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Washington, DC 20301-3140

REPORT OF THE

DEFENSE SCIENCE BOARD

TASK FORCE

On

NATIONAL AERO-SPACE PLANE (NASP)

PROGRAM

NOVEMBER 1992

Defense Science Board
Director of Defense Research and Engineering
Washington, D.C. 20301-3140

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OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE
BOARD

August 6, 1992

Dr. John S. Foster, Jr.
Chairman
Defense Science Board

Dear Mr. Chairman:

I am pleased to submit to you the final report of this second Defense Science Board (DSB) Task Force on the National Aero-Space Plane (NASP).

The Task Force was charged with the assessment of the degree to which the many technical challenges of the program have been resolved thus far, or are likely to be resolved by the end of Phase II. To this end, the Task Force gathered information by conducting two day meetings at the Joint Program Office in Dayton, Ohio, with the engine and airframe manufactures at Palmdale, California, and at the NASA Langley Research Center, Hampton, Virginia.

The initial DSB Task Force on NASP completed its review in the summer of 1987. Since then, substantial technological progress has been made during Phase II of the program in all of the technological areas critical to NASP. It is clear that the program emphasis on the NASP vehicle configuration during the intervening years has resulted in a strongly focused, very productive, multi-discipline technology program.

We have concluded, however, that at the end of Phase II, as currently structured, fundamental uncertainties will continue to exist in at least four critical areas: boundary layer transition; stability and controllability; propulsion performance; and structural and sub-system weight. Boundary layer transition and scramjet performance cannot be validated in existing ground test facilities and the weight estimates have insufficient reserves for the inevitable growth attendant to material allowables, fastening and joining, and detailed configuration issues. The essential criterion for entering Phase III is an X-30 vehicle design with reasonable assurance of demonstrating single stage to orbit (SSTO) performance. Using optimistic assumptions on transition and scramjet performance, and the present weight estimates on material performance and active cooling, the vehicle design does not yet close; the velocity achieved is short of orbital requirements.

We recommend that the program not enter into a Phase III experimental flight vehicle program at this time but rather proceed with a revised next phase, which we would define as Phase IIE. This phase, lasting approximately three years, would continue work in design, materials, computation and propulsion up to the limits of ground based facilities (Mach 6.5 to Mach 8). The central focus of Phase IIE should be an unmanned, scaled flight test program to demonstrate performance and validate

computer codes for scramjet performance and boundary layer transition. This program would explore the hypersonic flight regime from about Mach 12 to Mach 16/18.

The Task Force was fortunate to be able to include in its membership six members who participated in the previous review. All of the members were exceptionally well qualified. University, industry and ex-government experience in program management and the technologies related to NASP were represented. This Task Force, as did its predecessor, strongly supports the goals of the program because of the major potential benefits to space launch vehicles, projection of military presence, and commercial air transport.

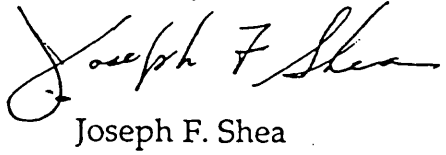
The program today is on much firmer ground than it was five years ago. Our views and recommendations will be generally accepted and concurred in by NASA, the JPO and the various supporting contractors.

I am concerned, however, that the recommendation to invest in reducing the uncertainties in critical technologies (Phase IIE) can be interpreted by some as a vote of no confidence in the NASP concept. Nothing could be further from the truth. The Aerospace Plane will be a major national program. At the time of commitment to the experimental flight test vehicle, confidence in cost, schedule and performance projections must be high. The program we are recommending is intended to provide the technical data-base to make those projections realistic. Too often, in recent years, major programs have experienced significant cost over-runs, schedule slips and performance shortfalls because they were started with an inadequate technical base, or succumbed to unreasonable fiscal or schedule pressures to get the program started. The Aerospace Plane can and should avoid such pitfalls.

A second area of concern is the apparent requirement that the X-30 vehicle demonstrate SSTO capability. SSTO with horizontal take off and landing is a desirable goal for some operational vehicles resulting from X-30 technology. However, the experimental vehicle is intended to explore the envelope of the various flight regimes, from take off to orbit insertion, in order to provide the data-base for design of the operational vehicles. Low speed and high speed flight can be demonstrated separately. For example, removing the requirement that the X-30 take off horizontally could result in a less expensive flight test program that would still provide all required technical data. This and other alternatives should be explored before committing to the final X-30 flight test programs.

On behalf of the Task Force, thank you for the opportunity to constructively review this most important national program.

Sincerely,



Joseph F. Shea

SUMMARY

Six years ago, the Defense Science Board (DSB) initiated a review of the concept, technical basis, program content, and missions of the National Aerospace Plane (NASP) program. The report was completed in September, 1988, and the recommendations contributed to strengthening the technical efforts in the NASP program.

Since then, substantial technological progress has been made in the technology development phase (Phase II) of the program. Phase II of the program is currently scheduled to end in late Fiscal Year 1993, with a decision whether to proceed to the experimental flight vehicle phase (Phase III) to be made at that time. This decision will be a very significant one for the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA).

In February of this year, the DSB was chartered to revisit the NASP program to assess the degree to which the many technical challenges of the program have been resolved, or are likely to be resolved by the end of Phase II. A Task Force comprised of six members of the original study group and three new members was formed to perform this assessment. The Task Force gathered information by conducting two-day meetings at the NASP Joint Program Office (JPO) at Wright Patterson Air Force Base, Ohio, the NASP National Program Office, at Palmdale, California, and the NASA Langley Research Center, Hampton, Virginia.

The Task Force was impressed by the technical progress which has been achieved over the past four years in the technologies critical to hypersonic flight aerodynamics, materials and structures, propulsion, and computational fluid dynamics (CFD) (which also supports several other disciplines). It is clear that the emphasis on the NASP vehicle configuration has resulted in a strongly focused, multi-discipline technology

program which has been more productive than an equivalent investment in advanced research and technology in the individual disciplines.

We also note that the NASP JPO has developed a strong team and an excellent spirit of cooperation between the Air Force and NASA, and with the contractor team. We found the JPO very cooperative and realistic in assessing the status of the program.

The NASP contractors are now teamed -- three for the vehicle and two for propulsion. A common configuration has emerged, incorporating the advances to date in each discipline with sufficient design detail to enable evaluation of the remaining performance uncertainties.

Our review concluded that, at the end of Phase II, fundamental uncertainties will exist in at least four critical areas: boundary layer transition (which affects drag and thermal loads); propulsion performance (which determines effective specific impulse (Isp)); stability and controllability; and structural and sub-system weight (which determines mass fraction and, with Isp, payload potential).

High-speed boundary layer transition of scramjet performance cannot be validated in existing ground test facilities. Weight estimates have inadequate reserves for the inevitable growth attendant to material allowables, fastening and joining, control needs, and configuration changes.

The essential criterion for entering Phase III is an X-30 vehicle design with reasonable assurance of demonstrating single stage to orbit (SSTO) performance. Using optimistic assumptions on transition and scramjet performance, and present weight estimates on material performance and active cooling, the vehicle design does not close; the velocity achieved is short of orbital requirements. The Task Force concludes that the technology and design base required to justify initiating the

X-30 experimental flight vehicle program will not be available at the end of Phase II in 1993, if SSTO remains the major requirement.

This conclusion is a blunt answer to the charter of the Task Force. It is not, however it may be otherwise interpreted, a vote of no confidence in the NASP concept and the potentially significant technical and operational benefits of continued investment in this focused hypersonic technology program.

The problem is tough. The progress in almost all areas since our last report is impressive. With reasonable, yet constrained investment, we believe the remaining uncertainties can be narrowed and technologies improved to the point where sufficient data will be available to determine whether an SSTO vehicle design can be closed with credible performance margins.

The NASP JPO recognizes that the accomplishments against Phase II exit criteria will not justify a Phase III start. They have proposed a continuation of the technology effort to work in design, materials, computation and propulsion up to the limits of ground based facilities (Mach 6.5 to Mach 8). In the opinion of the Task Force, that approach will never resolve the fundamental technical issues.

We strongly recommend that an unmanned, scaled vehicle flight test program to demonstrate performance and validate computer codes for scramjet performance and boundary layer transition be the central focus of the next phase, designated Phase IIE. Unmanned, and launched on an available low cost vehicle, it could explore the suborbital hypersonic flight regime from (with different geometries), about Mach 12 to Mach 16/18.

The JPO is studying this concept; seems receptive; and is indicating that the design and mission costs should be "affordable". In today's fiscal environment,

"affordable" is an imprecise term. To be more precise, the flight test program should be completed within four years; cost no more than about $100M per year; and fit within a continuation of the present NASP program funding, augmented, hopefully, by a more equitable sharing from NASA.

The above discussion encapsulates our recommendations, which are:

(1) Do not enter the experimental flight vehicle phase (Phase III) at the end of 1993, as presently planned.

(2) Continue the NASP program as a substantial focused technology program. The operational potential in the next century is unique.

(3) Revise the presently proposed program to include unmanned, sub-scale flight tests to address the fundamental uncertainties in scramjet performance above M-12 and hypersonic boundary layer transition. As indicated above, we would define this effort as Phase IIE.

(4) During Phase IIE, continue to refine material selection and vehicle design as technology evolves.

(5) Redress the balance in funding between DoD and NASA. Pursuit of hypersonic technology is important to the mission of NASA: "to maintain the Nation preeminent in aeronautics and space technology." Application of the technology to specific mission areas should continue to be studied by DoD (Military) or other potentially benefiting sectors of our society (e.g. commercial transport).

TERMS OF REFERENCE*

The Task Force was chartered to address, but not limited to, the following issues:

1. The adequacy of the current Phase II Exit Criteria, if satisfied, to justify a decision to proceed to Phase III.

2. The likelihood of the completed and planned technical efforts to satisfy the current Phase II exit criteria or the exit criteria needed to justify a decision to proceed to Phase III. The efforts in materials and structures for both airframe and engine are of particular interest.

3. The identification of candidate military missions for operational vehicles which result from X-30 technology and the technical achievements required in the current NASP program to make such vehicles viable.

4. The adequacy of current plans for the Phase III effort, if completely successful, to produce the basis needed to enter system development for a militarily useful vehicle.

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*The full text of the Terms of Reference, as set forth by the Director, Defense Research and Engineering in his letter of 20 February 1992 to the Chairman, Defense Science Board, is at Appendix A.

RESPONSE TO ISSUES POSED

This section summarizes the Task Force response to the issues raised in our terms of reference.

1. In general, the current Phase II Exit Criteria, if satisfied, are adequate to justify a decision to proceed to Phase III. The essential criterion is a credible X-30 vehicle design with reasonable assurance of demonstrating SSTO performance. As we discuss subsequently, it is desirable to make this criterion more explicit with regard to demonstration of scramjet performance, boundary layer transition, and controllability, and the characteristics that would make the subsequent development of an operational vehicle resulting from X-30 technology feasible.

2. Critical Phase II Exit Criteria are not likely to be met. Vehicle design margins are inadequate for an SSTO configuration because of structural and subsystem weight uncertainties, uncertainty in engine performance, and unresolved stability and control issues. Analysis capabilities and ground test facilities are not capable of substantiating quantitative performance in at least two critical areas; scramjet performance above Mach 10 and where boundary layer transition will occur.

3. The Military have not yet identified realistic candidate missions for operational vehicles which result from X-30 technology. However, there are several potentially valuable military missions for such a vehicle.

The SSTO characteristic is the feature that will give an operational vehicle resulting from X-30 technology unique military capabilities and ability to perform useful missions. These missions take advantage of the performance and physical domain of an orbital vehicle launched from and recovered to a standard military runway and delivering military payloads to any point on the earth in a short period of time. The performance capability of such a vehicle will challenge future military operators and planners to derive military missions not yet conceived.

The technologies being demonstrated in such a program will have wide application for other military missions and capabilities. These technologies will be demonstrated sooner than would have been otherwise possible if such a program did not exist. NASP program contributions to U.S. competitiveness in the world marketplace are important factors that should be considered in designing the future NASP program.

4. Current plans for the Phase III effort are in a state of flux. The Task Force believes that when the Phase III program is defined, it can and must be designed to make subsequent development of a militarily useful vehicle possible.

The following sections address the technical concerns encountered in our review, and amplify our convictions concerning militarily useful missions for operational vehicles resulting from X-30 technology.

DISCUSSION

1. GENERAL

The Task Force is impressed by the progress which has been made by the NASP program over the past five years in the technologies critical to hypersonic flight.

The NASP technology program has come a long way in reducing the uncertainty in our ability to build an experimental flight vehicle that would demonstrate the desirable characteristics and technologies of a future operational military vehicle resulting from X-30 technology. Significant strides have been made in engine technology, materials, thermodynamic protection and design techniques, all of which bring the vehicle closer to achieving the "design closure" to meet the required performance characteristics.

It has only been in the last year, subsequent to the teaming of the NASP contractors, that a common configuration has emerged with sufficient design detail, and size, weight and performance estimates, with which to develop the specific developmental programs to remove the remaining performance uncertainties. Earlier, there were multiple configurations, each with unique design problems and performance uncertainties that precluded the development of detailed plans for further risk reduction.

However, even with the new common NASP configuration and the technical progress to date, there remain significant uncertainties which preclude final design closure. Weight margins are inadequate and engine performance uncertainties are

too large to give high confidence of achieving the design performance at high Mach numbers.

Furthermore, transitioning the NASP to an operational vehicle resulting from X-30 technology has additional uncertainties that increase the risk of being able to construct an operational vehicle upon completion of the NASP experimental flight vehicle program. The addition of operational characteristics into the vehicle, such as additional payload capacity, additional performance margins, longer orbital duration and standard maintenance provisions, will require increased engine performance and weight reduction which can only be achieved by further technological progress.

The NASP JPO has summarized the achievements to date in Appendix D, NASP Status Report Response to the Defense Science Board, dated 14 May 1992.

The recommendations of the Task Force are based on detailed review of the critical technologies and the technical and management experience of the Task Force members. The following sections summarize the concerns in structures and materials, propulsion and aerodynamics, control, and computational fluid dynamics which have shaped our recommendations.

2. STRUCTURES AND MATERIALS

Clearly, the progress of this program in quality of effort, data produced and management competency since the previous DSB review has been significant. The exit criteria preparatory to initiation of vehicle design are considered marginal, but would be satisfactory with the correction of some apparent deficiencies. The relationship of controllability to failure modes (e.g. unstart) and to structural design criteria (which can relieve or add) is not clear. The selection of liquid cooled panels to accomodate the temperature environment introduces a critical subsystem design (which is now safety of flight). Exit criteria for this and other subsystems (i.e., flight instrumentation and electrical system) are not explicit. In addition, it is not clear why metal matrix material is used if the panels are liquid cooled. The potential for using currently available material for these panels should be examined.

The current structural design criteria indicate a factor of safety requirement of 1.5 limit (anticipated loads) to ultimate (failure) for aero-elastic induced strains. There is at least the same degree or uncertainty in temperature induced strains as there is in aero-elastic and they may combine or relieve. Good design practice would require proper combination of strains and a factor of 1.5 on these combined strains (limit to ultimate).

The consideration of permitting panel buckling to alleviate some thermal strains is probably valid, providing body bending continuity and end bulkhead integrity are maintained. Buckling of metal matrix panels, particularly beyond yield (i.e. permanent set), is questionable without verification of effect on the low ductility matrix fibers. Buckling of cooled panels should be avoided.

The use of S* values for allowables is satisfactory if, when combined with proper load factors on predicted combined strains, it satisfies a high confidence value of no failures.

The exit criteria would be considered satisfactory if modified as suggested in the preceeding paragraphs, and if the panel tests (all types: TI matrix, cooled, et al) are representative of the full scale vehicle and if sufficient (under aero/thermal/acoustic loadings) testing is accomplished to validate allowable, analysis methodology with a confidence level of 90-95%.

The structural weight fraction is critical in this vehicle, but cautious optimistic judgement must be used. While normal fatigue considerations are not a factor in this vehicle, the relationship of static strength criteria to normal good aircraft design practice is valid. There would appear to be no rationale to deviate and accept greater risk of structural failure.

3. PROPULSION AND AERODYNAMICS

The NASP program has in place a broad based technology program which addresses the critical aspects of an SSTO airbreathing design. However, there are some aspects of the technology that are critical to the success of the NASP concept that cannot be fully matured via ground based testing to the high Mach numbers of critical importance.

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* **The minimum data point obtained from test with insufficient data to establish statistical significance. As a rule, S base allowable values shall not be above the minimum value obtained from testing.**

The two most critical of these are scramjet engine performance and boundary layer transition. The NASP program is dependent upon realizing the high-speed performance predicted for the scramjet propulsion cycle. Perhaps the highest technical risk in the program is the ability to quantify the characteristics of the scramjet and its flowpath integration into the airplane. Not far behind in technical risk is the uncertainty associated with boundary layer transition. It is essential to understand the boundary layer behavior at hypersonic speeds in order to insure thermal survival of the airplane structure as designed, as well as to accurately predict the propulsion system performance and airplane drag. Excessive conservatism in boundary layer predictions will lead to an overweight design incapable of achieving SSTO, while excessive optimism will lead to an airplane unable to survive in the hypersonic flight environment. Further design development and increased confidence in these two technical areas must be of paramount importance to the NASP program.

The research and development of the scramjet engine is hampered by inherent physical limitations of ground-based test facilities in the hypersonic speed regime. These physical limitations preclude ground testing of an entire propulsion flowpath (inlet, combustor, and nozzle) at anything above about Mach 8. Even at Mach 8, the scramjet cycle is just beginning to be established and, consequently, there is uncertainty associated with extrapolating the results into the higher Mach regime. At speeds above Mach 8, only small components of the scramjet can be tested. These limited component test results are then used in predictive codes to estimate overall cycle performance, operability characteristics, and aerodynamic and thermal loads in the scramjet engine in the higher Mach regime.

Boundary layer transition and its implications on airplane design are a continuing area of research even for subsonic airplanes. For hypersonic airplanes, the challenge is even greater due to the sensitivity of the airplane design to location of boundary layer transition, and the lack of necessary data to predict boundary layer behavior. CFD codes are used to predict boundary layer characteristics, but these codes must be anchored with experimental data to enable their use with confidence. Experimental data in the hypersonic regime are limited. Wind-tunnel noise contamination prohibits the acquisition of high-quality data from that source. To counter that problem, special low-noise wind-tunnels have been developed, but these quiet tunnels only operate at lower speeds, requiring considerable extrapolation to apply the results to hypersonic flight. Reentry vehicles (RVs) would appear to be sources of flight data but these are also compromised. Almost all RV data are from conical ablating vehicles that introduce contamination into a flowfield lacking in crossflow and adverse pressure gradients. Much uncertainty exists in hypersonic boundary layer behavior.

To reduce the risk in these technical areas, the task force recommends that the NASP program include a flight vehicle research program as an integral part of the technology development program. It appears to us that without such an activity, the risk associated with embarking upon a multi-billion dollar X-30 is excessive. The exact characteristics of the flight research activity need to be defined through technical studies by the program technical staff and should, as a minimum, include the following:

A. Operation of a scramjet high enough into the hypersonic flight regime to establish the ability to predict the performance of the total integrated airframe/propulsion system. To minimize cost of the scramjet flight experiment,

the scope of the activity needs to be carefully constrained. We envision the experiment to be focused on high Mach number (minimum Mach 12 through 15/18) tests of a scaled version of X-30 flowpath. The program should include key physics and modeling, specifically for CFD validation. An appropriate size appears to be about the size of the Concept Demonstrator Engine (CDE). Furthermore, the flowpath should be carried to the test conditions by a vehicle that does not necessarily use the scramjet for acceleration. Principal data objectives should be to verify the end-to-end flowpath performance methodologies and to collect data to enable an optimized structural design of the X-30 engine. It is envisioned that a number of flights will be required to obtain sufficient information. Reusability must be considered for the carrier vehicle and the experimental engine. (A potential concern is that this experiment be seen as a replacement for the X-30 or that it becomes the X-30 itself. The scramjet flight experiment, involving a low-cost simple carrier vehicle and scramjet module, cannot and will not address all of the technical issues for airbreathing SSTO vehicles.)

B. Hypersonic boundary layer transition data in the same hypersonic flight regime are needed to validate the predictions for the X-30. This will require a shape similar to the X-30 so that 3-D effects and representative pressure gradients can be achieved. It may be possible, but not necessary, that the same flight research vehicle be used for both the scramjet tests and the boundary layer transition studies.

The need to acquire these data is so important that a significant portion of the near-term technology activity should be applied. We fully expect that the recommended flight activity will result in a relatively large (perhaps 40-50 ft long) and expensive ($200-$300M) vehicle that could require a majority of the available

near-term funding. It is recognized that this will require curtailing other important technology development efforts; however, this trade-off is essential.

In addition to the concern about scramjet performance, we also note that the X-30 must take-off, climb and accelerate to approximately Mach 3.5, if hypersonic flight is to be reached. Thus, some planning is recommended to prepare for an experimental program to develop, verify performance, and certify the engine in this speed range. As long as the inlet is properly designed, it will be possible to conduct meaningful tests on the engine at Arnold Engineering Development Center (AEDC). These tests will provide the low speed data necessary for the kinds of assessments mentioned above.

Note that some preliminary tests are needed to understand the flow field near the inlet, and can be obtained by standard model test procedures.

4. CONTROL

Controllability

"Controllability" demands that the aircraft/engine combination can be controlled and regulated throughout the operating space with adequate margins to allow for uncertainties and off-nominal conditions. A central prerequisite is that sufficient total "control power" be available over adequate effector "bandwidth" ranges. Sufficiency implies that: the aircraft can be trimmed to appropriate equilibrium states; open-loop aircraft stability and control deficiencies (e.g. instabilities) can be redressed; mission-centered and emergency maneuvers/tasks can be accomplished; effects of disturbances can be suppressed; etc. Total "control power" incorporates the rate and intensity limits for all means of modulating the forces and moments on the airplane. It is conventionally defined in terms of force and moment rate and position limits on aerodynamic effectors (all-moving-wings, rudders, drag devices, speed brakes, etc.), rate and position limits on engine geometry and fuel flow effectors, etc., and includes base-burning rockets, and reaction controls as effectors. The "bandwidth" of a given effector characterizes the controller dynamics as a frequency range over which the effector can exert control within the rate and position limiting constraints.

Controllability Status-General

The emphasis to date on controllability has been on SSTO with takeoff and landing from a conventional runway. There is, as yet, no assurance that minimal command/regulation tasks and maneuvers appropriate for envelope expansion prior to SSTO operations or for the collection of atmospheric hypersonic cruise data

(usually cited as a secondary NASP mission) can be accomplished. Based on the information we reviewed, "controllability" for the most modest of SSTO operations appears to be marginally feasible. With the notable exception of approach and landing, the more severe maneuvering environment requirements associated with envelope expansion and hypersonic cruise missions have yet to play a significant role in controllability considerations.

Controllability-Current Status

At the outset it is fair to say that controllability issues for NASP are so complex, so widely ranging in dynamics and frequency, and so interactive between technical disciplines as to have no parallels in aeronautical history. Yet, perhaps because of this extreme spectrum of ubiquitous interactions and the consequent difficulty of dividing the total controllability problem into easily comprehended constituents, "controllability" has received only very modest support thus far in the program. For example, many of the possible stability and control problems and deficiencies which are likely possibilities somewhere in the envelope have not yet been adequately surveyed, much less assessed. Consequently the most fundamental initial requirements for elementary aircraft control are not yet fully comprehended.

In the DSB NASP Task Force progress reviews, existing controllability synthesis and analysis areas have been cited by project personnel as "satisfactory" in general. These conclusions are based on very preliminary and incomplete analyses, with very little simulation or assessment of realism. In the main, the analyses are based on very optimistic assumptions, such as first-order actuation dynamics, no flexible or slosh modes, impractical "calibrated" feedback, and extremely modest maneuvering requirements--basically SSTO and idealized approach and landing.

Considering the aerodynamic controls alone:

a. The effector rate and position limits control power quantities are strongly dependent on the maneuvers to be performed, disturbances to be encountered and offset, abort transients, and the minimum backup positions assumed for the actuation. The maneuver complex for the mission phases which drive total controllability requirements have not yet been completely defined, so general feasibility in this respect cannot currently be determined.

b. Fortunately, the effector rate and position control power aspects for aerodynamic controls are usually set by the lower speed (e.g. approach and landing) and trim conditions--which have been examined in a preliminary fashion. To the extent that this obtains for NASP, the aero control power effector rate/position quantities may be suitable. The aero-surface actuation backups are certainly minimums (e.g. single thread rudder actuators, assuming streamlining in the event of failure, tandem actuators on other surfaces, etc.).

c. Another major aspect of control power is controller and effector bandwidths. At present these are unrealistically large. When the presence of flexible modes, realistic actuation and other higher frequency dynamics is taken into account the higher-frequency controller dynamics will result in significant modifications and limitations to the attainable closed-loop (aircraft plus Stability and Control Augmentation System (SCAS)) vehicle stability and control characteristics.

d. The analytical procedures used thus far to determine the controller characteristics essentially modify the stability derivatives to values appropriate for

certain specifications. These procedures imply exceptionally complete knowledge of certain key derivatives of the airplane and effective adjustment of such derivatives to desired values via feedback and/or crossfeed control using idealized feedback. Uncertainties in the derivatives, difficulty in determining reasonable surrogates for the needed aircraft states (e.g. sideslip angle), and potentially very high gains to achieve the desired values, require much more detailed consideration of higher frequency effects such as flexible modes if this procedure is to be used as a basis for feasibility assessment.

Considering the engine controls alone:

a. The Vehicle Management System (VMS) is an integrated aircraft/engine system which must cope with enormous ranges of control modes, dynamic frequencies, and dynamic interactions. The degree of understanding of the propulsive/aerodynamic forces and moments which have to be countered by the VMS is still in an embryonic state.

b. In their current manifestations, the engine effectors (geometry and fuel flow controls) have bandwidths which may be adequate at very-low amplitude levels. But the maximum rates are far too low for any but the mildest maneuvers (perhaps idealized SSTO). Any higher-frequency engine control fluctuations needed to satisfy propulsion/aerodynamic decoupling or similar requirements are not yet included. These can demand major changes in the VMS actuation.

Considering the thermal control system alone:

a. Very great uncertainties exist at a fundamental level. For example, design depends on knowledge of inside and outside heat transfer processes. On the outside this depends on boundary layer transition, while on the inside, major uncertainties are connected with supersonic burning.

b. Because of the highly diverse thermal states at various points of the vehicle, the overall thermal control system is intrinsically very diffuse. Yet the number of sensor and actuation "control points" presently planned is quite small, implying a high degree of open-loop and/or calibrated control.

Potential Help From Controls

One of the current deficiencies in the NASP, from the standpoint of SSTO capability, is the marginal structural weight fraction. There are at least three ways in which the structural weight might be reduced using the VMS. These are:

a. Active structural maneuver load and flexible modes controls.

b. Active flutter control.

c. Ultra-precision landing control.

5. COMPUTATIONAL FLUID DYNAMICS

The primary CFD techniques in widespread use within the NASP program are 3-D inviscid techniques or 2-D viscous techniques. The 2-D viscous techniques

are primarily used to provide calibrations of the less expensive methods. Turbulence modeling is based, for the most part, on eddy viscosity modeling. The algebraic models are most commonly used along with some application of differential equation models. Capability to use the Reynolds stress models is under development, but not within the program, and not on a schedule driven by the program. Development of turbulence/chemistry interaction models is proceeding under a Government Work Package and remarkable progress has been made. The modeling work is slated to complete next year, but there are not specific plans for validation other than use of the existing sparse database. Transition modeling is focused around the e^n method with the 2-D codes transferred to the contractors in 1989 and the 3-D codes transferred to the contractors in June 1992. The 2-D n-factor codes have correlated transition location prediction with RV flight data quite accurately (15% according to the contractors). The 3-D code is currently being validated and substantial work remains to bring this code into practice in the program. When the contractor user community becomes skilled in the use of this methodology it should offer a similar improvement in prediction accuracy. Comparisons of prediction transition location by the 3-D n-factor codes compared with quiet tunnel data are quite good, but tunnel data are available only at low Mach numbers (up to approximately Mach 3.5). The hypersonic, 3-D transition prediction capability is as yet too new to assign uncertainty numbers, and lack of validation data makes this area critical.

6. APPLICATIONS

The Department of Defense (DoD) elected to become a partner in the development of NASP in the mid-1980's because of the potential, if the concept proved feasible, for effective accomplishment of military missions using very high

speed hypersonic and orbital vehicles. In addition, it had the capability for very rapid and potentially inexpensive access to space for military satellites and other payloads. With the Soviet threat greatly dissipated, the world environment has undergone drastic restructuring and the funding for military capabilities has declined. Therefore, the need for a NASP flight test program, subsequently leading to the development of operational vehicles for military operations, must be reassessed. The Defense Science Board Task Force has accomplished this reassessment with particular focus on the need for SSTO capability --the single most demanding requirement on the performance of NASP and operational vehicles which result from X-30 technology.

Most assessments of this type fall into the trap of comparing future capabilities, like that of an operational vehicle resulting from X-30 technology, to today's military capabilities in performing what may be well defined missions of today's military forces, a mistake avoided by the current DSB assessment.

The time frame for the consideration of operational vehicles resulting from X-30 technology in conducting future military operations is in the period of 2020-2025, about thirty years from today. The NASP must complete the X-30 experimental flight vehicle program, and operational vehicle system development must be completed before achieving an operational configuration and operational status.

Realistically, then:

- First flight of the X-30 experimental flight vehicle will not likely occur before 2002 and first SSTO demonstration before 2005.

- It is unlikely that a decision to proceed with system development of an operational vehicle resulting from X-30 technology will occur until after flight test evaluations are completed some two years or more after SSTO. This puts the decision period about 2007.

- Development of the operational configuration and the initial production will take about 10 years, leading to an initial operational capability about 2017 and full operational capability possible in the 2020-21 period.

- The operationally useful period for the vehicle to perform military missions will probably be 20-40 years -- through the period 2020-2060.

The realization of the extensive time frame before NASP would lead to an operationally useful vehicle demands some new and innovative thinking about the future military and political environment in which NASP must operate. Current technologies will no longer be applicable; political realities of today will be history in 40 years or so; military alignments of today could be drastically changed; and the comparison of capabilities of operational vehicles which result from X-30 technology to current means of conducting military missions would be obsolete. In the time frame of the future we must not only think of these vehicles as a way to perform classic military missions but, in addition, as a technology that would permit us to perform new military missions that would enhance our security.

While it is next to impossible to predict with any certainty the environment of the future world and what military capability will be demanded of U.S. forces in that environment, there are some common characteristics of that environment that are likely:

- there will be a proliferation of high technology weapon systems around the world to those nations which had not previously had access to such capabilities,

- many of those systems and platforms will have the ability to deliver devices and weapons of mass destruction,

- many countries who have such weapon systems will have internal goals and objectives which are in conflict with the interests of the United States and our allies,

- not only will such countries possess threatening military capabilities, they will also possess the surveillance and reconnaissance capabilities to observe U.S. and allied activities and deliver these weapons at long range with precision.

These common environmental conditions some thirty years in the future provide strong arguments for providing the military commanders and the President with a military weapon system having a reasonable turn around and short preparation time; capable of reaching long distances, rapidly and undetected; capable of doing its own surveillance; and able to deliver weapons with great precision. The flexibility of a manned system would be particularly attractive. The technology being developed in the X-30 program would be directly applicable to a future military platform resulting from X-30 technology that would meet these requirements. Such a system would give the U.S. the following unique military advantages:

- an ability to enter into a performance and physical domain not easily available to other potential military powers,

- very rapid access to space for a variety of classical military satellite delivery or anti-satellite missions,

- ability to put a manned vehicle over any part of the world within the shortest feasible period of time (orbital velocity) and return quickly to a secure base.

- faster speeds would put the vehicle into an earth escape velocity and slower speeds would require very demanding, long-range intra-atmospheric hypersonic flights,

- a payload capacity to perform surveillance, communications and global power projection missions,

- ability to maintain an on-orbit "alert" capability with the NASP-type fleet of vehicles for even more rapid response or for a "show of force" capability,

- through basing, atmospheric maneuvers, and orbital plane changes, essentially deny an adversary knowledge of the ultimate target and the ability to take effective defensive actions,

- exploitation of the combinations of advancing technologies in communications, computational capabilities, sensors, guidance systems, laser weapons developments, munitions and electronics in a unique military platform for future, and as yet undefined, military missions.

The tremendous potential of the technologies being developed for NASP, either in a direct military application, or as spin-offs to other military systems, argues strongly for the continued development of NASP leading to an ultimate flight test including the SSTO demonstration, and an operational vehicle resulting from X-30 technology. SSTO is clearly one of the features of NASP that makes most

of the mission attributes discussed above worthwhile and the vehicle highly valuable to military operations. It is the single most important performance parameter that should be retained.

RECOMMENDATIONS

Based on the above, Task Force deliberations led to the following recommendations:

1. Continue the NASP program, including the requirement to ultimately demonstrate the SSTO capability, so long as the vehicle performance appears to be feasible. The unique capability and military flexibility such a vehicle would give a future President and military commander, in light of future world uncertainties, should be preserved.

2. Do not enter into a Phase III, Experimental Flight Vehicle Phase, at this time. While program progress has been impressive, the NASP configuration is still immature and there remains sufficient risk and uncertainty that proceeding with a prototype flight test program for the current configuration would be premature.

3. Proceed with a revised next phase, which we would define as Phase IIE, over the next three years to emphasize continued risk reduction and the addition of engine component flight tests to validate computational design techniques. We recognize that while flight tests short of the full configuration will never demonstrate the performance feasibility of the NASP design, tests of unmanned sub-scale vehicles incorporating boundary layer transition measurements and engine components will be extremely valuable to validate the design and computational techniques essential for completing the full scale engine and vehicle design.

4. Technology options should be revised during Phase IIE. The press of the schedule to enter Phase III resulted in decisions being made to "freeze" technology, especially in materials, to permit design solutions to be completed. With additional

time being provided in the Phase IIE period, these decisions should be revisited and modified as appropriate.

5. Government funding for Phase IIE should be sufficient that by the end of this phase the component flight test program would yield adequate data to proceed into the next phase. We would estimate that the annual funding for the next three years would be roughly $250-400 million per year. The "Exit Criteria" for a decision to proceed would be the same as have been established for the previously defined Phase III, but with more explicit criteria for assessment of the knowledge of boundary layer transition on NASP, scramjet performance at high Mach numbers, and feasibility of developing an operational vehicle resulting from X-30 technology.

6. NASA should begin to assume an equal share of the NASP Program Funding.

7. The DoD and NASA should conduct a joint utility study to evaluate the uses of X-30 technologies and potential missions for future operational vehicles.

APPENDICIES

APPENDIX A

DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING

WASHINGTON, DC 20301-3010

20 FEB 1992

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference--Defense Science Board Task Force on National Aero-Space Plane (NASP) Program

You are requested to organize a Defense Science Board Task Force to review technical progress and report your assessment of the technology development associated with the National Aero-Space Plane (NASP) Program. The task force should hold its first meeting in March 1992 and brief its findings and recommendations to me three months after the first meeting. A final report is required 30 days following the briefing. The task force should be supported by government advisors from OSD, SDIO, the Joint Staff, NASA, USAF, and Navy.

Six years ago, the Defense Science Board (DSB) initiated a review of the concept, technical basis, program content, and missions of the NASP program. The report was completed in September, 1988, and the recommendations contributed to strengthening the technical efforts in the NASP program.

Since then, substantial technological progress has been made in the technology development phase (Phase II) of the program. Phase II of the program is currently scheduled to end in late Fiscal Year 1993, with a decision whether to proceed to the experimental flight vehicle phase (Phase III) to be made at that time. This decision will be a very significant one for the Department of Defense and NASA. It is therefore desirable for the DSB to revisit the NASP program to assess the degree to which the many technical challenges of the program have been resolved, or are likely to be resolved by the end of Phase II.

The issues that the Task Force should address include, but are not limited to:

1. Are the current Phase II Exit Criteria, if satisfied, adequate to justify a decision to proceed to Phase III?

2. Regarding Phase II, are completed and planned technical efforts likely to satisfy the current Phase II Exit Criteria, or the exit criteria needed to justify a decision to proceed to Phase III? The efforts in materials and structures for both airframe and engine are of particular interest.

3. What are the candidate military missions for NASP-derived vehicles, and what are the technical achievements required in the current NASP program to make such vehicles viable?

4. Will the current plans for the Phase III effort, if completely successful, produce the basis needed to enter system development for a militarily useful vehicle?

The Director, Defense Research and Engineering is the sponsor of this Task Force. Dr. Joseph F. Shea will serve as Chairman, Dr. Donald M. Dix will be the Executive Secretary, and LtCol David L. Beadner, USAF, will be the DSB Secretariat Representative. The DDDR&E(P&R) will provide necessary additional travel funding and DDDR&E(R&AT) will make arrangements for and provide funding of any support contract efforts. It is not anticipated that this study will cause any member to be placed in the position of acting as a "procurement official" for the purposes of section 27 of the Office of Federal Procurement Policy Act.

Victor H. Reis

APPENDIX B

MEMBERSHIP OF THE DSB TASK FORCE ON NATIONAL AERO SPACE PLANE (NASP)

Chairman

Professor Joseph F. Shea
Massachusetts Institute of Technology

Task Force Members

Mr. Edward C. Aldridge, Jr.
The Aerospace Corporation

Professor Seymour M. Bogdonoff
Princeton University

Professor Eugene E. Covert
Massachusetts Institute of Technology

Major General Ralph H. Jacobson, USAF (Ret.)
The Charles Stark Draper Laboratory

Professor Jack L. Kerrebrock
Massachusetts Institute of Technology

Mr. Sol Love
BASLE Corporation

General Robert T. Marsh, USAF (Ret.)
Private Consultant

Mr. Duane McRuer
Systems Technology, Inc.

Executive Secretary

Dr. Donald M. Dix
Office of the Deputy Director of Defense
Research and Engineering, S&T/ET

DSB Secretariat Representative

Lt. Col. David L. Beadner, USAF

GOVERNMENT ADVISORS TO THE NASP TASK FORCE

OSD

Dr. Gene Sevin
Office of the Undersecretary of Defense (Aquisition)

Navy

Mr. Robert H. Thompson
Office of the Assistant Secretary of the Navy,
Research, Development and Acquisition

Air Force

Brig Gen Stephen P. Condon
Office of the Secretary of the Air Force,
Director (Science and Technology)

Mr. Ming Tang
Office of the Secretary of the Air Force,
Science and Technology Division

OJCS (J-8)

Col. James Burke, USAF
System Program Evaluation Division

National Aeronautics and Space Administration

Dr. H. Lee Beach, Jr.
Deputy Director, NASA
Langley Research Center

Mr. Vincent Rausch
Director, National Aerospace Plane

APPENDIX C

AGENDAS

DSB AGENDA
NASP JOINT PROGRAM OFFICE
WRIGHT PATTERSON AFB, OHIO
MARCH 12-13, 1992

March 12, 1992

0730	Chairman's Time / Ethics Brief	Dr. Shea / Lt Col Beadner
0815	Program Overview / Exit Criteria	Dr. Barthelemy
0930	Break	
0945	Air Vehicle Design Status	Mr. Imfeld
1145	Working Lunch	
1230	Aerodynamics	Mr. Thor
1300	Structures & Materials	Dr. Ronald
1400	Break	
1415	Structures & Materials (cont)	Mr. Imfeld
1445	Propulsion	Mr. Imfeld
1615	Discussion	Dr. Shea
1730	Adjourn	

March 13, 1992

0730	Chairman's Time	Dr. Shea
0800	Propulsion (cont)	Mr. Imfeld
1000	Break	
1015	Flight Control	Mr. Mutzman
1100	Subsystems	Mr. Imfeld
1130	Tracking Milestones	Mr. Imfeld
1145	Working Lunch	
1230	Phase 3 Program Plans	Col Wierzbanowski
1300	NDV Applications	LtCol Xiques
1400	Break	
1415	Executive Session (DSB MEMBERS)	Dr. Shea
1500	Adjourn	

DSB AGENDA
NASP National Program Office
Palmdale, California
April 16-17, 1992

April 16, 1992

0800	Overview	Mr. Waldman
0900	X-30 Design	Dr. Chaput
	- System Overview	
	- Closure	
1000	Break	
1015	Vehicle Definition	Dr. Chaput
1145	Vehicle Management	Dr. Schwanz
1230	Working Lunch	
1300	Closing Comments	Dr. Chaput
1315	Hardware Display	Mr. Newmann/ Dr. Chaput
1400	Splinter Sessions	
	- Structures	Mr. Ellis
	- Boundary Layer Trans.	Mr. Haney
	- Flight Test/Applications	Col. Wierzbanowski/ Ltc. Matthews
1730	Working Dinner	
1930	Executive Session	Dr. Shea & DSB
2130	Adjourn	

April 17, 1992

0800	Engine Flowpath Physics	Dr. Moon
0930	Break	
0945	Engine Aerodynamic Design	Dr. Kawecki
1200	Working Lunch	
1245	Closing Remarks	Dr. Moon
1300	X-30 Engine Design	Mr. Ratekin
1315	Integrated Propulsion System	Mr. O'Connor
1400	Break	
1415	Low Speed System	Mr. Sack
1445	Engine Mechanical	Mr. Ernst
1615	Development Plans	Mr. Ratekin
1630	Executive Session	Dr. Shea & DSB
1730	Adjourn	

DSB AGENDA
NASA Langley Research Center
Newport News, Virginia
May 14-15, 1992

May 14, 1992

0800	Welcome	
	- NASP Program Discussion	Dr. Beach
0830	Overview of NASA's NASP Role	Ms. Couch
0900	Computational Fluid Dynamics	Dr. Dwoyer
	- Transition Prediction Methods Development	Dr. Zang
	- Transition Methods Application to X-30	Dr. Kei Lau, MDAC
1000	Break	
1015	Aero/Aerothermodynamics	Mr. Paulson
1045	Propulsion	Mr. Anderson
	- High Speed Performance and Methods	Mr. McClinton
	- 100 Megawatt Facility Propulsion Tests	Mr. Covington
1200	Structures	Mr. Moses
1230	Subsystems - Slush	Mr. Hannum
	Working Lunch	
1300	Air Force Hypersonics Technology Initiative	Dr. Richey
1345	Phase 2D	Mr. Imfeld
1445	Break	
1500	Risk Reduction	Dr. Harsha
1545	Phase 3A	Dr. Barthelemy
1645	Scale up to SSTO NDV's	Mr. Kasten
1730	Chairman's Time	Dr. Shea
1830	Adjourn	
	Evening Executive Session at Hotel	Dr. Shea & DSB

May 15, 1992

0800	All day DSB Executive Session	Dr. Shea & DSB
1230	Working Lunch	
1430	Adjourn	

APPENDIX D

NASP STATUS REPORT

JOINT PROGRAM OFFICE

RESPONSE TO DEFENSE SCIENCE BOARD

May 14, 1992

PAGE	TOPIC
D-2	PROGRAM DIRECTOR'S LETTER
D-4	INTRODUCTION
D-5	AIRFRAME & ENGINE STRUCTURES / MATERIALS
D-8	AERODYNAMICS
D-10	AEROTHERMAL
D-12	X-30 VEHICLE DESIGN
D-14	X-30 ENGINE DESIGN
D-17	GUIDANCE & CONTROL
D-20	COMPUTATIONAL FLUID DYNAMICS

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AERONAUTICAL SYSTEMS CENTER (AFMC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FROM: ASC/NA

14 MAY 1992

SUBJ: NASP Status Report

TO: Massachusetts Institute of Technology
ATTN: Dr. Joseph F. Shea
Department of Aeronautics and Astronautics
Cambridge MA 02139

Attached to this letter is the NASP status report for your use with the NASP Defense Science Board Task Force activities. If you have any questions, don't hesitate to call Mr. Jim Arrington, my NASA Principal Deputy, for additional information. He can be reached at 513-255-8158.

DR. ROBERT R. BARTHELEMY, SES
Program Director
National Aero-Space Plane Joint Program Office

1 Atch
NASP Status Report

SECTION 1.0

INTRODUCTION

The purpose of this document is to summarize the status of the National Aerospace Plane Program relative to the reviews of the program by the Defense Science Board. The format used in each of the major technical areas is to status the program as it was at the time of the last DSB review, summarize what has been accomplished since then, status the present state of the program, and explain what needs to be done in the remainder of phase 2D.

SECTION 2.0

AIRFRAME AND ENGINE STRUCTURES AND MATERIALS

• WHERE WE WERE (1987-1988)

At this time lightweight materials with sufficient high temperature capabilities were not available to meet NASP single-stage-to-orbit (SSTO) requirements. The NASP design lacked maturity in that thermal/ structural analysis associated with both the engine and airframe designs were very limited. There was no funded plan in place to validate thermal/structural component concepts, loads, or design tools. Improvements in high temperature strength, oxidation resistance, and fabrication quality were needed for titanium matrix composite (TMC) airframe fuselage panels and support structures. Advancements in thermal protection system (TPS) materials were needed to protect the vehicle flowpath and engine nozzle surfaces. Refractory composite (RC) materials which could meet this need required improvements in oxidation resistance and development of lightweight designs and fabrication methods. Actively cooled structural designs applicable to very highly heated regions such as ramps, nozzles, and leading edges were just beginning to be developed. Materials for high temperature engine applications also had not been developed or demonstrated for NASP requirements.

• WHAT WE DID (1988-1991)

In October 1987 Phase 2 of the NASP program was initiated. Under this phase of the NASP contract, structural analysis tools were developed and materials and structures risk reduction activities (Task D of each contractors contract) were initiated. Significant contributions were made as a result of these activities as follows:

- Developed automated thermal/structural design and analysis tools to evaluate the complex structural response of the NASP vehicle.
- Defined and initiated technology development programs to validate component concepts, design tools, and weights to meet the NASP Phase 2D exit criteria.
- Defined non-uniform and dynamic engine and airframe pressure and acoustic loads.
- Defined and initiated plans to develop facilities to test structural components under X-30 conditions.
- Fabricated large (up to 8'x8'x4') cryotank and fuselage structures, representative of those in the vehicle design and successfully tested them with combined liquid hydrogen cryogen, external heating, and applied fuselage bending loads.
- Fabricated and tested large (up to 4'x8') TMC and C-C wing structures.
- Initiated development of IM-7/977-2 carbon epoxy for cryogenic tankage.

In late 1987 the NASP Materials and Structures Augmentation Program (NMASAP) was initiated, at the recommendation of the Defense Science Board. The objective was to develop materials, manufacturing processes, and structural concepts that

would enable the United States to achieve the NASP goal of demonstrating a SSTO space-capable aircraft. This program has been a cooperative effort between five prime engine and airframe contractors, several government agencies and a large number of subcontractors. The consortium carried out research and development in five key material areas: 1) Titanium Matrix Composites; 2) Titanium Aluminides; 3) Refractory Composites; 4) High Conductivity Composites; and 5) High Specific Creep Strength Materials. Activities and accomplishments of this consortium include:

- Defined low-to-moderate risk baseline materials.
- Conducted preliminary and detailed thermal/structural analyses to substantiate material selection, design concepts, and weights.
- Tested thousands of material and structural coupons to determine properties and response to NASP environments.
- Developed a new titanium matrix alloy (Beta 21S) with capabilities that exceed the required life at temperatures of 1500°F (higher than 1200°F previously available) in both low pressure hydrogen and air atmospheres.
- Developed and tested high quality titanium matrix composite fuselage structural panels to demonstrate load and thermal cycling capability.
- Developed and demonstrated manufacturing methods and processes for lightweight refractory composite TPS designs (carbon-carbon and carbon-silicon carbide).
- Developed reliable carbon-carbon oxidation protection systems for 50 to 100 hours at peak temperatures up to 2600°F.
- Developed and demonstrated fasteners, attachment concepts and joints for the various material systems and structural requirements.
- Conducted limited manufacturing scale-up demonstrations.

• WHERE WE ARE

Significant advances have been made in materials development for NASP airframe and engine structures. These advancements have been made in a relatively short time. They are being integrated into the vehicle design process to give it increased fidelity as it matures. In addition to the significant technology advances which feed directly into the design definition, the industry, vendor, and government laboratory community capability to proceed efficiently both individually and as a team has been vastly upgraded as a result of the NASP program.

We are designing, fabricating and testing subelement articles to expand/validate the actively cooled structures concepts. Continuing to design and fabricate components to demonstrate scaleup capabilities in the areas of TMC and C/C. TPS work is continuing in the area of material characterization to expand the database to provide higher confidence and understanding of the X-30 materials.

• WHAT REMAINS TO BE DONE (1992-1994)

Work to be done before Phase 3 includes:

- Complete airframe and engine materials characterization coupon testing to provide an acceptable level of confidence in material properties.

- Conduct large scale thermal/structural validation of representative engine flowpath components.
- Test and validate performance of representative cooled panels.
- Continue development of facilities to provide manufacturing scale-up for X-30 parts and demonstration.
- Continue development of test facilities to provide combined cryogenic, thermal, and mechanical loads representative of NASP environments.

SECTION 3.0

AERODYNAMICS

- **WHERE WE WERE (1987- 1988)**

During this time different methods were used by each of the CTMs for developing the Aero/S&C database and for sizing the control surfaces. The Aero/S&C databases on these pre-teaming vehicle concepts were only partially substantiated by wind tunnel testing and CFD results. The aero-propulsion interactions were not substantiated by powered wind tunnel testing for anything above Mach 1.5. In addition the CFD codes used for aerodynamic prediction were not fully validated.

- **WHAT WE DID (1988 - 1991)**

After initiation of Phase 2 of the program in late 1987 several contributions to this area were made, increasing confidence in the database and analysis. Some of these were:

- Reconciled aerodynamic prediction methods for conceptual design, using applicable pre-team test data and calibrated engineering codes (e.g., HABP).
- Defined control surface sizing criteria for conceptual design, using static S&C analysis at critical flight conditions.
- Defined and executed wind tunnel test program to provide initial Aero/S&C database, including configuration parametrics, for conceptual design.
- Defined and initiated wind tunnel test program to provide high-fidelity aerodynamic database for vehicle performance and stability & control analyses, including inlet- and exhaust-induced aero-propulsion interactions.
- Continued calibration of CFD codes with applicable wind tunnel test data.
- Defined and initiated plan to enhance high speed wind tunnel facility capabilities (e.g., Mach 18 at NSWC).
- Defined initial aerodynamic uncertainty estimates using pre-team results.

- **WHERE WE ARE (1992)**

Fidelity of the Aero/S&C database has been enhanced through utilization of experimental data from the initial series of wind tunnel tests covering the Mach no. range from 0.2 to 10.0. Confidence in aerodynamic prediction methods has been improved through calibration of CFD and engineering codes with wind tunnel test data for X-30 vehicle shapes. Initial aero control concept and control surface design criteria have been defined, and control surface size/shape have been modified to satisfy design criteria. There is insufficient CFD and test data available to substantiate aero-propulsion interactions for X-30 vehicle shapes.

- **WHAT REMAINS TO BE DONE (1992 - 1994)**

Before instituting Phase 3 some of the work needed includes:

- Complete the Phase 2D wind tunnel test program to (a) substantiate aerodynamic force & moment predictions and (b) calibrate aerodynamic prediction tools.
- Continue nose-to-tail CFD analyses to investigate aero-propulsion interactions at hypersonic speeds.
- Refine control surface design criteria, using static and dynamic S&C analyses.

SECTION 4.0

AEROTHERMAL

- **WHERE WE WERE (1988 - 1989)**

In this time frame the aerothermal analysis methods used by each of the CTMs varied widely in scope, complexity, and level of integration. The aerothermal design analysis being performed then were done primarily with engineering codes, due to cost and schedule constraints. Any engineering code validation was limited to comparisons with unvalidated CFD codes or with wind tunnel data. The boundary layer transition prediction methods were empirical correlations of widely varying flight/ground test transition datasets of limited applicability.

- **WHAT WE DID (1990 - 1991)**

Initial aerothermal distributions and boundary layer transition data was collected on each CTM configuration.

During this time frame efforts began to focus on the team configuration and strengthening prediction methods and analysis. These efforts included:

- Compared aerothermal analysis codes, determined causes for major prediction differences, and selected codes for specific applications consistent with code capabilities.
- Planned and executed wind tunnel testing to provide additional aerothermal distributions and boundary layer transition data on current NASP configuration to existing pre-teamed database.
- Defined high-fidelity wind tunnel test program (Model D) to provide high-Mach aerothermal data on current NASP configuration, including detailed fuselage, wing, tail, and reentry engine components.
- Defined and initiated a phased upgrade plan to improve the design criteria for boundary layer transition through use of parametric linear stability analysis and quiet tunnel test data.
- Commenced extensive effort to checkout, validate, and implement the e-Malik 2D linear stability code, including benchmark solutions, investigation of quality requirements for CFD mean flow solutions, and evaluation of specific requirements for blunt body solutions.

- **WHERE WE ARE (1992)**

Boundary layer transition analysis capability has been enhanced by the availability of new tools:

- Quiet tunnel test facilities
- Two-and three-dimensional linear stability codes

Much progress has been made in the implementation of the linear stability codes. The current design transition criterion was based entirely on 2D linear stability analysis.

Tasks are underway to combine available quiet tunnel data and analysis results to further refine the criterion. There is insufficient experimental data available at high Mach number conditions for validation of boundary layer transition methods for X-30 vehicle shapes.

• WHAT REMAINS TO BE DONE (1992 - 1994)

During this phase of the program efforts are still needed to:

- Complete the Phase 2D wind tunnel test program to provide (a) data for aerothermal code validation and (b) data to augment aerothermal database in situations where analysis is uncertain.
- As vehicle external shape matures, increase use of CFD analyses to substantiate engineering predictions and investigate issues such as flow separation, shock interactions, and wall catalycity.

SECTION 5.0

X-30 VEHICLE DESIGN

• WHERE WE WERE (1987-1988)

The X-30 design effort reflected the imbalance between design knowledge and actual technology status. Design decisions were made with assumed technology trends, resulting in very different design paths. Many models and experiments to obtain technology were initiated. Technology was beginning to become available for the pre-team design effort. Also, the contractors were aware of the design drivers, the need for inter-functional integration, airframe/engine integration and sensitivity of designs to various parameters. The design activities included parametric optimizations based upon technical interactions. The importance of engine on the controllability of the aircraft was noted. Concerns existed in areas critical to the design. Plans were in place to understand and reduce the risk in these critical areas.

The Technology Maturation Program (TMP) was working on a broad set of generic technology and had not focused on a single configuration because of the ongoing competition.

• WHAT WE DID (1988-1991)

To ensure orbit capability the design criteria were aggressively established. Design efforts were downscaled in favor of technology development. Technology concerns critical to the design were emphasized and prioritized. Advanced materials, slush hydrogen, engine technology and CFD technology were greatly enhanced. Test data from efforts initiated pre-team were converted into a team database. Critical technology issues were re-evaluated and prioritized from a team point of view.

The TMP received increased effort in critical areas to enhance exit from Phase 2. The Material Consortium was formed to accelerate the rate of material technology and directed toward providing required material property data. Capability in high temperature and heat flux, severe acoustic and non-uniform environments were addressed. Some large components built in pre-team were modified. Many non-critical technology developments were deferred. Program technology milestones were developed to structure performance and risk tracking. Scheduled completion would fall out from milestone completion and available funds. The first flight date was delayed to meet certain milestones, but was still aggressive.

• WHERE WE ARE (1992)

The design is now consistent with technology. Configuration optimization shows hope of improving performance or reducing risk. The team has demonstrated ability to optimize the design with new technology, assumptions and requirements. Technology concerns have diminished in areas critical to the design. Prediction of the BLT location is improving. Material selections are now compatible. Uncertainty reduction

and success in ground tests have improved airframe structural design fidelity. Affordable 3D CFD is utilized in design with increasing accuracy due to TMP testing.

The overall program effort is close to achieving the technical objectives of Phase 2. Some technology issues have been deferred. The team design has been shown to be superior to pre-team designs in terms of increased realism and shape optimization.

• WHAT REMAINS TO BE DONE (1992-1994)

During the remainder of Phase 2 the design will be matured by considering simultaneous changes to multiple parameters in trade studies. Integration of test results into the design will continue focusing on risk reduction:

SECTION 6.0

X-30 ENGINE DESIGN

• WHERE WE WERE (1987 - 1988)

In 1987 the X-30 engine concept had consisted of a low speed accelerator for Mach numbers from 0 to about 3, a ramjet for operation between about 3 to 6, and a scramjet for operation between about Mach 6 to orbit. Prior to 1988, no NASP applicable data had been developed for the program. Data from experiments conducted in the 1950's and 1960's demonstrated the feasibility for each of the modes. No external burning design data existed for this type of engine. The challenge was to combine these multiple modes into a usable propulsion system.

The 1987 engine structure and its associated weight was based on advanced materials, including new rapid-solidification-rate titanium alloys, metal-matrix composites, and advanced beryllium. The X-30 structural arrangements were very conceptual with little depth of structural analysis to substantiate them. Sizing of flowpath primary structure was accomplished using very approximate beam equations for the maximum started pressure flight condition. Predicted unstart loads using normal shock theory were as much as five to ten times the started loads and no reasonable structural solution to accommodate them was apparent at that time. Global flutter predictions for large structural panels subject to aerodynamic instabilities did not exist.

Only first order approximations existed for the inelastic strains experienced by flowpath heat exchangers and leading edges when subjected to very high heat fluxes. The extreme local heat flux (as high as 100,000 BTU/ft sec) on the cowl leading edge due to shock interactions was feared by many to be a "show-stopper". Acoustic load predictions were made using an empirical approach based on limited ramjet rig data at Mach numbers below 6.

• WHAT WE DID (1988 - 1991)

LOW SPEED ACCELERATOR: The liquid air system has been tested on an integrated rig, complete with the whole sequence of heat exchangers consisting of dehumidifier, precooler, and condenser.

The aerodynamic performance of the low speed system has been well characterized through extensive small scale cold flow rig tests and hot-fired large scale rig tests. Data from the large scale tests, covered the Mach range of 0 to 2.7.

INLET: Significant progress has been made over the last 5 years in the understanding of the aerodynamics of hypersonic inlets. This understanding has been brought about by the advances in computational fluid dynamics and the extensive experimental evaluations that have been conducted.

Nine dedicated inlet tests have been conducted to generate parametric data and evaluate specific geometries. These tests covered the Mach range from takeoff through M=16 and accounted for over 4500 test runs. The experimental objectives included evaluation operability characteristics as well as basic performance. Mode transitions were investigated as well as integration of the low speed system and subcritical spillage drags. Unstart loads have been extensively explored.

Sub and large scale integrated engine tests have also provided much information in combustor-inlet interactions, unstart characteristics, module interactions and basic operability characteristics. These tests have been conducted over the Mach range from takeoff to M=6.0.

COMBUSTORS: The design data base for the X-30 combustor has been extensively expanded through sequential series of component tests, leading to subscale engine tests, small leading to large-scale engine tests. Multiple component tests have provided an experimental benchmark for calibration of CFD methods. The small scale engine tests were parametric in nature, and the results provided the design data base for designing the larger-scale design specific rigs that followed. Large scale combustor data have been and continue to be collected extensively. Since 1987, parametric data have been generated with large scale rigs covering the Mach range from 2.5 to 8, in configurations representing ram and scram for the appropriate Mach numbers. The early test articles were parametric, with the more recent ones reflecting X-30 design specific configurations.

NOZZLE: As with inlets, significant progress has been made over the last five years in understanding the aerodynamics of hypersonic nozzles. Both generic and configuration-specific wind tunnel evaluations of nozzle/aftbody combinations have been made from takeoff to M=3.5 flight conditions. Nozzle-only evaluations of thrust coefficient and pitching moments have been accomplished at simulated engine conditions up to M=20. These investigations also looked at the influence of module out and provide insight into pressure distributions and the resultant panel loadings. Although the tests were designed to provide stand-alone design-performance data, much useful CFD calibration data was obtained. Kinetic reaction rate experiments have been conducted for key H_2/O_2 reactions at higher temperatures than previously obtained. Unique experiments were accomplished in a Shock Tunnel using "Time Equivalent Nozzles." Experiments have been conducted with external burning both in wind tunnels and in flight on an F-18. These tests were aimed at performance, piloting, and stability limit definition.

ENGINE STRUCTURES: Currently, flowpath primary structure is sized using detailed finite element models of engine components coupled with a structural optimization code to produce minimum weight designs. Unstart loads have been shown through extensive rig testing to be less severe than previously predicted and feasible structural designs have been developed to accommodate these loads. Flutter codes have been developed. A completely new code based on supersonic wave theory was developed for the transonic regime. Flowpath heat exchangers and cooled leading edges are currently analyzed with detailed three dimensional finite element models using non-linear codes that account for all material and geometric non-linearities. The X-30 heat exchangers and leading edges have been shown to be viable designs and are being substantiated through extensive testing in high heat flux and laser facilities. Empirical acoustic load prediction methods have been

modified based on additional rig data, and an analytical approach based on viscid algorithms for attached boundary layer flow has been developed.

- **WHERE WE ARE (1992)**

Although the measured LSS efficiencies were lower than desired, the operability data obtained substantiates the current design system. These tests also provided transition characteristics that provide guidance in designing follow-on test articles to demonstrate transition from the low sped mode to the ramjet mode.

Advances in the computational fluids and kinetics areas have made it possible, knowing combustor exit conditions, to analyze nozzle configurations not possible five years ago. Boundary layer routines are now in existence that include mass addition and allow evaluations of its influence on heat transfer and skin friction.

Today the engine structure consists of conventional materials. To minimize system weight impacts, innovative/structural concepts have been employed. Simultaneously, the engine structure has been modularized in a structurally repeatable fashion to ensure testability of the engine flowpath.

- **WHAT REMAINS TO BE DONE (1992 - 1994)**

Future combustor tests will evaluate updated X-30 lines at Mach 6-17. These tests will be conducted in continuous flow (Mach 6-12) and impulse (Mach 10-17) facilities in a coordinated effort that will provide data to verify the test techniques and provide design data. These tests will include parametrics on fuel injectors, base pressurization techniques, film cooling and combustor length as a benchmark for CFD code calibration. A valuable product of the test program is the formulation and continuous refinement of a combustor design system.

The planned Phase 2 approach is to demonstrate the X-30 engine design in a small scale, pre-demonstrator engine, followed by a larger (30%) engine scale CDE (Concept Demonstrator Engine). The CDE engine will incorporate enough flexibility in its mechanical arrangement to evaluate geometry perturbations about the baseline design. It will be tested at Mach 5, 6, and 6.8.

SECTION 7.0

GUIDANCE AND CONTROL

• WHERE WE WERE (1987 - 1988)

The guidance and control system for the NASP integrates the operation of the airframe, the main engine and rocket, the power generation, the thermal protection and the propellant distribution subsystems at the direction of the crew.

The design and technology results in 1987 were limited:

- Vehicle and mission optimization was partially complete for non real-time simulation.
- Guidance and control logic relied upon an incomplete knowledge of the airframe, engine, and rocket system.
- Dynamics included rigid airframe and a simple time-lag engine model, but no subsystem representations.
- Environment was for a "standard atmosphere" appropriate for subsonic and supersonic flight by conventional aircraft.
- Computer hardware and software were undefined and suppliers were not identified.
- Engine control was not well defined or was limited to uncomplicated SSTO vehicle operations.

• WHAT WE DID (1988-1991)

Vehicle and Mission Optimization: Trajectory optimization algorithms a priori define an SSTO ascent and descent flight profile and correct the profile in real time during flight. Two optimizers were developed and tested using X-30 configurations. In one test the algorithms were evaluated on a real-time simulator in which the aircraft was flown from lift-off to orbital insertion. An abort guidance algorithm was developed and simulated that predicts available landing sites and suggests a new trajectory to follow to the site that is selected. The abort scenarios for SSTO and flight test expansion are now being analyzed for situations thought to be critical for sizing the aircraft,the engine,and its subsystems. A preliminary assessment of the Mach 12 flight test mission indicated the power subsystems are driven by the more demanding, high dynamic pressure SSTO mission.

Guidance and Control Logic: A preliminary set of logic equations that implement the guidance and control solutions on the flight computers have been developed and simulated

in both real and non real-time. The emphasis has been on the SSTO ascent and descent missions.

Dynamics: The X-30 exhibits unique and complex dynamic behavior due to 1) the interactive lower surface flowpath, 2) the distribution of nozzle lift and moments, and 3) the dependence of airframe and engine safety and operability on the subsystems. The design of the vehicle and control system has dealt with these problems by decoupling the engine and airframe time scales as much as possible and by adding operational margins to both the airframe and engine control systems.

Environment Definition: The X-30 ascends and descends through the entire atmosphere to and from space. It encounters large statistical variations from the "standard atmosphere" depending upon the altitude, global location and time of the year. A new global reference atmosphere has been developed for the X-30. This new model is applicable to all vehicle design applications and is presently being approximated for real-time simulation purposes. Initial assessments indicate that the engine and the airframe will operate with large air density and temperature variations that must be accommodated by the control system, the subsystems and the structure during flight.

Computer Hardware and Software: The VMS hardware and software and related electronics and crew vision systems, implement the airframe and engine guidance and control logic, monitor and adjust the subsystems, and collect the flight test data. Design since 1987 has resulted in computers sized with excess throughput and memory to accommodate flight uncertainty. Also the operating software has been partitioned by function and subsystem to facilitate necessary changes during the test program. Real-time simulation and two separate flight test programs were conducted in 1989-1990 to verify the vision system requirements. Two separate crew vision systems have been flight tested. Seventy five landings were performed on a NASA F-104 and one hundred and fifty landings were performed on a NASA B-737 using these new crew vision systems.

Engine Control: The NASP airbreathing engine control concept has evolved and improved with each iteration of the engine design. Pre-prototype electronic control fabrication has been completed. These controls have been used to develop low speed and ramjet control concepts during large scale freejet engine tests and on the closed-loop electronic controls bench.

Candidate component concepts have been identified for the Full Authority Digital Electronic Control (FADEC), the propellant and ancillary system valves, sensors, and the engine variable geometry actuation system. The development of a valve to modulate and seal hydrogen at temperatures as high as 2000 degrees Rankine is a risk. A prototype valve concept was selected, designed and built and successfully tested at a hot hydrogen facility.

- **WHERE WE ARE (1992)**

Presently the guidance and control system for the X-30 is conceptually designed for the SSTO and reentry trajectory. Current design activity is determining failure conditions on the SSTO trajectory and creating guidance and control logic to maintain fail safe operation. Flight test operation analyses have been initiated. This involves more detailed dynamics models of the airframe, engine and their subsystems, which adds further fidelity to the SSTO

solutions. Technology programs for real time simulation, high temperature instrumentation, reliable communication, forward and side vision and engine control hardware and software are in place and proceeding per the schedule and budget plan.

- **WHAT REMAINS TO BE DONE (1992-1994)**

The current guidance and control designs and technology programs will proceed to an additional level of confidence before the end of Phase IID:

- Vehicle and mission optimization will reflect flight test envelope expansion requirements verified by simulation.

- Dynamics will include mode transition, transient thrust operation and engine-out transient effects on the airframe, the engine, and the propellant, power and thermal subsystems. Parametric uncertainty will be introduced to determine performance and stability margins on the SSTO trajectory and within the flight test envelope.

SECTION 8.0

COMPUTATIONAL FLUID DYNAMICS

• WHERE WE WERE (1987 - 1988)

CFD in 1987 was still in the developmental stage. Basic codes that are being applied to the design process of NASP today were being developed at that time. Most of the code development up to that time had centered around 2D solutions, mainly Parabolized Navier-Stokes, PNS, and 3D Euler solutions. Simple zero equation turbulence models were mainly utilized in full Navier-Stokes, FNS, codes though two equation models were available in simple PNS codes. Code development was at the point where each component of the vehicle/flow path was analyzed with a different code. However, capability to analyze a complete vehicle using either 2D or 3D full Navier-Stokes algorithms was in early development This new capability captured the equilibrium air effects but did not account for the flow path chemical kinetics effects.

Application of CFD for aerodynamic analysis was limited to 3D Euler(Inviscid) results with adjustments for viscous effects using either 2D PNS or FNS solutions. Most of the application of CFD for aerodynamic effects was limited to forebody flow fields though complete vehicle solutions had been demonstrated. Applications of CFD for the flow path trade studies and design performance estimates were limited to 2D PNS solutions with 2D FNS results coming on line.

Calibration of the CFD codes was limited to simple benchmark cases or component solutions at a limited Mach number range. Therefore, design applications were geared to obtaining solutions with limited knowledge on requirements for accurate solutions.

Boundary layer transition prediction capability was also limited to empirical correlations of the available experimental data bases which consisted mainly of conical shapes with limited flight data. Linear stability theory was being investigated but no applications had been made to NASP vehicles.

• WHAT WE DID (1988 - 1991)

Since 1987 CFD code development has continued to the point where the entire airframe and engine can be and is being analyzed with CFD. Code development has involved both industry and government with codes now capable of 3D nose to tail analysis developed. The code development has included upgrades to both turbulence models and transition prediction. This has been supported by activities performed by the government in the Technology Maturation Program and currently in the Government Work Packages in the areas of transition and turbulence modeling and linear stability theory. As part of the code development, code calibration activities have also expanded. This calibration has included new benchmarks investigating more complicated physics than studied previously, especially in the area of

combustion and mixing. CFD codes, both those developed by the contractors and the government have been calibrated against complete NASP configurations. In the process of calibration against data code to code bench marking has occurred and sensitivity studies performed investigating the sensitivities to turbulence modeling and grid densities.

- **WHERE WE ARE (1992)**

Boundary layer transition prediction capability has advanced by the combination of linear stability theory with CFD. Linear stability code development by the government provided a 2D/axisymmetric code. CFD codes are used to provide the mean flow solutions that are the inputs to the linear stability analysis. This added capability allows the impact of transition to be studied and modeled for many parameters such as vehicle wall temperature and nose bluntness. 3D CFD analysis has also provided the capability to study the effects of vehicle shapes on cross flow Reynolds numbers.

Today CFD has become an integral part of design process and is utilized in several ways. Both 2D and 3D CFD codes are used to analyze the effects of vehicle geometry trade studies in the component and vehicle level to optimize component and vehicle performance. 3D Euler, PNS, and FNS solutions supplement 2D analysis providing 3D increments to performance quantities. CFD provides basic inlet and nozzle performance across the Mach number range supplementing ground test data. CFD is also used to upgrade and enhance predictions made with simpler aerodynamics and aeroheating engineering codes. Wind tunnel testing has begun to make use of CFD prior to testing in the model developmental stages to insure that test objectives will be met and understand flow field characteristics to aid in placing instrumentation.

It can be said that application of 2D and 3D Euler, PNS, and FNS algorithms to external airframe, inlet, and nozzle flow fields are routine. 3D full Navier-Stokes simulations of combustor flow fields have been demonstrated. However much effort is still required to improve productivity for this type of flow field and to model the mixing properly. The codes used today are capable codes that capture the features of the NASP flow fields and provide a reasonable definition of most of the physics, though areas for significant improvement still exist.

Todays CFD solutions are more accurate than in the past due to an improved awareness and understanding of what is required for solution accuracy. This has been accomplished by bench marking, grid studies, and expanded code calibration activities. CFD is now calibrated against booth component and global vehicle test data including combustion physics and comparisons are generally very good. Conservation of flow parameters has improved with control volume conservation of mass, momentum, and energy demonstrated to better that 0.05%.

- **WHAT REMAINS TO BE DONE (1992 - 1994)**

Activity in CFD development will continue in several areas; code calibration, physics enhancement, and productivity improvement. Code calibration activities will continue to cover the test database. The efforts in understanding and quantifying sensitivities to grid density and algorithm selection will continue. Enhancement of physics in the CFD

codes will be pursued in the turbulence and transition modeling and in turbulence-chemistry interactions. 3D effects will be modeled into a transition criteria that can be used in the design process.