 5. The tightly coupled methodology will be described in more detail below because of its unique relevance to HPCCP.

The third type of coupling being proposed for inclusion in NPSS is tight coupling. In some propulsion system problems, the interdependence of the disciplines is so "tightly coupled" that the loose coupling at the data access and process coupling levels cannot capture the physics of the problem. These cases require an analysis that couples the disciplines at a fundamental equation level. For these problems the entire system matrix must be solved simultaneously using implicit methods. Tightly coupled solutions also have the advantage that the communication overhead is significantly reduced. A reduced communication overhead has the potential for substantially increasing the scalability and parallel efficiency of multidisciplinary analysis. While this approach is applicable to general multidisciplinary problems, its use will probably be limited to a small number of tightly coupled disciplines and individual components in the near term because of the extensive computational demands. SPECTRUM, a commercial code from ANSYS, Inc., is currently being evaluated to determine whether it meets the NPSS customer requirements (ref. 6). The code uses an Arbitrary Lagrangian-Eulerian (ALE) methodology for solution of the fluid-solid interface. SPECTRUM has been successfully demonstrated on a number of nonturbomachinery applications. The severe operating environment in an aircraft engine is a major new challenge for this technique.

Variable Complexity Analysis

The detailed simulation of a complex system like a gas turbine engine will require computing resources and/or wall clock times that are beyond practical limits for use in industrial design environments. Consequently, it will be necessary to provide modeling techniques that permit the analyst or designer to vary the level of analysis detail throughout the engine based upon the particular physical processes being studied as the result of a design change. For instance, determining the effect of a change in the shape of a fan blade on engine performance may only require a three-dimensional simulation of the fan stage. The rest of the engine could be modeled at lower levels of detail (two-, one-, or zero-dimensional) to minimize simulation setup and execution time.

The hybrid engine model is an example of a kind of multifidelity analysis called zooming. The high-pressure core of the engine (i.e., compressor, combustor, and turbine) is modeled as a zero-dimensional, aerothermodynamic cycle analysis with component performance maps. In this example, however, the low-pressure subsystem (i.e., inlet, fan, core inlet, bypass duct, nozzle) is modeled in three dimensions using a CFD turbomachinery code, ADAPC (ref. 7). Aerothermodynamic boundary condition data is exchanged directly between the low- and high-pressure subsystems. In addition, shaft power balances are achieved using

both the CFD and engine cycle analysis. Since the cycle analysis executes much faster than the three-dimensional simulation, the three-dimensional simulation is executed in parallel over a large cluster of workstations (64) to minimize the turnaround time. The hybrid model greatly simplifies the high-fidelity simulation of the engine by using three-dimensional modeling only where required. In this example, the propulsion and airframe integration or the impact of atmospheric disturbances on the engine would be modeled in detail without requiring a three-dimensional solution of the core engine. The latter would be extremely time consuming to set up, execute, and analyze.

Several different types of zooming that require a more robust software architecture have been identified for the NPSS system. Currently, these capabilities are being integrated into the overall NPSS architecture. The system simulations will be based on the view that only phenomena that affect system attributes, such as propulsion system life, reliability, performance, and stability, are of interest to the designer or analyst. While the physics that affect these attributes could be captured by modeling the entire propulsion system at the highest level of fidelity—three-dimensional transient and multidisciplinary—two problems prevent this from being a viable option in most cases. First, the level of detailed information needed to use for boundary and initial conditions to get a converged, validated solution would be extremely difficult to collect. Second, the computational time and cost would be prohibitively high for effective use in a design environment. Therefore, the designer or analyst must tailor the fidelity of the simulation to capture the appropriate physics for each component and discipline. This results in an analysis of variable complexity being performed across different components and disciplines, which makes their integration into an overall subsystem or system simulation extremely difficult. Consequently, the NPSS framework is being developed to allow the physical processes resolved from a detailed analysis of a component or subcomponent to be communicated to a system analysis performed at a lower level of detail for the purpose of evaluating system attributes. Conversely, the system analysis will help evaluate which physical processes occurring on the component and subcomponent level are important to system performance. This will allow the engineer or scientist to rapidly focus on the relevant processes within components or subcomponents.

Zooming requires a hierarchy of codes and models to be in place to provide a wide range of simulation capabilities, from detailed three-dimensional transient analyses down to zero-dimensional steady-state analyses. Modeling approaches will be developed for communicating information from a detailed analysis to a filtered, lower level analysis. This will require additional research to understand the mechanisms by which phenomena on different length and time scales communicate. Research is already underway in computational fluid dynamics and structural mechanics to develop this modeling approach and will be extended to consider processes and scales appropriate for the entire propulsion system.

Simulation Environment

The simulation environment for NPSS will provide a common interface for a variety of users to access all of the capabilities within NPSS. This means the interface will have to accommodate users of various skill levels and enable users to modify code, easily replace analysis tools, and accept data from a variety of sources such as simulations, existing data bases, and experiments. In addition, the environment must enable the seamless integration of all planned NPSS capabilities, such as multidisciplinary analysis, zooming, and distributed computing on heterogeneous computing platforms.

The NPSS project is building a simulation environment that provides a generic zero-dimensional view of an aeropropulsion engine and provides tools and standards for data exchange for the coupling of multidisciplinary codes. The environment allows the engineer to zoom to finer levels of fidelity on a component-specific basis while operating at the zero-dimensional view of the engine. NPSS will execute on a variety of computers and allow distribution of engine components in any user-specified fashion. The approach taken for developing NPSS incorporates the following key elements as part of the simulation environment:

1. Clear data interfaces through the development and/or use of data exchange standards
2. Modular and flexible software construction through the use of object-oriented methodologies
3. Integrated multilevel fidelity analysis techniques that capture the appropriate physics at the appropriate fidelity for engine system simulations
4. High-performance, parallel, and distributed computing

The multidisciplinary nature of propulsion systems and the idea of “numerical zooming” between disparate timescale codes suggests that the engine computations would take place in a distributed heterogeneous computing environment. Given this, and the fact that current programming techniques do not facilitate the development of large software systems, a shift in programming approach is required. Fortunately, new

technologies in software development such as object-oriented languages are becoming available. Object-oriented languages were created to aid software development and management with maximum code reusability, clear data connectivity, and code modularity.

The NPSS architecture is intended to be open and extensible. To this end, the architecture exploits the capabilities of object-oriented programming (inheritance, polymorphism, and encapsulation), as well as modern object-oriented concepts including frameworks, component objects, and distributed object standards such as the common object request broker architecture (CORBA). The objects in the architecture will know how to expand and contract data for zooming from three-dimensional codes to zero-dimensional codes, and vice versa. They will know what components are connected up and downstream of themselves for the purpose of generating execution sequences, and they will know how to connect aer propulsion disciplines together. In fact, it is because of these object-oriented features that the idea of providing an engine simulation environment like NPSS is conceivable.

Within the environment, an engineer can assemble aer propulsion simulations without restrictions on fidelity, choice, or location of code. The engineer can accept modules that are resident in the NPSS architecture or replace them with codes available at their respective sites. The "plug and play" capability illustrated here is essential for keeping the architecture current and facilitating new analytical approaches. The cornerstone of the NPSS architecture is its development from the object-oriented paradigm; it provides a computing and engineering white board from which engine simulations can be created (ref. 8).

Figure 4 shows how zooming is incorporated into the cycle simulation. The entire engine is modeled at the zero-dimensional level with data exchange from a one-dimensional mean line compressor code. The codes are CORBA compliant, and communication is established through the object request broker (ORB). This implementation is a general approach that allows other analyses to be linked together, other mathematical operations to be performed as the data is being expanded or contracted, and the simulation to be distributed across a wide area network to facilitate remote team member involvement. This capability is being developed in part under contract with Pratt & Whitney and the United Technologies Corporation.

High-Performance Computing

The detailed simulation of a complex system like the gas turbine engine requires significant computing capacity that is not available today in practical terms. A three-dimensional simulation of the primary flow path in a full engine requires more than 10^{12} floating-point operations/sec (teraFLOPS). Today this speed is only available in a few very expensive machines and has not been achieved on propulsion system applications. The capabilities planned for NPSS would require 10^{15} floating-point operations/sec (petaFLOPS). It is not expected that a serial machine or even a moderately parallel machine will be able to accomplish this with current trends in hardware technology.

Therefore, the approach in the NPSS Project under the HPCCP is to develop application and system software that will enable the use of large numbers of parallel processors. Technologies that provide good scalability to even larger numbers of parallel computers will be of particular interest for this approach. The ability to do distributed computing allows the system user to take advantage of the large number of commodity workstations and personal computers that normally exist within an organization and to benefit from the continuing reduction in the cost-to-performance ratio of these machines. The NPSS Project, supported by the HPCCP, developed the software required to accomplish much of this objective under the Affordable High Performance Computing (AHPC) Cooperative Agreement (ref. 9).

The original objective of the AHPC effort was to achieve similar performance and reliability to a 1994 vector supercomputer at 25 percent of the cost. Much larger computing resources would thus be available to the designer, analyst, and researcher than ever before. Consequently, the project also demonstrated a reduction of more than an order of magnitude in the time needed to perform an aerodynamic simulation of a complete high-pressure compressor by taking advantage of much larger computing resources than are available on a single vector machine. It is estimated that this reduction in analysis turnaround time will result in a 33-percent reduction in compressor design time and a savings of several million dollars. The actual performance of the workstation cluster far exceeded the original goal. The cluster actually achieved the same performance and reliability as a vector supercomputer at 8 percent of the cost.

This accomplishment has led to further research in the area of cluster computing to reduce the cost-to-performance ratio of supercomputing. At the NASA Glenn Research Center, a cluster of 64 Pentium II processors is being used to achieve another tenfold reduction in the cost-to-performance ratio below that of workstation clusters. The Pentium II machines, each with two 400-MHz processors, are configured in two banks of 16 machines. The machines are interconnected with the Fast Ethernet network and the two banks are connected through a Gigabit Ethernet. The turbomachinery and combustion simulations in use under NPSS are

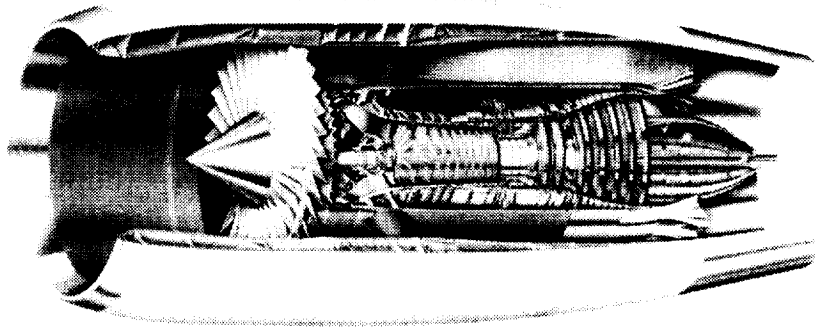
currently being ported to the Pentium processors. At this point, approximately 50 percent of the project goal has been achieved.

CONCLUSION

Detailed, multidisciplinary, full-engine simulations are possible with the integration of advanced physics-based propulsion modeling with high-performance computing and communications technologies. Modeling techniques must include component integration to capture interactions, multidisciplinary coupling to capture key physical processes, and multifidelity analysis to minimize the time-to-solution. Computing and communications technologies must provide system software to enable the user to quickly build and analyze large simulations and to execute simulations over a large number of parallel, distributed, heterogeneous computers. Achieving these capabilities will lead to substantial reductions in the design and development time of new aerospace products. The rapid increase in the size and complexity of simulations over the past decade demonstrates the high feasibility of accomplishing these goals.

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NPSS

**Integrated interdisciplinary analysis
and design of propulsion systems**

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- Expert systems
- Interactive three-dimensional graphics
- Networks
- Data base management systems
- Automated video displays

Figure 1.—Numerical test cell for aerospace propulsion systems.

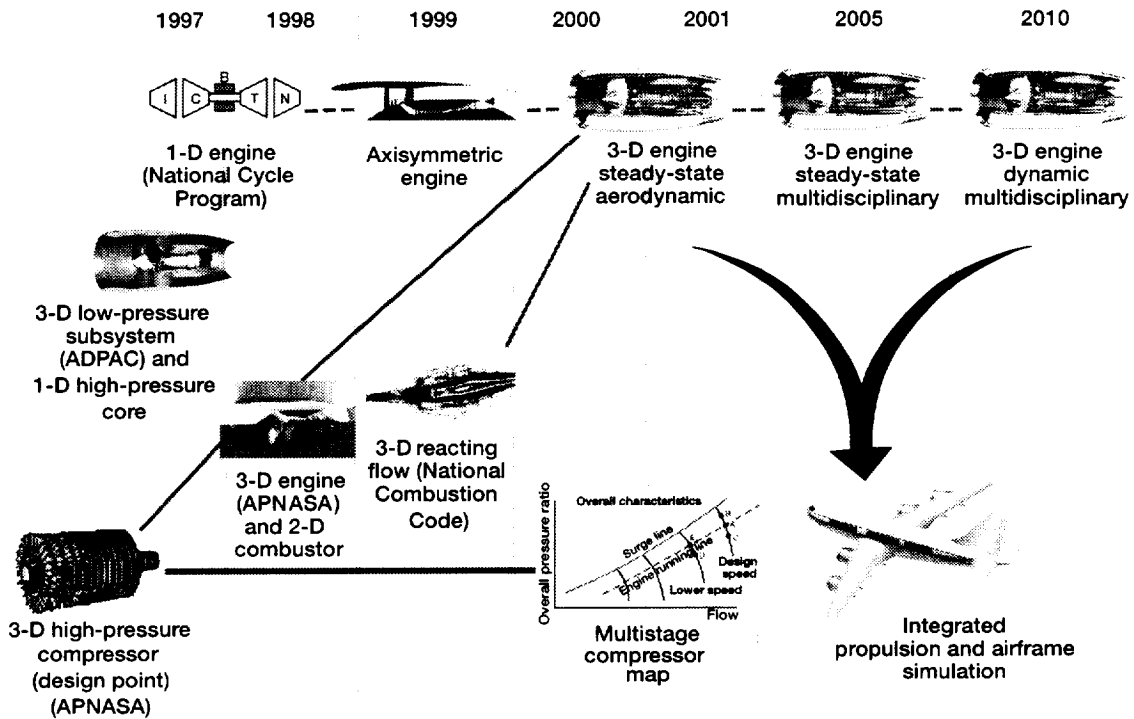


Figure 2.—Roadmap for NPSS overnight simulations. The National Cycle Program is an early release of the NPSS object-oriented architecture, ADPAC represents the advanced ducted propfan analysis code, and APNASA is the average passage NASA code.

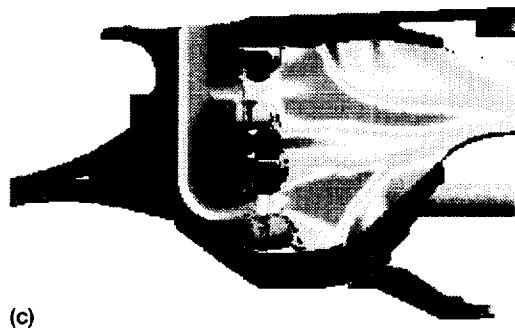
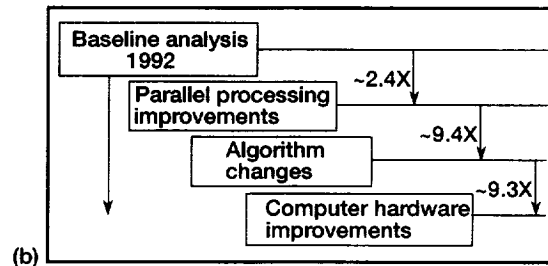
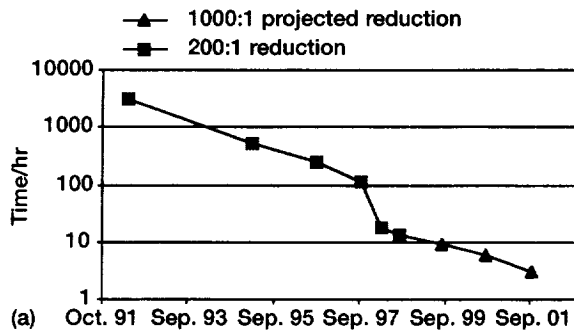


Figure 3.—200:1 reduction of full combustor simulation demonstrated relative to 1992 baseline. (a) Estimated reduced turnaround time. (b) Multidisciplinary approach to reducing turnaround time. (c) Three-dimensional reacting flow.

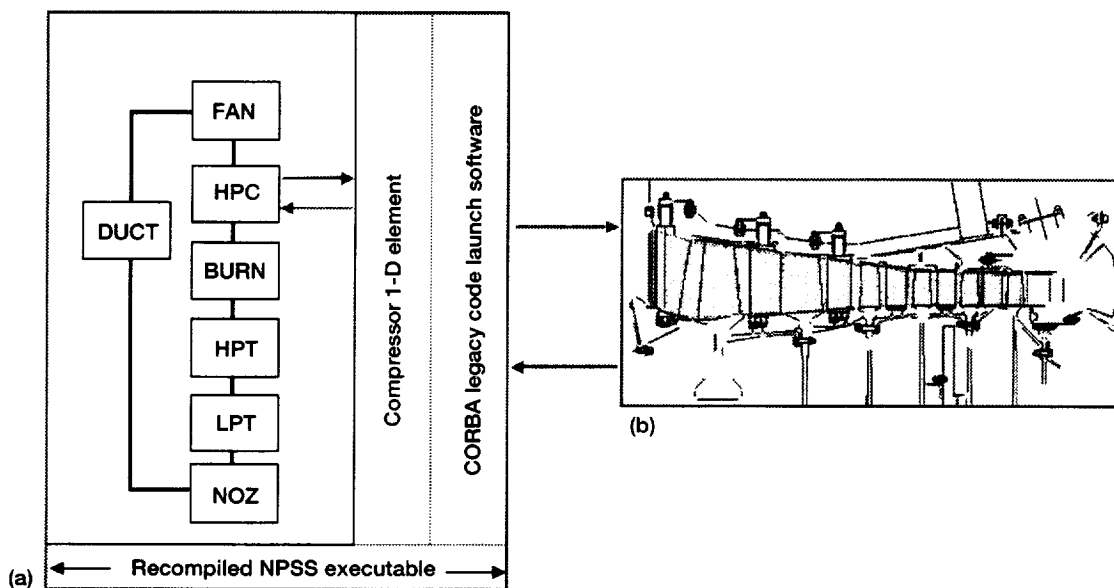


Figure 4.—High-level architecture for multifidelity zooming. (a) NPSS zero-dimensional engine representation. (b) One-dimensional meanline compressor code (speed, eff = f (tip clearance, vane setting, bleed)). Fan, FAN; high-pressure compressor, HPC; burner or combustor, BURN; high-pressure turbine, HPT; low-pressure turbine, LPT; nozzle, NOZ; duct, DUCT.

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