Advanced Engineering Environments –
Implications for Aerospace Manufacturing

by

Dale Thomas, Ph.D., P.E.
NASA Marshall Space Flight Center
Mail Stop VS10
Huntsville, Alabama 35812

Telephone: 256-544-1180
Email: dale.Thomas@msfc.nasa.gov

INTRODUCTION

There are significant challenges facing today's aerospace industry. Global competition, more complex products, geographically-distributed design teams, demands for lower cost, higher reliability and safer vehicles, and the need to incorporate the latest technologies quicker, all face the developer of aerospace systems. New information technologies offer promising opportunities to develop advanced engineering environments (AEEs) to meet these challenges. Significant advances in the state-of-the-art of aerospace engineering practice are envisioned in the areas of engineering design and analytical tools, cost and risk tools, collaborative engineering, and high-fidelity simulations early in the development cycle. These advances will enable modeling and simulation of manufacturing methods, which will in turn allow manufacturing considerations to be included much earlier in the system development cycle. Significant cost savings, increased quality, and decreased manufacturing cycle time are expected to result.

This paper will give an overview of the NASA's Intelligent Synthesis Environment, the agency initiative to develop an AEE, with a focus on the anticipated benefits in aerospace manufacturing.

BACKGROUND

The development of aerospace systems has historically been a costly and time-consuming endeavor, particularly so for the systems developed for NASA missions. To illustrate, consider that the Apollo Saturn V launch vehicle required 8 years to develop (through first launch) at a cost of ~$5B, while the Space Shuttle required 11 years to develop at a cost of ~$11B; the unmanned Ariane V launch vehicle required 10 years and ~$7B to develop (all costs reflect actual year dollars). It should also be noted that the Ariane V may be considered to be an evolutionary development of the Ariane IV, otherwise the time and cost to develop would have been greater. A space transportation system typically includes a launch vehicle, a spacecraft, a ground launch processing infrastructure, and a mission operations infrastructure. Each of these component systems represents a significant development effort in its own right; developed in conjunction, the complexity of the development only increases.

In planning for the next generation of aerospace systems, NASA has chosen to focus on the life cycle cost of the system. In the case of a space transportation system, this would include a launch vehicle as well as its associated system components. The costs include the amortized cost to develop, the fabrication costs of the launch vehicle, and the development and operations costs of the associated/support systems. The operations costs are not negligible, even when compared to the significant development costs given in the foregoing paragraph. Consider that ~140,000 direct labor hours are required to process the Space Shuttle between flights, excluding propulsion elements and any servicing required on the launch pad. Hence, clearly all elements of the life cycle must be considered in development of any future space transportation system.

CURRENT SYSTEM DEVELOPMENT ENVIRONMENT

NASA aerospace systems are typified by small production lot size, complex architecture, and relatively little design heritage. Attempts to utilize legacy parts in a new design often result in spectacular failures, as evidenced by the failure of the inaugural launch of the Ariane V. (Gleick) In this instance, an Ariane IV subassembly and associated software used within the Ariane V Guidance, Navigation, and Control subsystem functioned per Ariane IV specification, but in a mode inconsistent with the Ariane V design. This subtle functional characteristic was not detected in the Ariane V qualification testing. As is commonly the case in complex systems including software, system testing can catch only the anticipated failure modes.

These development challenges are exacerbated by the nature of the development team. The development team typically consists of a systems integrator and many component vendors; the development team itself is usually dispersed across a large geographical area, often across international boundaries. Furthermore, the development team is rarely located proximate to the customer. When the complexity of the system development is considered, the communications problem becomes evident. Since the quality of any system engineering task depends on technical communication, the difficulty of system engineering grows as a function of geographical dispersion. Also, as the quantity of embedded software in today's systems grows, the system engineering challenge grows. Indeed, the Ariane V failure discussed in the foregoing paragraph has been attributed to poor system engineering. (Gerard, 1997) Likewise, failures in recent NASA missions have cited poor system engineering as a root cause. (McDonald, Spear, Stephenson, Young)

While advances in information technology have led to significant advances in engineering tools and infrastructure, engineering processes have remained largely unchanged since the days of drafting tables. The current engineering life cycle of a space transportation system is illustrated in Figure 1; this life cycle may be considered typical of the aerospace system life cycle. This traditional process is largely sequential in nature, usually requires long development times, and does not easily integrate customers and suppliers into the design process. Furthermore, following traditional design practices, approximately 90% of the total cost of an aerospace vehicle is built into the design in the first 10% of the development cycle. Unfortunately, the total cumulative knowledge of the design is still very low at this point, about 15-20% of the knowledge available at the end of the development cycle.

Efforts to accelerate the development cycle within NASA, commonly referred to as "Faster, Better, and Cheaper," have met with limited success. While in many cases the development cycle time and cost have indeed decreased, the mission success rate has likewise decreased. (Dickey) Given that the overall engineering process remains fundamentally unchanged, complex systems remain exceptionally expensive and time consuming to develop, as the quantum improvements in efficiency and quality that are characteristic of information technology applications in general have proven elusive.

ADVANCED ENGINEERING ENVIRONMENTS

Let the engineering environment be defined as the processes, tools, and infrastructure used by people to engineer systems. Here the engineering process describes the structured methods and procedures by which a complex system evolves through the conceptual definition, design, manufacture, integration and testing, and delivery for operations. The tools consist of hardware devices and software codes used by engineers to perform the various component tasks comprising the engineering process. The infrastructure is commonly described as the "physical plant" including office space, thermal vacuum chambers, etc. but has come to include the data networks and other elements of a computational and communications infrastructure.

AEEs are defined as particular implementations of computational and communications systems that create integrated virtual and/or distributed environments which link researchers, technologists, designers, analysts, manufacturers, suppliers, customers and managers involved in mission-oriented, leading-edge engineering teams comprised of industry, government, and academia. (NRC)

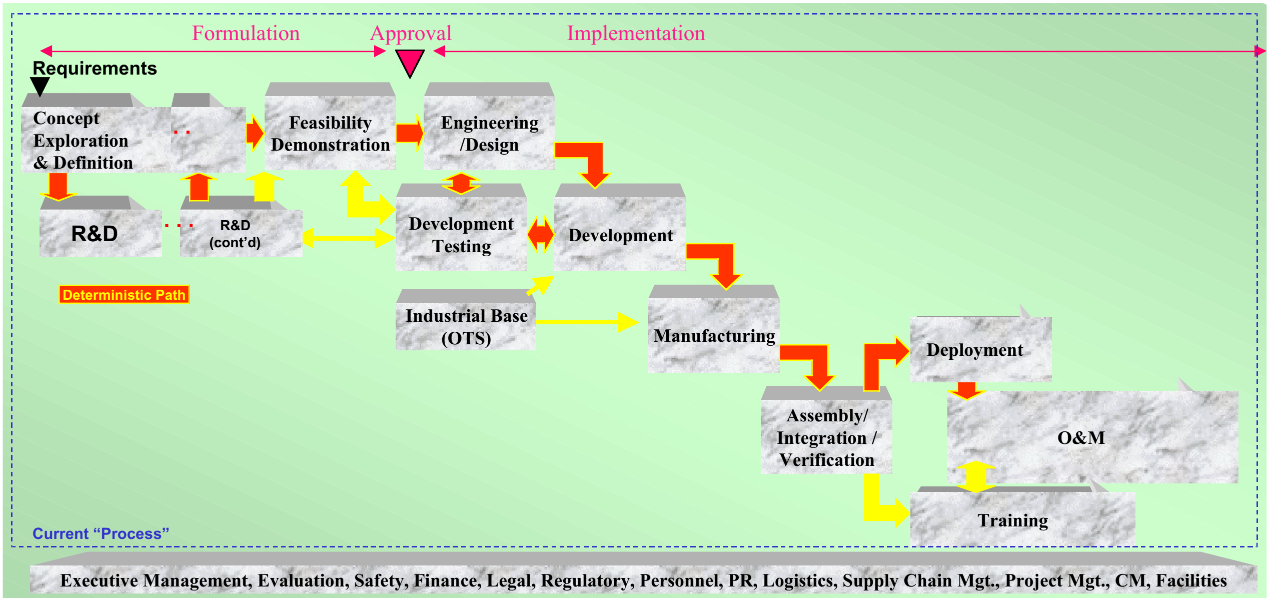

Figure 1. Current Life Cycle

THE INTELLIGENT SYNTHESIS ENVIRONMENT (ISE) CONCEPT

To meet NASA's unique needs the future product and mission development environment must accommodate different groups of people, such as engineers, designers, scientists and technology developers. These groups must be able to work together collaboratively, and must also be able to integrate both customers' and suppliers' requirements into the process (Goldin, Goldin, Noor). These diverse teams will collaborate in utilizing new computational resources in innovative and meaningful ways. Teams will not be in one location, so the design environment must support collaboration of geographically distributed teams. Computational tools that are utilized within this environment must be easy and intuitive to use, and make use of a balanced mix of multi-sensory technologies. The design environment must allow scientists to interact with simulated vehicles and missions so as to study science payload, mission performance and interaction of science requirements with vehicle and mission engineering. Ultimately, this environment should be usable by engineers, scientists, operators, program sponsors, and stakeholders.

Therefore, the vision of this new design and mission synthesis environment is:

To effect a cultural change that integrates into practice widely distributed science, technology and engineering teams to rapidly create innovative, affordable products. This is accomplished by using a combination of technologies to build/assemble an integrated Intelligent Synthesis Environment (ISE) for creative engineering and science.

ISE: A NEW NASA INITIATIVE

In order for NASA to meet its unique mission needs in space science, human exploration, earth science and aeronautics, NASA proposes a new Initiative to develop an Intelligent Synthesis Environment (ISE). ISE will utilize computational intelligence to synthesize existing, newly developing and future relevant technologies to provide the future product and mission development environment. In the ISE, synthesis takes place in three ways:

- Collaborative synthesis of scientists, engineers, technology developers, operational personnel and training personnel all working in geographically, as well as temporally, distributed locations;

- Synthesis of cutting-edge technologies and diverse, life cycle design tools seamlessly integrated together both horizontally and vertically at all levels of fidelity;

- Synthesis of humans, computers, intelligent hardware (e.g., robotics) and the synthetic (virtual reality) simulated designs and design languages.

The intelligent nature of ISE is derived from its concentrated use of non-traditional, intelligent computational systems such as intelligent product objects, intelligent agents and intelligent computational methods. The computational intelligence, which will be built into the design environment, will guide the utilization of the vast resources of knowledge and predictive capability to which the environment will have access.

Very importantly, the ISE program will make meaningful use of related developments sponsored by other government agencies and industry. This will be accomplished through the use of R&D ISE laboratories in which technologies from government, industry and universities will be synthesized, assessed, validated and demonstrated. To this end, NASA will form partnerships and coalitions with other government agencies, the software vendor industry, aerospace and non-aerospace industries and universities. In addition, ISE Large-Scale testbeds will be created to apply new ISE products to engineering projects and science missions of importance to NASA. These testbeds will be distributed geographically and will be reconfigurable to meet new requirements as these are identified. They will provide a showcase for demonstrating how state-of-the-art computational and communication facilities and tools can be synthesized with engineering, science, manufacturing, operations and training teams to dramatically improve productivity, enhance creativity and foster innovation at all levels of product and mission development.

THE ISE IN PRACTICE

The ISE Initiative will develop, validate, assess and demonstrate, through ISE LargeScale Applications, a revolutionary product and mission development environment which synthesizes existing, newly developing and future relevant technologies to provide the future environment for collaborative science, engineering, designing, manufacturing, certifying, operating and training. Such an environment will revolutionize design so that the conceptual, preliminary and detailed design phases merge, therefore dramatically shrinking the design cycle. Products and missions will be rapidly configured and assessed for scientific payoff or product performance leading to innovative and creative design solutions. Production, operations and training issues will be addressed early, and costs and risks accurately predicted and dramatically reduced. Redesign and manufacturing rework costs will be virtually eliminated. Certification testing requirements and costs will be dramatically reduced. In total, ISE will result in significant increases in productivity, affordability and performance.

The ISE is a comprehensive, completely integrated environment. It provides a holistic view of the product development process. It addresses the entire mission and life cycle of the aerospace system. It makes effective use of intelligent agents to increase the creativity bandwidth of the science and engineering teams. CEC's will be assembled/built to demonstrate the ISE concept, and to help in identifying technology developments needed for realizing its full potential in large-scale science and engineering applications. The testbeds will be re-configurable, and will rapidly accommodate new synthesis paradigms as new technologies develop.

SPACE TRANSPORTATION SYSTEM DEVELOPMENT IN AN AEE

To illustrate the ISE concept of an AEE, consider the development of the NASA Spaceliner 100. (Lyles) The process of developing and deploying this vehicle is in its earliest stages such that the AEE can be illustrated throughout the full life cycle. Following are the primary goals for the vehicle:

- Increase Crew Safety
  - 1/1,000,000 probability of crew loss
  - Increase over current crew safety by a factor of over 10,000
- Increase Vehicle Reliability
  - 1/1,000,000 probability of vehicle loss
  - Increase over current reliability by a factor of over 10,000
- Lower launch vehicle costs
  - $100 per pound to LEO
  - Decrease current costs by a factor of 100.

The following paragraphs very briefly discuss the derivation of AEE functional requirements based on these Spaceliner 100 goals.

Orders of magnitude of <u>vehicle</u> endurance improvement are required. Specifically, the <u>vehicle</u> must turn out to be about 10,000 times more reliable/safe than the baseline vehicle – the Space Shuttle. This will require a combination of dramatic improvements involving principally materials and structural design – focused on increasing the overall fatigue life of the vehicle system, subsystems, and components. This focus will affect the conceptual through detailed design phases, as well as the manufacturing/ production phases. Thus, in order to support this focus, the AEE must facilitate design, materials selection, and loading simulation, and the AEE must facilitate the application of performance and fatigue life prediction tools at the vehicle system, subsystem, and component levels. This must include a probabilistic design approach that will provide multiple design alternatives, which will foster the understanding and reduction of risk, sensitivity and uncertainty. The AEE must enable and facilitate the prediction of performance and fatigue life at a level of accuracy far improved over such predictive capabilities as were available at the time of the Shuttle design. (Note, for example, that the Shuttle design plan predicted that the main engines would have to be removed and refurbished only after <u>20+</u> flights. As it turned out, they must be removed and refurbished after <u>every</u> flight – and at great cost.) In addition, the AEE must facilitate integration of comprehensive safety considerations and the "ilities" into the overall process and in all supporting subprocesses, as well.

The Spaceliner 100 goals require two orders of magnitude reduction in vehicle life cycle costs, with specific emphasis on the operations phase of the life cycle. Vehicle *development* cost is highly dependent on the overall length of time taken to complete the development. (The standing army of developers generally stays on the payroll throughout this length of time.) Thus, the AEE must provide methods and capabilities to accelerate the overall development process. A proposed, future, AEE-enabled engineering life cycle process is illustrated in Figure 2. This process utilizes state-of-the-art information technology to significantly reduce the vehicle development cycle time while simultaneously increasing the quality and thoroughness of the system engineering process as measured by increased system safety and reliability. The derived requirements for this AEE are further described in three paragraphs that follow. Subsequently, the AEE architecture will be described.

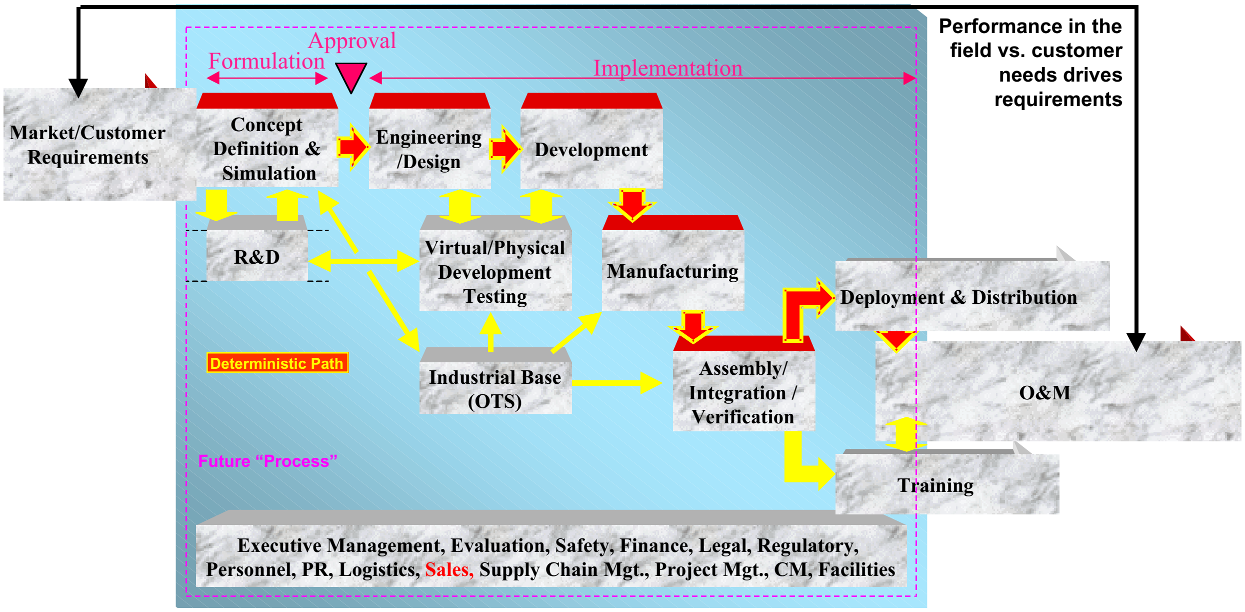

Figure 2. Future Life Cycle

Vehicle *development* (and ultimately operations) costs are principally driven by the decisions made in the conceptual and preliminary design phases. These decisions are based on lessons learned and particularly on the results of iterative rules-based design analyses. Vehicle performance and endurance capabilities are predicted based on anticipated loading/duty cycle/etc. These decisions include trades relative to utilization of actual and planned technology capabilities, such as materials performance characteristics. The speed at which these decisions can be made is dependent on the speed at which the computationally intensive iterations can occur in converging to a satisfactory design plan. Thus, in order to shorten the design phase while improving the quality of the outcome, the AEE must facilitate: rapid access to lessons learned and corporate knowledge, seamless integration of design/analysis tools, rapid completion of design and analysis steps/iterations, rapid insertion of alternative/ improved analysis tools, and intelligent selection of needed/compatible tools and techniques. These AEE-provided capabilities will require (and enable) a substantial accompanying process change from that of today since information derived in one process step/iteration will be immediately and seamlessly available as inputs for other process steps/iterations. This process change will enable the capability for essentially real-time/parallel processing among the engineering and analytical disciplines. To fully enable and implement this parallelism, the AEE implementation must facilitate integration of the people which support the engineering and analytical subprocesses. They must be trained to work in an environment that does not include the long periods of time – waiting for computations to complete, waiting for a colleague or supplier to finish a step, etc. – as is characteristic of current design environments.

The conceptual AEE architecture employs a building block approach to achieving the required AEE end-product capabilities. As shown in Figure 3 the blocks are analogous to the International Organization for Standardization (ISO) Open Systems Interconnect Model. Infrastructure blocks support tool and application blocks, and the aggregate of the blocks will be assembled within the architecture for a transportation vehicle – nominally the Spaceliner 100. It is noted that this architecture is readily applicable for the requirements of the other space transportation systems. The architecture provides these highlights:

- On-line/rapid connectivity and collaboration within MSFC and between MSFC and its supporting contractor, academic, and supplier communities. This enables the parallel processing required for shortening design cycles and/or enabling larger numbers of analysis iterations.
- On-line/rapid connectivity and collaboration between MSFC and the NASA Centers of Excellence. This enables MSFC organizations to expand the rapid/parallel processing capability to include Programs and Projects at the other Centers. This *external* connectivity and

collaboration is planned to be facilitated by the NASA Intelligent Synthesis Environment (ISE) Program. The AEE requirements in this regard will be developed to ensure MSFC's *internal* processes, tools, and infrastructure evolve to be compatible with the ISE.

- Tools integration and process automation environment. This enables the engineers and analysts to utilize the best tools available for each discipline in a plug-and-play environment. It also enables definition of multi-discipline analyses and optimization processes for automated solution convergence/ closure.

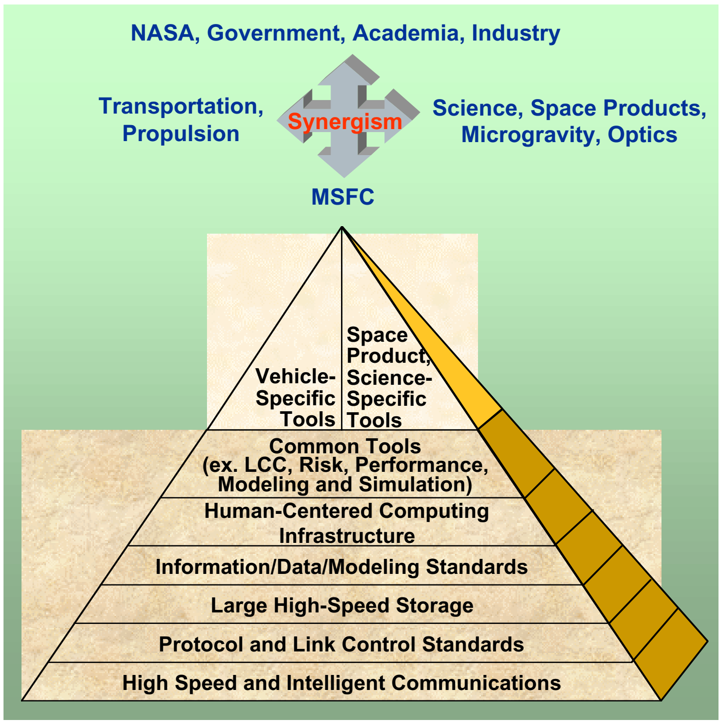

Figure 3. AEE Architecture

IMPLICATIONS FOR AEROSPACE MANUFACTURING

The Next-Generation Manufacturing Project (NGM) was initiated in 1995 to develop a framework for action that manufacturers can use to chart a course for success in an increasingly complex and competitive global environment. The NGM Project identified three high-leverage technology-related imperatives within an overall set of ten generic enabling practices and technologies deemed critical for NGM success:

- Next-Generation Manufacturing Processes and Equipment,
- Pervasive Modeling & Simulation,
- Adaptive, Responsive Information Systems.

Of these three imperatives, the second – Pervasive Modeling & Simulation, is most directly aligned with the goals and objectives of the Intelligent Synthesis Environment.

> "In the NGM Enterprise, modeling and simulation (M&S) will reflect a new way of doing business rather than a supporting technology. It will make virtual production a reality. All production decisions will be made on the basis of modeling and simulation methods, rather than on build-and-test methods. M&S tools will move from being the domain of the technologist, to being a tool for all involved in the product realization, production, and business processes. M&S will eliminate the need for developing hardware prototypes and allow for lot sizes of one. This will dramatically decrease time-

to-market for new products and services. It will provide products and services optimized for the customer and other stakeholders. It will require significantly fewer resources in the development process than build-and-test methods" (NGM)

Clearly, the inclusion of manufacturing M&S within the overall aerospace system development process will enable the consideration of manufacturing tradeoffs including the plant, the equipment, and the production processes at a much earlier point in the system design process than is typical today. Furthermore, this earlier inclusion of manufacturing considerations will include a higher degree of fidelity, enabling manufacturing plans to more appropriately influence the system design.

REMARKS

Today, the developer of an aerospace system is faced with more complex products, geographically-distributed design teams, demands for lower cost, higher reliability and safer vehicles, and the need to incorporate the latest technologies quicker. Within NASA, multiple technology development and demonstration projects are underway toward the objectives of safe, reliable, and affordable access to space. AEEs incorporating new information technologies offer promising opportunities to meet these challenges. The preceding discussion has identified significant advances in the state-of-the-art of aerospace engineering practice that are envisioned in the areas of engineering design and analytical tools, cost and risk tools, collaborative engineering, and high-fidelity simulations early in the development cycle for NASA aerospace systems. Furthermore, the implications of these advances within the specific context of aerospace manufacturing were discussed – namely, the routine usage of advanced manufacturing modeling and simulation methods, enabling manufacturing considerations to influence the system design much earlier in the development cycle than is common today.

REFERENCES

Dickey, B. "Midcourse Correction." Government Executive, September 2000.

Gerard, L. L. "Analysis of the Ariane V Flight 501 Failure – A System Engineering Perspective." Proceedings of the IEEE Conference and Workshop on Engineering of Computer-Based Systems, March 24-27, 1997, Monterey, California, pp. 339-46.

Gleick, J. M. "A Bug and a Crash." The New York Times Magazine, 1 December 1996.

Goldin, D. S., S. L. Venneri, and A. K. Noor. "Beyond Incremental Change", Computer, Vol. 31, No. 10, Oct. 1998, pp. 31-39.

Goldin, D.S., S. L. Venneri, A. K. Noor. "A New Frontier in Engineering", Mechanical Engineering Magazine, Vol. 120, No. 2, Feb. 1998, pp. 62-69.

Lyles, G. M. "Spaceliner 100 – Developing the Technologies to Enable 3rd Generation Launch Vehicles," Proceedings of the 1999 Space Transportation Day Conference, October 27, 1999, Huntsville, Alabama.

McDonald, H. (Chair) "Space Shuttle Independent Assessment Team – Report to Associate Administrator Office of Space Flight," March 7, 2000.

NGM (Next-Generation Manufacturing Project). 1997. Next-Generation Manufacturing Report, Volume I, p. 48. Bethlehem, Pennsylvania: Agility Forum

Noor, A.K., S. L. Venneri,, J. M. Housner, and J. C. Peterson. "A Virtual Environment for Intelligent Design", Aerospace America, Vol. 35, No. 4, April 1997, pp. 28-35.

NRC (National Research Council). 1999. Advanced Engineering Environments: Achieving the Vision. Washington, D.C. National Academy Press.

Spear, T. (FBC Task Master). "NASA Faster, Better, Cheaper Task Final Report," March 2000.

Stephenson, A. G. (Chair). "Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board," March 13, 2000.

Young, T. (Chair). "The Mars Program Independent Assessment Team Report." March 14, 2000.