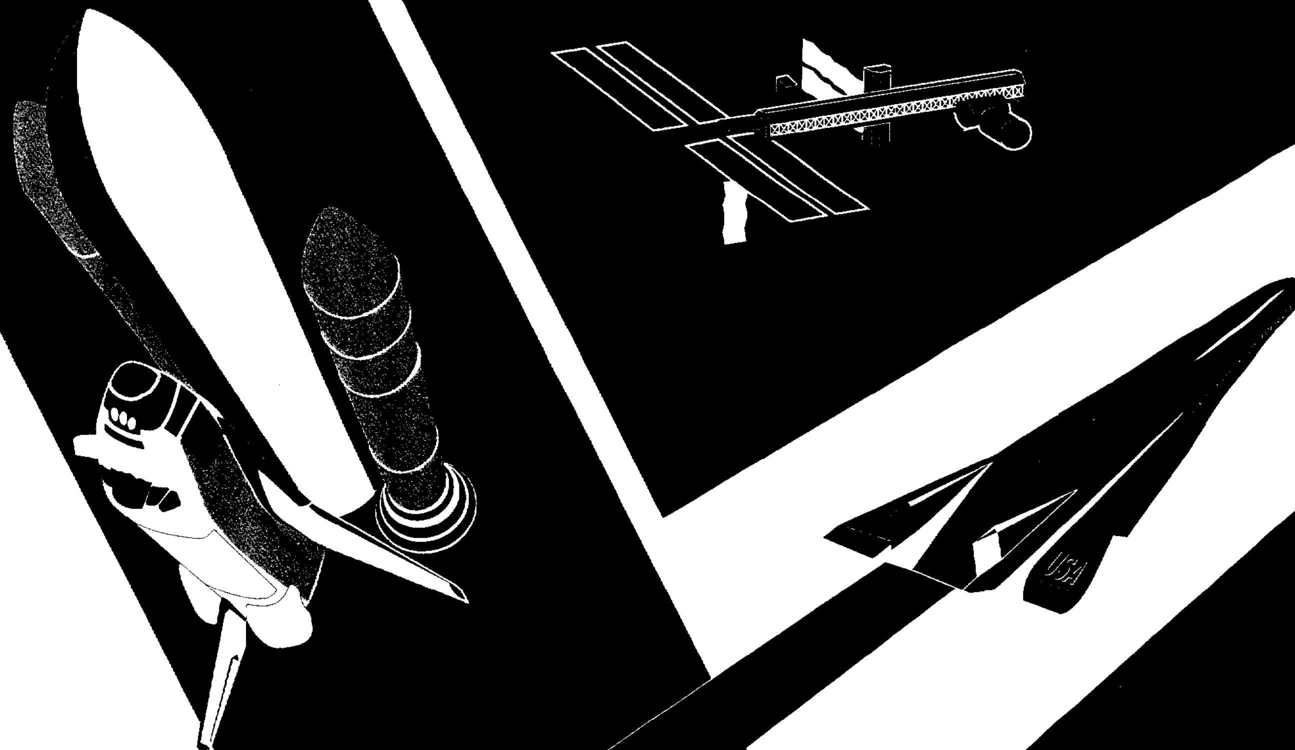

AEROSPACE SAFETY ADVISORY PANEL

Annual Report March 1994

NASA

National Aeronautics and
Space Administration

Aerospace Safety Advisory Panel

Annual Report

March 1994

Aerospace Safety Advisory Panel
Code Q-1
NASA Headquarters
Washington, DC 20546

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NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

Reply to Attn of: Q-1

March 1994

Honorable Daniel S. Goldin
Administrator
NASA Headquarters
Washington, D.C. 20546

Dear Mr. Goldin:

The Aerospace Safety Advisory Panel (ASAP) is pleased to submit its Annual Report covering the period from February 1993 through January 1994. The report contains findings, recommendations, and supporting material; however, we ask that you respond only to Section II, "Findings and Recommendations."

Over the past year, we have appreciated the support you have shown for our work through your careful consideration of our previous analyses and recommendations and the several special assignments you have given us. We have explored topics such as the impact of demanding schedules, Structured Surveillance, and cost reductions on launch processing; orbital debris; Space Shuttle main engine fabrication and processing; and NASA's response to the National Research Council's report on Space Shuttle software. We also have reviewed a number of NASA's aeronautics programs. We have kept abreast of developments with the Space Station, although our normal safety oversight activities were impossible given the Station's state of flux throughout the year.

We enter the new year with continued admiration for the successful NASA team but with some significant concerns about potential problems. While we realize that NASA must respond to imposed budgetary constraints, we are uncomfortable about deferring needed safety improvements such as the High Pressure Fuel Turbopump. We also are concerned about organizational changes that could impact the safety of NASA's programs. Finally, now that a firm direction for the Space Station has been established, we wish to obtain a better understanding of any safety implications inherent in the integration of elements of the Russian space program because we understand that it has heretofore adopted a somewhat different design approach and safety philosophy from those of NASA.

The ASAP will continue its advisory role to you and the Congress in the upcoming year by providing safety oversight to assist in minimizing the risks inherent in aeronautics and space operations.

Very truly yours,

Norman R. Parmet

Norman R. Parmet
Chairman
Aerospace Safety Advisory Panel

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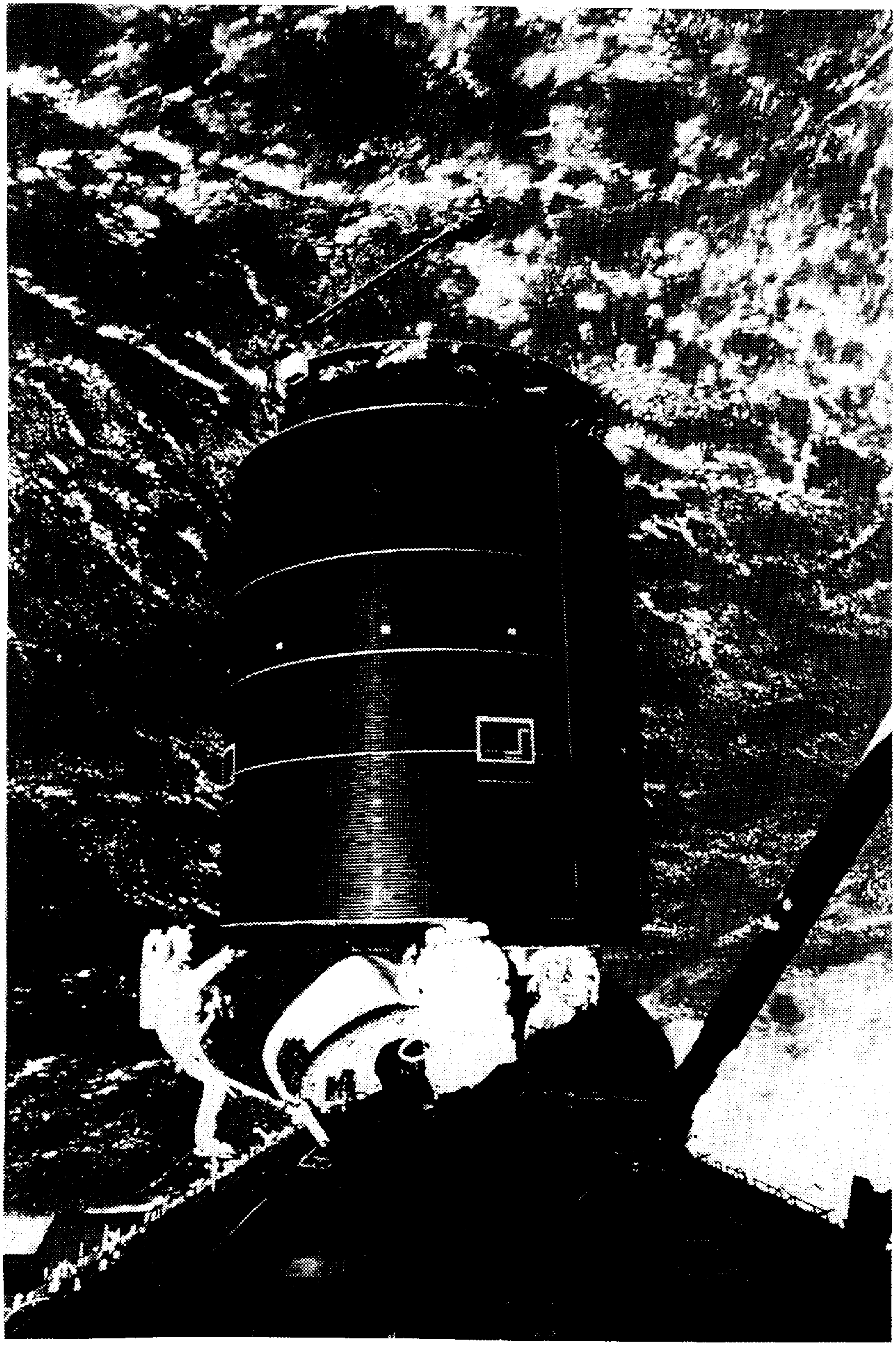


I. INTRODUCTION

I

INTRODUCTION

The success of the complex Hubble Space Telescope repair mission capped a year of major transition for NASA. In a period of severe budget cutbacks and organizational change, the Space Shuttle continued its successful operations, although it experienced numerous minor problems. The decision to enter a partnership with the Russian space program for the development of a space station will have a profound impact on the way the station's and NASA's futures evolve. Aeronautics research programs also continued their significant advances.

As in previous years, the role of the Aerospace Safety Advisory Panel (ASAP) was one of oversight and counsel to the NASA Administrator and the Congress on the safety aspects of the various programs. Fulfilling this role over the past year was both challenging and frustrating. Changes in the Space Shuttle and Space Station programs during the year made it difficult for the Panel to determine where to devote its attention. The Panel decided it was best to defer looking at the transitioning programs and to focus its primary efforts on the continuing launch processing activities at the Kennedy Space Center (KSC) and several special assignments requested by the Administrator. These included a review of the Space Shuttle Main Engine (SSME) manufacturing processes, an audit of NASA's response to the National Research Council's report on Space Shuttle software, a review of the implications of cost reductions on the safety of launch processing at KSC, and a review of NASA and contractor Total Quality Management (TQM) programs.

Notably absent from the Panel's efforts during the year was a detailed focus on the Space Station or the Advanced Solid Rocket Motor (ASRM). Both programs were in a state of flux throughout the year. As this report was being written, however, clear directions for the upcoming year appear to have emerged. Because the ASRM program has been canceled, future Panel efforts will be directed towards the Redesigned Solid Rocket Motor (RSRM) and possible incorporation of safety and performance improvements from the ASRM development effort.

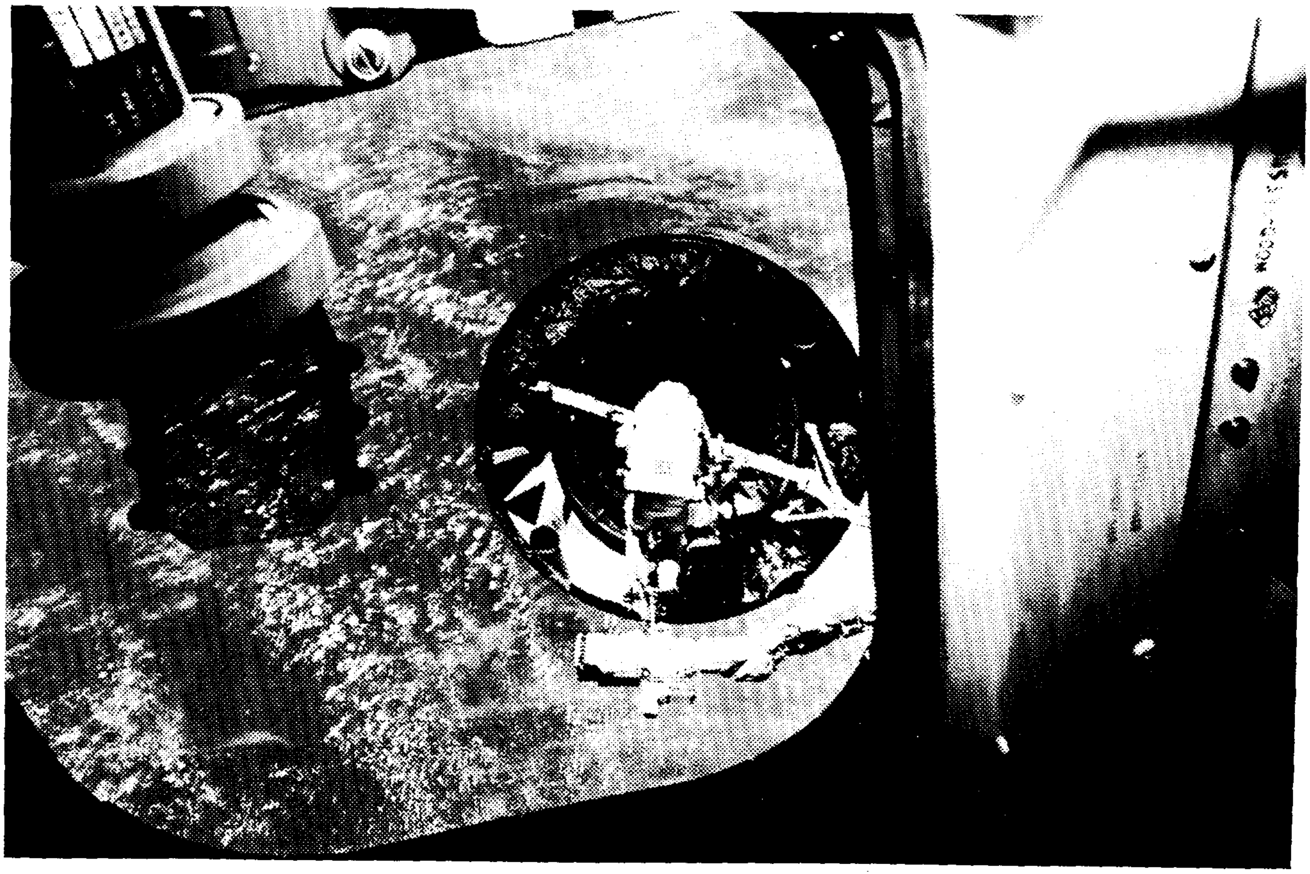
The decision to pursue joint space programs with the Russians raises several areas of possible safety concern. These include the integration of hardware and software from two operations with somewhat different philosophies, outlooks, and constraints, and the methods available for generating and verifying requirements. Thus, the Panel will place particular emphasis on the joint programs during the upcoming year.

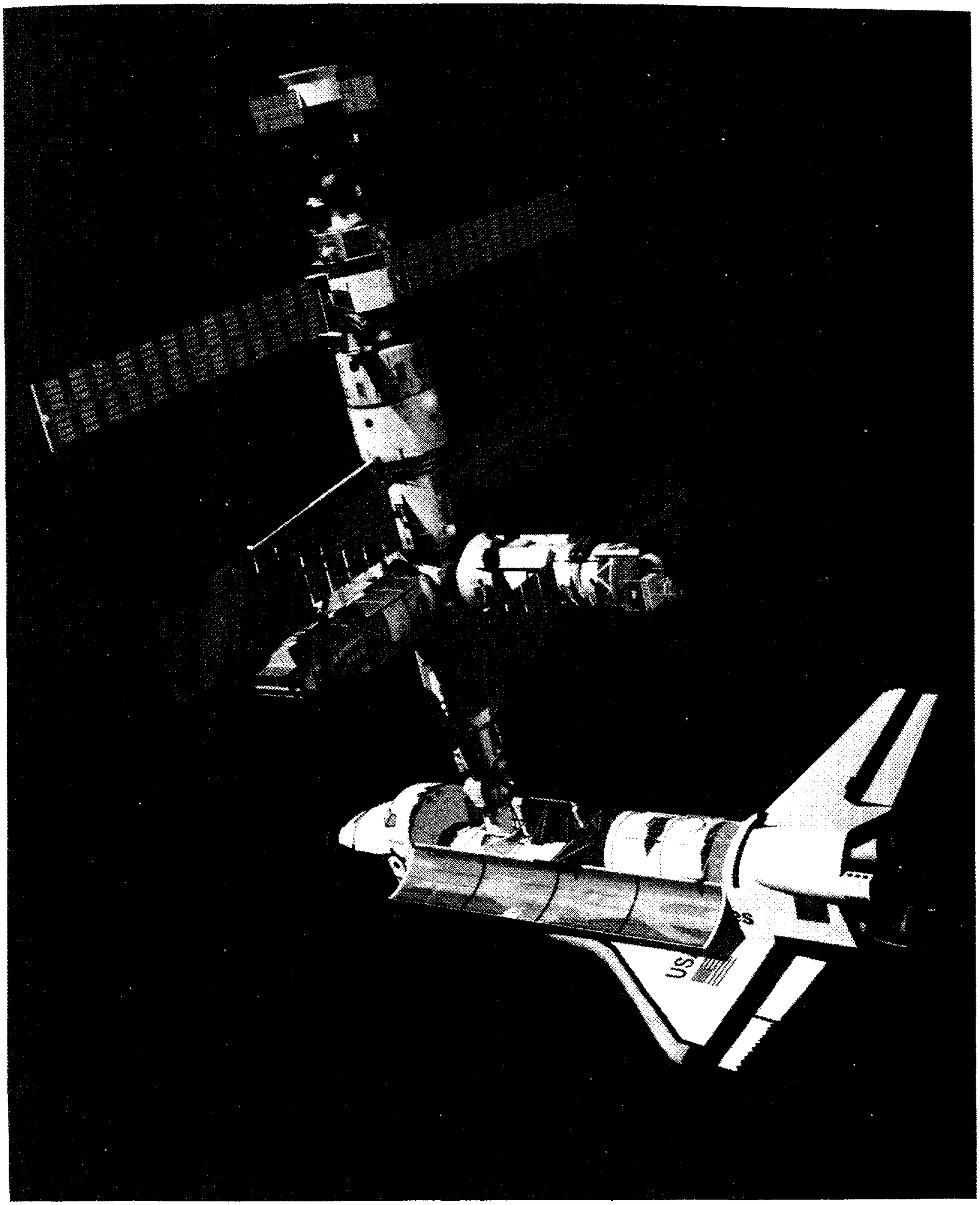
NASA continues to demonstrate a strong commitment to safety. The processes and procedures in place have resulted in highly successful Space Shuttle missions. They also have been effective in identifying and dealing with technical anomalies that have arisen. The potential impacts on safety of organizational and budgetary changes will be significantly more difficult to assess. The Panel will have to take these changes into account so that it can continue to provide safety oversight to the Agency. The ASAP is confident that, working cooperatively with

NASA and contractor personnel, it will be able to help minimize risk in our nation's aerospace programs.

Section II presents "Findings and Recommendations." Section III provides "Information in Support of Findings and Recommendations" for readers interested in more details. Appendices in Section IV contain data about the Panel membership, the NASA response to the March 1993 ASAP report, and a chronology of the Panel's activities during the past year.

As the year came to a close, Mr. Arthur V. Palmer retired from NASA and his position as Staff Director of the Panel. He was replaced in this position by Mr. Frank L. Manning.





II. FINDINGS AND RECOMMENDATIONS

II

FINDINGS AND RECOMMENDATIONS

A. SPACE STATION PROGRAM

Finding #1: Joint U.S. and Russian space programs, including the Space Station, are now underway. Potential safety concerns arising from these collaborative efforts have not yet been completely defined or addressed.

Recommendation #1: Safety requirements for the joint programs should be established from a thorough understanding of the underlying policies of design, test, and review in use by each country. Timely total systems analyses should be conducted to ensure adequate safety of components and interfaces as well as overall system safety.

Finding #2: Much good work has been done to assess the impact of space debris on the long-duration mission of the Space Station, and significant accomplishments have been made in developing shielding to protect the Station. However, there is still insufficient information on the probability that penetrations will have a catastrophic effect.

Recommendation #2: To support effective risk management, NASA should continue its emphasis on space debris problems, including a better characterization of the risk of catastrophic failures and an assessment of the capability to add shielding on-orbit.

Finding #3: Consideration is being given to maneuvering the Space Station to avoid larger debris that are capable of being tracked. Such maneuvers raise concerns about Station structural dynamics, disruption of the microgravity environment, and the ability of existing or planned systems to provide adequate debris tracking data.

Recommendation #3: Before adopting any maneuvering option, care must be taken to ensure that the dynamics of operation, including their effects on hardware, e.g., solar and radiator panels, and their influence on microgravity experiment operations, are considered. Realistic evaluation must also be made of the ability of ground-based and on-orbit systems to support maneuvering options with adequate debris tracking.

Finding #4: Present plans for rescue of Space Station personnel are not fully defined and may prove unsatisfactory without more precise and detailed planning, including necessary training and restrictions on the Station population.

Recommendation #4: NASA should reexamine current plans to ensure that they meet the required safety criteria. If they do not, priority should be given to the protocols necessary to ensure rescue of the entire Station crew if the Station must be evacuated.

B. SPACE SHUTTLE PROGRAM

LAUNCH AND LANDING

Finding #5: The organization and management of Space Shuttle launch operations at Kennedy Space Center (KSC) continue to benefit from a "continuous improvement process" managed by the Shuttle Processing Contractor (SPC). Greater employee involvement, better communications, strengthened employee training and the use of task teams, process improvement teams, and a management steering committee have been major factors in this improvement.

Recommendation #5: A strong commitment to achieving "continuous improvement," despite budget cutbacks, should be maintained, at the same time recognizing the paramount priority of safety.

Finding #6: More than 1,200 positions have been eliminated by the SPC since September 1991 with only about 22 percent being achieved through involuntary separations. Present reductions have been achieved without an apparent adverse effect on the safety of launch processing. A comparable further reduction has been called for by the end of FY 1995. These additional reductions cannot likely be made without a higher probability of impacting safety.

Recommendation #6: KSC and SPC management must be vigilant and vocal in avoiding any unacceptable impacts on safety as a result of cost reductions planned for FY 1995 and beyond.

Finding #7: Several Space Shuttle processing problems at KSC have been attributed to human factors issues. KSC has recently formed a human factors task force to address these problems.

Recommendation #7: KSC should ensure that the human factors task force includes individuals with training and experience in the field. Specific assistance should be sought from appropriate research centers and technology groups within NASA.

Finding #8: KSC has developed a Structured Surveillance Program with the objectives of decreasing overall process flow time, increasing "first-time quality," and reducing cost. The program approach involves reducing the reliance on inspections for assuring quality. Structured Surveillance also is proving valuable as a tool for the effective deployment of quality assurance resources.

Recommendation #8: The Structured Surveillance program should be continued and cautiously expanded.

ORBITER

Finding #9: Thermal damage was noted on the STS-56 (OV-103) elevon tiles. The slumping of the tiles indicated that the tile surface reached a temperature of approximately 1,000° F. A temperature of this magnitude suggests that the temper and strength of the underlying aluminum structure could have been affected.

Recommendation #9: NASA should initiate an analysis to determine the temperature profile of the underlying aluminum structure of the elevons and its possible consequences on the strength of the Orbiter structure.

Finding #10: The Shuttle tiles have provided effective heat protection. However, the surface of the tiles is easily damaged and their shrinkage and distortion properties are not as low as desired. A new tile formulation with superior characteristics and possibly lower density is being explored.

Recommendation #10: NASA is encouraged to support the development of thermal protection tiles with improved mechanical properties and lower density than the current Shuttle tiles.

Finding #11: NASA has made excellent progress on the engineering of the Multipurpose Electronic Display System (MEDS) for retrofitting Orbiter displays. However, there is no formal program to identify and include the safety advantages possible from a fully exploited MEDS.

Recommendation #11: A thorough review of the performance and safety improvements possible from a completely developed MEDS should be conducted based on crew inputs to system designers and researchers. A definitive plan should be developed to determine the schedule/cost implications of such improvements, and, if warranted, implementation should be scheduled as soon as possible.

Finding #12: The Improved Auxiliary Power Unit (IAPU) has experienced problems that have impacted Space Shuttle processing and logistics.

Recommendation #12: A new focus on increasing the reliability of the total IAPU system should be initiated and supported until the identified problems are solved.

Finding #13: In its response to the Panel's last Annual Report, NASA indicated that "The program is reviewing the operational flight rules pertaining to Autoland, we have budgeted upgrades in software and hardware to improve the Autoland functionality, the life sciences organization is collecting physiological data and developing countermeasures to ensure adequate crew performance as the mission duration increases. We are confident with using Autoland in a contingency mode, but do not plan to demonstrate Autoland until a firm requirement mandates a demonstration."

Recommendation #13: The focus of Autoland should not be exclusively on long-duration missions. NASA should formulate a complete set of operational procedures needed for emergency use of Autoland, taking into account a full range of operational scenarios and equipment modifications that might be beneficial. These include upgrades to the Microwave Scanning Beam Landing System (MSBLS) receiver group, and installation and certification of Global Positioning System (GPS) capability.

SPACE SHUTTLE MAIN ENGINES (SSME)

Finding #14: The SSME has performed well in flight but has been the cause of launch delays and on-pad launch aborts that were primarily attributable to manufacturing control problems.

Recommendation #14: Continue to implement the corrective actions developed by the NASA and Rocketdyne manufacturing process review teams and devise techniques for detecting and/or precluding recurrence of the types of problems identified.

Finding #15: "Sheetmetal" cracks in the Phase II (current) High Pressure Fuel Turbopump (HPFTP) have become more frequent and are larger than previously experienced. This has led to the imposition of a 4,250-second operating time limit and a reduction of allowable crack size by a factor of four. Congress has delayed the funding for restarting the development of the alternate HPFTP. This new turbopump design should eliminate the cracking problem.

Recommendation #15: Restart the development and certification of the alternate HPFTP immediately.

Finding #16: The approved parts of the engine component improvement programs, now organized into block changes, are progressing well. The Block I grouping will enter formal certification testing by mid-1994. Progress in the Block II effort is, however, hampered by the delay in restarting the alternate HPFTP development effort.

Recommendation #16: Continue efforts to complete ***all*** of the Block II development as soon as possible.

Finding #17: Engine sensor failures have become more frequent and are a source of increased risk of launch delays, on-pad aborts, or potential unwarranted engine shutdown in flight.

Recommendation #17: Undertake a program to secure or develop and certify improved, more reliable engine condition sensors.

Finding #18: The SSME health monitoring system comprising the engine controller and its algorithms, software, and sensors is old technology. The controller's limited computational capacity precludes incorporation of more state-of-the-art algorithms and decision rules. As a result, the probabilities of either shutting down a healthy engine or failing to detect an engine anomaly are higher than necessary.

Recommendation #18: The SSME program should undertake a comprehensive effort to improve the capability and reliability of the SSME health monitoring system. Such a program should include not only improved sensors but also a more capable controller and advanced algorithms.

SOLID ROCKET MOTORS

Finding #19: A segment of an aft skirt will be used to test the effectiveness of an external bracket modification in reducing the overall bending stress of the skirt. The validity of using an 11-inch-wide test specimen to determine the effectiveness of the bracket is yet to be demonstrated.

Recommendation #19: NASA should evaluate the first specimen test results to see if the strains in the weld area duplicate the strains found when a full aft skirt was tested in the Static Test Article-3 (STA-3) test. If not, another test approach should be pursued.

Finding #20: A small crack was found in the inner wall of a forward Redesigned Solid Rocket Motor (RSRM) casing used for STS-54. Although slightly above the specified minimum detectable size, it was well within the acceptable limits for safe flight. This was the first time that a crack had been found in a forward segment, although cracks have previously been detected in other segments. The crack occurred during the manufacturing heat treatment process because of an inclusion in the parent material.

Recommendation #20: The X-ray and magnetic particle inspection program criteria should be re-evaluated to assess their ability to detect cracks of the size found.

Finding #21: The Advanced Solid Rocket Motor (ASRM) project has been canceled. Some elements from the ASRM development have possible reliability and/or performance benefits if they were applied to the RSRM.

Recommendation #21: Examine the potential applicability and cost-effectiveness of including selected ASRM design features in the RSRM.

Finding #22: A chamber pressure excursion of 13 psi (equivalent to a thrust perturbation of 54,000 pounds) occurred in one of the RSRMs of STS-54 at 67 seconds of motor operation. A thorough investigation of the phenomenon was initiated and found that the most probable cause was the expulsion of a "slug" of liquid slag (aluminum oxide) generated during normal propellant combustion. Analyses showed that, even under statistical worst-case conditions, the safety of the Shuttle system is not compromised by such perturbations. Some testing and analyses are still scheduled to complete the investigation.

Recommendation #22: Complete and document the investigation, and continue the established practice of monitoring chamber pressures and examining possible remedial actions.

EXTERNAL TANK

Finding #23: A Super Light Weight External Tank (SLWT) has been proposed as a means of increasing the payload performance of the Space Shuttle. The tank would employ structural changes and be made from an Aluminum-Lithium (Al-Li) alloy. The SLWT appears to involve no safety decrement and low technical risk.

Recommendation #23: The impact of the SLWT on the total system should be carefully examined.

LOGISTICS AND SUPPORT

Finding #24: The Integrated Logistics Panel (ILP), which meets at 6-month intervals to report and coordinate the activities of the NASA Centers and their contractors, is performing a vital service in helping to control the entire Space Shuttle logistics program.

Recommendation #24: The ILP should continue to be supported as an effective means of maintaining control and coordination of the entire logistics program.

Finding #25: The *Vision 2000* cost-reduction program promulgated in May 1993 includes some major changes in the logistics and support areas.

Recommendation #25: All changes that might impair logistics and support functions in the name of cost-cutting should be most carefully reviewed before implementation.

Finding #26: Introduction of the Just-In-Time (JIT) manufacturing and shelf-stocking concept by NASA logistics at KSC is a potentially effective method of cost control.

Recommendation #26: JIT should be used with caution and with a thorough understanding of how it may impact the availability of Space Shuttle spares and hardware supplies.

Finding #27: A review of the main logistics system performance parameters indicates that the program is generally performing effectively. There are minor problems with zero balances, and repair turnaround times appear to be worsening. Cannibalization, with the exception of the IAPU, is at a minimum. Because of manufacturing and assembly quality problems, the number of spare engines is at a minimum and could become a logistics problem.

Recommendation #27: Additional emphasis should be focused on repair turnaround time improvement and the reduction of cannibalization of SSME and IAPU components. NASA should continue the efforts to improve SSME manufacturing control and quality processes to preclude future engine availability problems.

C. AERONAUTICS

Finding #28: The Dryden Flight Research Facility (DFRF) does not presently have a range safety policy and system for Unmanned Aerial Vehicles (UAVs) such as the Perseus, which is about to enter extensive testing. A working group under the DFRF Chief Engineer is examining the issue.

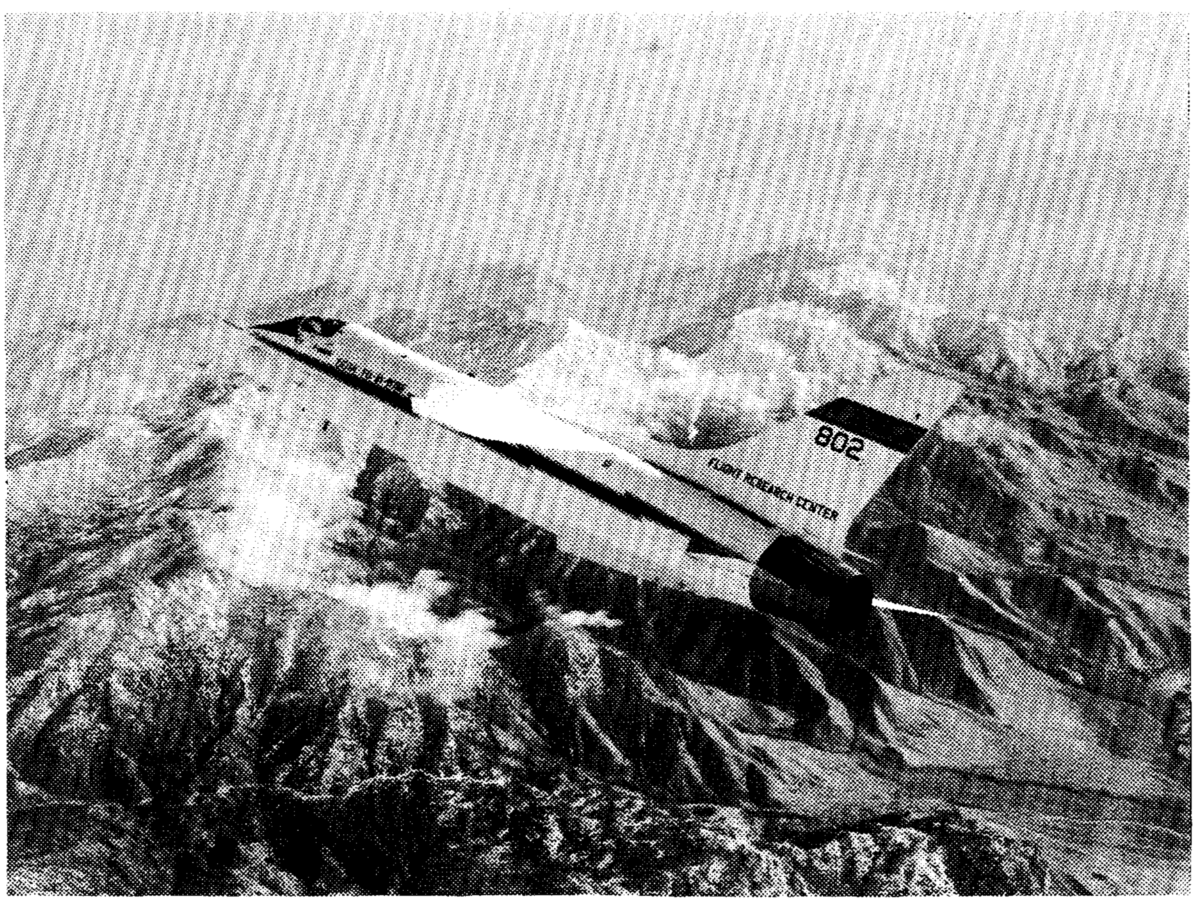
Recommendation #28: DFRF should develop a range safety policy and system that are adequate to cover its contemplated UAV projects.

Finding #29: The DFRF flight safety and mission assurance organization now reports directly to the Director of the facility.

Recommendation #29: None.

Finding #30: The X-31 aircraft exhibited some undesirable stability characteristics at higher subsonic speeds and an unexpected departure during a high angle of attack test. It also carries an insufficient quantity of hydrazine to run its emergency power unit long enough to return to the Edwards runway from the typically used flight test site.

Recommendation #30: Future test objectives for the X-31 should be based on an assessment of the specific program objectives that can only be uniquely and safely performed by this aircraft.



D. OTHER

Finding #31: NASA's past approach to software development has been to incorporate it within the individual programs, allowing them to determine their own requirements and development, verification, and validation procedures. In the future, as the complexity of NASA's computer systems and the need for interoperability grow, this mode of operation will be increasingly less satisfactory. While NASA has some good software practices, it does not have the overall management policies, procedures, or organizational structure to deal with these complex software issues.

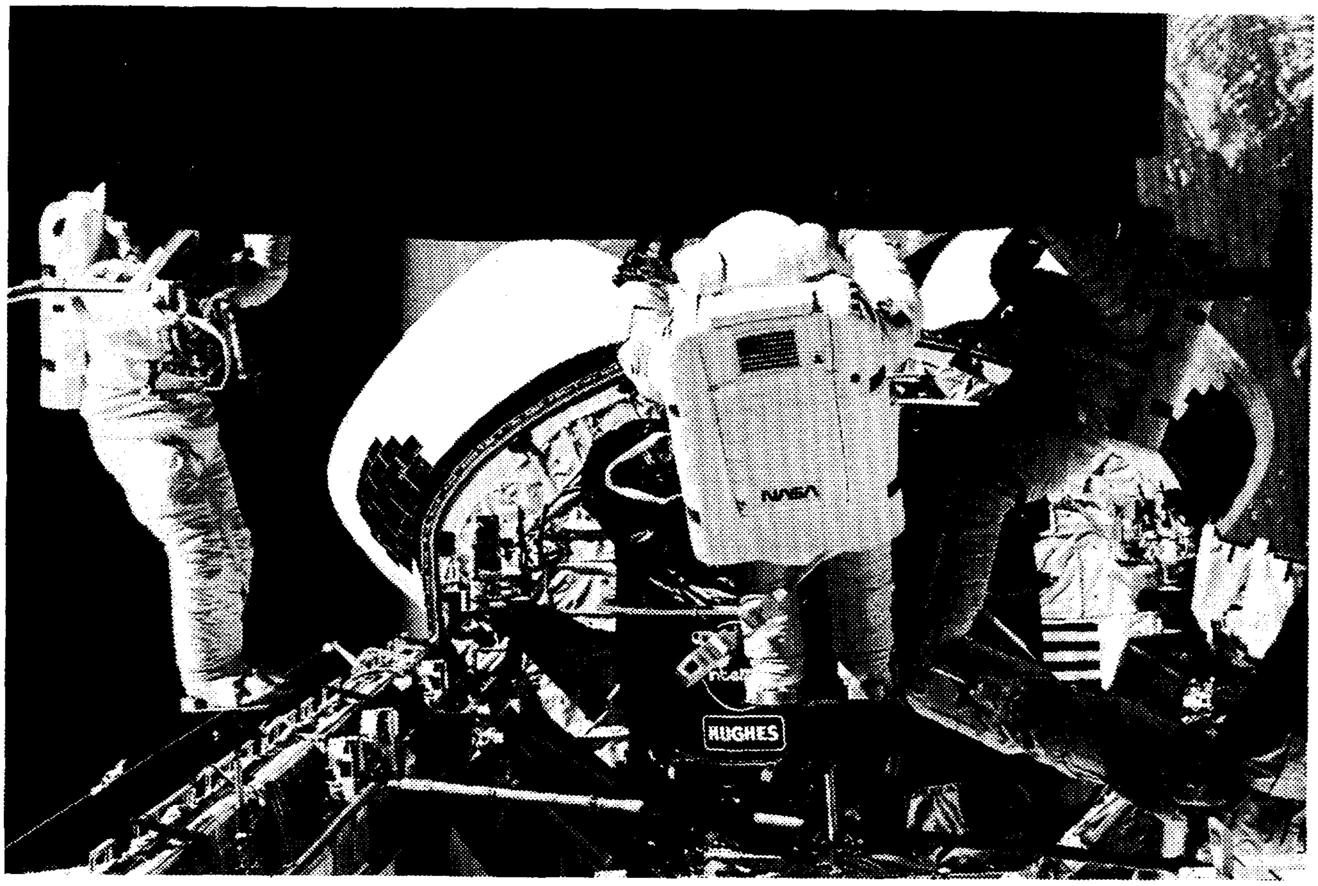
Recommendation #31: NASA should proceed to develop and implement an Agencywide policy and process for software development, verification, validation, and safety as quickly as possible.

Finding #32: NASA has consolidated Life and Microgravity Sciences and Applications, including human factors in NASA Headquarters Code U. A *Space Human Factors & Engineering Program Plan* is being prepared to guide future ***research*** activities. There remains, however, a clear need for more ***operational*** human factors input in both the Space Shuttle and Space Station programs.

Recommendation #32: The Program Plan should be expanded to include support of the operating space flight programs to ensure that sufficient human factors expertise is included.

Finding #33: There are excellent examples of Total Quality Management (TQM) principles and practices in various contractor and NASA activities.

Recommendation #33: NASA and contractor management should use the existing ***effective*** TQM implementations as models for their continuing TQM efforts.



III. INFORMATION IN SUPPORT OF FINDINGS AND RECOMMENDATIONS

III

INFORMATION IN SUPPORT OF FINDINGS AND RECOMMENDATIONS

A. SPACE STATION PROGRAM

Ref: Finding #1

The Space Station program has been in a state of flux for most of the year, and now incorporates components and hardware designed and manufactured in Russia. The decision has also been made to place the Space Station in a higher inclination orbit so that it can be reached from both nations' launch facilities. In addition, a Shuttle-Mir rendezvous and docking and astronaut/cosmonaut exchange program has been initiated and is in the hardware manufacturing stage. These changes could have profound impacts on the entire life cycle of operations. These impacts must be carefully studied ***now*** so that sufficient provisions are made for them in the Space Station and Space Shuttle programs. Activity has been so rapid that there has been little opportunity to examine information about the design and operating philosophies of the two countries that pertain to safety, e.g., structural design margins, redundancy policies, systems integration, operating priorities, and environmental test specifications. Also, the philosophy for Station crew emergency egress and return to Earth in the event of a major catastrophe remains of concern and should be reexamined in light of the new design.

The requirements for the joint programs should be established from a thorough understanding of the underlying policies of design, test, and review in use by each country. Timely end-to-end systems analyses should be conducted to ensure adequate safety of components and interfaces. Adequate attention should be given to lessons learned from previous collaborations on Apollo-Soyuz and the more recent experience from U.S./Russian commercial aircraft integration efforts.

Ref: Findings #2 and #3

The Space Station Program has recognized that the hazard of possible impact with orbital debris cannot be ignored given the large size of the Station and the planned long period on-orbit. Accordingly, a specification of a probability of no penetration (PNP) from such impact of 0.95 for a mission duration of 10 years was established. This duration represents a reduction from the originally planned Station life of 30 years. The Space Station, because of its large size, long mission life, and orbital altitude, is at greater risk than previous missions in low Earth orbit (LEO), and it is not certain whether the probability requirements can be met.

An orbital debris program has been underway for a number of years with the objectives of defining the environment, developing models, developing shielding concepts, and maintaining a data base. NASA, in conjunction with other agencies around the world, has compiled a comprehensive catalog of known objects in space with a diameter larger than 10-20 cm. In addition, they have developed detailed models of the distribution of debris of diameters less than 10 cm in terms of particle flux of various sizes as a function of altitude and latitude. These models can be combined with orbital data and the projected area and functional lifetime of a spacecraft to yield a probability of impact and an estimate of the mass and velocity of the impacting body. Hypervelocity test programs, carried out by NASA and other agencies, allow these data to be turned into damage assessments of structures, pressure vessels, and other vulnerable portions of a spacecraft.

The flux of orbiting debris depends on several physical factors that make the environment vary, creating considerable uncertainty over time. The principal factor that serves to remove debris from orbit is the retarding force of the drag that is proportional to the area-to-mass ratio of the debris object and to the density of the atmosphere. The latter varies over time, driven largely by the 11-year cycle of solar energy — the "sunspot cycle." The principal debris-increasing factor is the launch of new satellites and their accompanying rocket bodies, and other mission-related objects.

To put this in perspective, the orbital lifetime at an altitude of 200 km can vary from a few months to over 10 years. At altitudes of 1,000 to 1,500 km, the life can exceed 1,000 years. Orbital debris flux is several times what was predicted 7 to 10 years ago and is increasing at a rate of 2 to 5 percent per year. Given the great changes in Station design and configuration and the uncertainties involved, the analyses to date for PNP and probability of no catastrophic failure (PNCF) are only rudimentary. Therefore, the real risks are not yet well understood. Also, given the cost and work involved in developing the Station, it may be unduly limiting to base risk analyses on a life of only 10 years. The Program should also explore longer lifetimes.

The vulnerability of spacecraft surfaces to penetration by debris can be mitigated by shielding. Extensive, high-quality work has been done on developing shielding techniques to protect against objects of small diameter, e.g., 1 to 1.5 cm, at an average relative velocity of 10 km/sec. The initial shield design for the Station (0.050-inch thick aluminum bumpers with 4.5-inch standoff from an 0.125-inch aluminum manned module pressure wall) meets the present PNP requirements. Several advanced shield trade studies are being initiated to provide penetration protection, maintain schedule, and minimize launch weight for manned and unmanned critical elements. The launch weight can also be managed by augmenting shields on-orbit. It would seem prudent to give careful consideration to shielding designs that allow for the addition of debris protection on-orbit. It must also be noted that there is a range of debris, roughly 1-2 cm up to 10-20 cm in diameter, for which adequate means of protection do not presently exist.

It is reasonable to assume that not all penetration events will result in catastrophic failures, as the earlier studies had assumed. Studies show (for Space Station Freedom) that if the PNP of 0.95 is interpreted as a PNCF, it is equivalent to a PNP of 0.90. The allocation of PNP to modules depends on the severity of the consequences of penetration in each individual area. The allocation of PNP for each of the critical elements varies from 0.9920 to 0.9955 for the modeled configuration. Meeting these requirements could present severe weight and cost penalties as well as schedule constraints.

Further work is needed on fracture mechanics response of pressure vessels to hypervelocity impacts to determine which impacts would result in self-propagating cracks. The critical crack length for constant thickness aluminum skin is well characterized. However, the crack length for the waffle construction planned for the current design requires further analysis and testing. Unfortunately, FY 1993 funding for this type of fracture testing at MSFC has been frozen.

In addition, detailed analyses need to be conducted of crew injury or loss of Station due to critical element penetration. Such elements will include manned elements and stored energy elements, with the manned elements requiring many assumptions on crew location and reaction. Tests are required to verify crew egress time and depressurization limit assumptions. The problem is multidimensional, requiring a particular focus on structural analysis and crew factors. Optimum solutions will depend on weight and schedule limitations. Careful consideration should be given to developing realistic scenarios of crew condition and possible response behavior as a function of the nature of various relevant penetrations. On the one hand, worst case analyses may lead to requirements that are too restrictive and costly. A failure to be sufficiently conservative, on the other hand, can expose the crew to unreasonable risk.

A collision avoidance scheme involving ground radar tracking of potential impactors and maneuvering the Station to avoid impact has been proposed and may be technically feasible. Existing radar nets, however, are limited by geographic location and wavelength considerations to tracking objects 20 cm and larger (equivalent radar cross-section) in LEO. Ability to detect, track, and catalog debris falls off rapidly below 10 cm for these systems, which were not designed for this purpose. Because spacecraft are vulnerable to serious damage from objects as small as 0.5 cm, such a scheme is only partially effective without greatly improved and potentially very expensive enhanced radar capability and added operational tracking personnel and equipment. Maneuvering of the Station also imposes dynamic effects on deployed solar and radiation panels and on microgravity experiment operations.

Ref: Finding #4

The Panel's review did not uncover any detailed plan for rescue of Space Station personnel from the combined revised U.S. Space Station in the event of a catastrophic event. While acknowledging that Station plans have been in great flux this past year, information available to the Panel indicates that rescue plans center on either the continuous presence of an Orbiter or one or more small capacity Soyuz capsules. Both schemes are presently vague, giving rise to concern that neither will prove satisfactory without more precise and detailed planning, including necessary training and restrictions on Station population.

NASA should determine the extent to which current plans meet the necessary safety criteria. To the extent they do not, priority should be given to constructing the protocols necessary to ensure rescue of the entire Station crew in the event of any credible need to evacuate the Station. Where pertinent, the excellent groundwork represented by the requirements analysis for NASA's Assured Crew Return Vehicle (ACRV) should be utilized.

B. SPACE SHUTTLE PROGRAM

LAUNCH AND LANDING

Ref: Finding #5

The Panel has been following Space Shuttle launch processing for more than a decade. This predates the selection of Lockheed Space Operations Company as the Shuttle Processing Contractor (SPC). From this extended perspective, it is clear that considerable progress has been achieved in evolving a more reliable, orderly, efficient, and safe process. In particular, both management and workforce are committed to the proposition of "safety first, schedule second," as well as to the development of improved management procedures that build a greater sense of personal responsibility and pride among personnel. The principal challenge facing NASA and SPC management is to carry on this commitment to continuous improvement in the face of sharply reduced operating budget forecasts for the years beyond FY 1995 and externally imposed constraints.

The number and severity of Space Shuttle processing incidents continued a downward trend in FY 1993. A total of 20 incidents were reported from October 1992 through September 1993. Eight were attributed to human error, seven to procedures (permanent changes to the procedures are planned to eliminate the deficiencies), one to equipment breakdown, three to design deficiencies (in each case, a design change has been made or is in process), and one unknown. For July, August, and September 1993, the human error rate dropped to zero. Data on incident/accident frequencies during processing reveal no apparent correlations between frequency of incidents and work location, day of week, or particular shift.

Since FY 1988, the number of labor hours required for Space Shuttle launch processing has been cut in half. Factors accounting for this decrease include continuing reductions in non-standard work, gradual elimination of overtime, maturing of task teams, greater predictability in work schedules, fewer unplanned events, and a greater experience base among the workforce. Most parts for planned work in the Orbiter Processing Facility (OPF) for each flow are now kitted in advance. Spare parts are available for on-time delivery a high percentage of the time. Engineers are more readily available to resolve unclear or incorrect work authorization documents (WADs). The STS-58 flow for Columbia was the best ever, although a last-minute glitch on a range safety computer forced a scrub. Areas of concern remain the Improved Auxiliary Power Units (IAPUs) that still require frequent repairs, sometimes involving a Self-Contained Atmospheric Protection Ensemble (SCAPE) suit operation, and SSME turbopumps that require inspection after each flight.

The Task Team Leader (TTL) program has been instrumental in reducing the frequency of delays and incidents. The more positive work environment brought about by task teams has, in turn, contributed to more reporting of close calls. However, the need to make close call reporting even easier was stressed by the Panel and acknowledged by the SPC. Currently underway is a TTL-enhancement project to apply positive results of the TTL program to all processing areas and develop additional performance measures.

Ref: Finding #6

More than 1,200 positions have been eliminated by the SPC since September 1991, with only a small portion coming from involuntary separations. A comparable further reduction has been called for by the end of FY 1995. The present reductions have been achieved without an apparent adverse effect on the safety of launch processing. The operative question is whether planned cost reductions, which will inevitably reduce the number of processing personnel, can be achieved without compromising safety and whether recognized warning signs can indicate if safety margins are on the verge of being compromised. Based on information available to the Panel from its activities at Kennedy Space Center (KSC) during the year, it must be concluded that additional reductions of the magnitude already taken cannot likely be made without a higher probability of impacting safety.

In addressing these questions, the SPC has stipulated the following criteria: safety is and will remain the number one priority; capability for eight flights/year must be maintained; all unique and critical facilities, e.g., both launch pads, must remain open; and continuing improvement must be sustained. An ongoing program to enhance employee/management communications and greater reliance on structured teamwork provides the foundation for the SPC's continuous improvement process.

Of the personnel reductions during calendar year 1993 up to the time of this writing, incentivized/voluntary separations comprised 43 percent and normal attrition accounted for 35 percent. Involuntary separations amounted to 22 percent. Professional outplacement services have been provided to terminated employees as few, if any, of the terminated workers will likely be rehired. This also means there are few opportunities to bring in new workers. As the median age among existing workers continues to climb, the difficulty of recruiting and training younger employees who can develop the required knowledge and experience to sustain the program into the next century is a cause for concern.

Developing metrics to provide an alert with respect to the safety impacts of personnel cutbacks is particularly difficult. A large number of activities are routinely measured and evaluated. Specific metrics to identify cost-reduction danger levels in advance have not been identified although NASA officials believe that failing to achieve key milestones will be one indicator of problems. At the request of the Administrator, the Panel will continue to work with KSC and the SPC on the definition of appropriate warning measures that can be used when making decisions on future cutbacks.

Ref: Finding #7

Several Space Shuttle processing problems at KSC have been attributed to issues related to human factors. KSC has recently formed a human factors task force to examine the problem of human errors in Space Shuttle processing and to develop remedies. Unfortunately, this task force does not include sufficient representation of trained human factors professionals. Human factors workshops for the task force members will be held in an attempt to remedy this deficiency.

To provide appropriate impetus to its growing human factors efforts, NASA needs to increase the number of trained human factors professionals available to the programs. Workshops to acquaint managers and engineers with human factors principles such as those being contemplated for the KSC task force are an excellent way to create an understanding of the benefits that this discipline can provide. They are not, however, a substitute for specialists who have training and experience in the field.

Ref: Finding #8

Quality assurance must be an inherent part of any safe aerospace endeavor. One of the traditional methods of quality assurance is to use inspectors to verify the work of technicians. In recent years, many complex aerospace operations, such as airline maintenance, have attempted to improve their cost-effectiveness by limiting inspections to only those that provide a true "value added" to safety. If redundant or non-productive inspections and signoffs are eliminated, costs are reduced, and the major responsibility for quality is placed on the technician doing the work.

To decrease the overall process flow time, increase first-time quality, and reduce cost, KSC developed a Structured Surveillance program. The program approach involves reducing the reliance on hands-on inspections for assuring quality. As a result of the STS-51L accident and the additional requirements imposed on the return to flight, the number of inspections had been greatly increased. It was the judgment of KSC management that the Space Shuttle program had progressed sufficiently since the accident to warrant a cautious retreat from a position that essentially required mandatory inspection of all operations and redundant inspections of many. The essence of the Structured Surveillance process is to identify low criticality ("Crit 3") steps that need not be inspected each time they are performed. Included are tasks that do not impact flight or mission safety and tasks that will be verified later in the processing flow. For these operations, mandatory inspections are deleted, but some level of random inspection is retained.

To assess the effects of reduced reliance on inspections and to shed light on the Structured Surveillance process, KSC management undertook a Structured Surveillance Pilot Program. The goal of this program was to eliminate those inspections that, in the best engineering judgment, were not adding to the quality of the Space Shuttle processing, and to assess the impact on quality of those reductions. NASA and each of its major contractors at KSC were to implement a pilot Structured Surveillance plan and assess its effectiveness before the Center committed to a full-scale implementation of the concept. This was a prudent course to follow.

The Structured Surveillance program has now emerged from the pilot test stage. Based on experience to date, it appears that retaining the inspections inherent in the Structured Surveillance approach can help achieve at least the following objectives:

- Providing more rapid feedback for control and process improvement than would be possible without some inspections.

- Providing a reasonable basis for deploying quality assurance resources so that they cover the entire operation.

- Developing estimates of first-time quality in those Crit 3 tasks from which inspections have been removed.

- Developing KSC-wide estimates of performance that can be trended over time.

- Determining award fee for the SPC.

Each of these objectives is inherently reasonable. Given the nature and frequency of the Space Shuttle processing tasks, however, it may not be possible statistically to develop trend measures to replace the results of 100-percent inspections. In order to develop valid and reliable estimates, an extremely rigorous statistical sampling plan would have to be developed and scrupulously followed. The operational reality at KSC, however, will not likely permit this degree of rigor. It is not certain that any facility-wide trend measures could be reasonably interpreted. Moreover, attempting the rigorous sampling plan needed for such trend measures may actually prove counterproductive to the other objectives of Structured Surveillance.

Overall, it can be concluded that the Structured Surveillance concept is sound and worthy of continuation and cautious expansion.

ORBITER

Ref: Finding #9

Thermal damage was seen on the right and left hand elevon tiles after STS-56 (OV-103). The temperature indicators in these areas all exceeded the limit of the device, which is 290° F. The slumping of the tiles indicated that approximately 1,000° F must have been reached. This temperature is sufficiently high so that the temper and strength of the underlying aluminum may have been affected. In light of the observations from the STS-56 flight, an analysis should be conducted to determine the temperature profile seen by the aluminum structure of the elevons and its consequences on the strength of the underlying structure.

STS-56 was a heavy-weight vehicle at a high-inclination (57°) orbit, resulting in increased aero-heating during re-entry. At the time of this writing, inspections of other tiles on the wing were being made to determine if they had been similarly affected. The values assumed for pre-flight calculations of aero-heating during re-entry of heavy-weight orbiters from high-inclination orbits should also be re-examined in light of the thermal damage experienced by STS-56.

Ref: Finding #10

An effective, reliable thermal protection system is essential to the success of the Space Shuttle or any recoverable and reusable spacecraft. Various approaches and schemes involving both metal and ceramic designs have been explored over the years. One of the most successful applications of ceramics has been the tiles developed for the Space Shuttle. The present ceramic refractory tile has been employed on the Space Shuttle for over 10 years. While it has indeed proven to be an effective heat protection device, it has exhibited some operational deficiencies relating to brittleness and shrinkage. Also, it is heavier than desired.

Rockwell International, under contract to NASA, is examining a tile using a refractory block insulation called Alumina Enhanced Thermal Barrier (AETB) that, when coated with Toughened Uni-place Fibrous Insulation (TUFI), has considerably improved toughness, durability, and shrinkage-distortion characteristics over the current Shuttle tiles. This tile also promises a significant saving in weight that could be reflected in increased Shuttle payload, a capacity much coveted for higher inclination orbits. It is therefore reasonable for NASA to support the development of thermal protection tiles with improved mechanical properties and lower density than the current Shuttle tiles.

Ref: Finding #11

The existing Orbiter cockpit displays are based on 1970's technology. They provide basic "raw" data to the crew using numerous discrete electromechanical gauges and "green screen" Cathode Ray Tubes (CRTs) displaying alphanumeric characters. Modern display technology has evolved using both color CRTs and flat panel liquid crystal displays (LCDs). These displays have the capability to integrate information that was previously shown on separate instruments. Through the use of color and graphical formatting, they can show trends and predictions to assist a pilot in "staying ahead" of the aircraft.

The Space Shuttle program has embarked upon an instrument upgrade program that has been named the Multipurpose Electronic Display System (MEDS). The plan is to replace most of the discrete flight instruments and the existing CRTs with a set of flat panel color displays. The cost of MEDS has been variously justified on the basis of safety or as a remedy to the obsolescence of the existing instruments. In general, neither existing safety problems nor obsolescence can fully justify the cost of the retrofit, although MEDS should obviate any current obsolescence issues. MEDS also has the potential to improve significantly the operational safety of the Space Shuttle if enhanced capabilities are included in the displays. These capabilities include predictor information (trends), ascent data, and proximity operations information for on-orbit maneuvering.

Unfortunately, NASA has chosen to defer any enhanced functionality for MEDS and has not even embarked upon a coordinated program to define the optimum formatting for MEDS displays. Instead, the program initially intended to emulate the existing electro-mechanical instruments. That approach has been abandoned in favor of a consensus approach to iterating to an interim set of display formats. If additional funding is ultimately available, the interim displays will be updated and/or enhanced.

Research and experience with "glass cockpits" in aircraft have shown that flight crews acquire information differently from discrete electromechanical instruments and integrated CRT or flat panel displays. Safety problems may even be generated by attempting to simulate the conventional instruments on flat panel or CRT displays.

There are clearly some impediments to optimizing the MEDS functionality. NASA has limited training assets that must be capable of supporting both the present instruments and the MEDS suite while conversion is underway. Adding functionality would require changes in the primary flight software that runs on the General Purpose Computers (GPCs) in order to provide the necessary inputs. Funding is limited.

Notwithstanding the difficulties inherent in maximizing MEDS effectiveness, payback of the system's development and installation costs will not be realized until and unless MEDS is allowed to reach its full potential. The present approach to MEDS display formatting delays some MEDS benefits and may even derail them. NASA should commit immediately to a thorough program of research and development to define the optimum MEDS utilization and plan for its realization as quickly as possible. NASA should include specialists from its research centers and representatives of the flight crew and avionics offices in this effort.

In summary, the engineering of the MEDS looks good. The selection of experienced display suppliers appears prudent. However, NASA should reconsider the current plan to use MEDS as an electronic substitute for the current flight displays, and consider a plan to use MEDS with all the potential advantages of improved operational displays.

Ref: Finding #12

Problems with the support of the Auxiliary Power Unit (APU) and with the updated version known as the Improved Auxiliary Power Unit (IAPU) are among the most serious impediments to satisfactory launch processing and logistics support of the Orbiter. The difficulties with the earlier APU were limited life (21 months installed or 18 hours turbine time), unsatisfactory turbine life due to blade root cracks, and Gas Generator Valve Module (GGVM) seat cracking and leaking. The IAPU was intended to provide a 75-hour life based on upgrades, including a new turbine wheel design, better life limits for the IAPU of 36 months installed, and a redesigned GGVM. Nine IAPUs are currently installed in the Orbiters (three per vehicle) and eleven are in the repair cycle.

Problems with the IAPU include shaft corrosion and continued GGVM difficulties, particularly valve seat failures. Overall, the IAPU appears to have failed to produce the reliability and service life improvements envisioned when it was authorized. As a result, another review of the IAPU appears to be required if this long-standing unreliability problem is to be resolved.

Ref: Finding #13

The Space Shuttle's automatic landing (Autoland) system has never been tested to touchdown. The system follows the same guidance commands that are displayed to the pilots. Its design is intended to bring the Orbiter safely to the touchdown point but requires the crew to deploy the air data probes, landing gear, and drag chute manually and to control rollout guidance. There are several situations that could arise in which landing risk would be reduced by the use of an automatic landing system. These include:

- Weather deterioration at the landing site after the deorbit burn.
- Loss of visual access through the Orbiter's windshield due to a hardware failure or smoke in the cabin.
- Subtle incapacitation in which the crew's ability to pilot the Orbiter is impaired but the crew and ground controllers are unaware of the impairment.
- Obvious incapacitation in which the crew is awake and alert but recognizes that its ability to pilot the vehicle is diminished.
- Total crew incapacitation such as an unconscious crew due to toxic fumes or low oxygen levels.

The likelihood of each of these situations has not been systematically examined. The tacit assumption seems to have been made, however, that the chance of total, obvious or subtle incapacitation will increase as mission duration is increased with the availability of Extended Duration Orbiters (EDOs).

NASA has now made the decision to automate the deployment of the landing gear and air data probes. The automated gear and probe deployment essentially addresses only the situation in which the crew is totally incapacitated. In virtually all other situations of subtle or obvious incapacitation, the crew should be capable of throwing the switches for deployment. The air data probe deployment is not very time critical, and the gear drop can be initiated early in difficult situations.

It appears that decisions regarding automatic landings have been made based on minimal analyses or tradeoff studies. Situations of total crew incapacitation in which the crew is still alive and recoverable tend to be extremely rare. This is why no aircraft automatic landing system includes gear deployment (or arresting hook deployment for carrier landings).

It would be worthwhile for NASA to reassess the entire automatic landing issue before committing funds to hardware or software changes relevant to future automatic landing versions. A working group including crew, engineering, life sciences, and human factors should be formed to estimate the likelihood of each of the scenarios that could require an automatic landing. This will help define the need for enhancements to the existing autoland system and/or its certification and validation through flight test.

Also, NASA should consider upgrades to the Microwave Scanning Beam Landing System (MSBLS) receiver group to be of the same redundancy level (fail operational/fail safe) as the rest of the system components used in current auto approach/landing (pilot or autopilot) and the possible installation and certification of Global Positioning System (GPS) capability. The use of GPS will improve safety of the orbiter operation by allowing more flexibility in selection of alternate landing sites.

SPACE SHUTTLE MAIN ENGINES (SSME)

Ref: Findings #14 through #18

The current or "Phase II" engine has performed well in flight this year. The number of in-flight anomalies has been reduced to about 1.5 per flight, and most of these involve instrumentation. Success in flight has not been matched on the ground, however. There have been a number of aborted launch attempts and launch delays attributed to the engine system. These include a cutoff caused by a contaminated check valve and another resulting from the failure of a speed sensor. Corrective action has been implemented for these problems.

The launch delays were occasioned by problems in the control of manufacturing processes that resulted in events such as the installation of an incorrect dash-number part, mis-location of an etched marking on a bearing preload spring, and failure to install a turbine blade damper centerplate. Very thorough investigations, including a review of manufacturing with an operations standdown at Rocketdyne, have led to many revisions in the manufacturing processes and their control. The situation now appears to be under control.

These events led to a series of re-inspections of delivered hardware that required at least partial disassembly of major engine components, particularly turbomachines. This caused a shortage of usable turbopumps which, in addition to re-inspection of engine nozzle welds, presents a hardware shortage problem that it is estimated will persist until mid-1994.

"Sheetmetal" cracks in the High Pressure Fuel Turbopump (HPFTP) have proven to be more of a problem than anticipated. Thorough review of the situation has resulted in a tightening of the specification for allowable crack size by a factor of four and the reduction of allowable operating time to 4,250 seconds. Of greatest concern is the generation of fragments that can, if they strike a turbine blade, cause blade failure and lead to a catastrophic engine failure. No such fragment generation has occurred before approximately 5,000 seconds of operation.

Sensor failure, both temperature and pressure, is all too frequent and is a consequence of the use of fine wire required in the design of thermistor temperature sensors and strain gauge pressure transducers. There is some work ongoing to develop more rugged thermocouple-based temperature sensor systems. More rugged pressure sensors are also needed. It would be highly desirable to increase the activity level for such developments.

Several major component improvement programs currently underway have been grouped into two blocks in order to provide the most economical approach to their certification and incorporation under prevailing technical and budgetary conditions. Block I comprises the two duct (Phase II+) powerhead without baffles, the single tube heat exchanger, and the Alternate High Pressure Oxidizer Turbopump (HPOTP). This block is scheduled to complete certification in 1995. Block II, comprising the Alternate HPFTP and the Large Throat Main Combustion Chamber (LTMCC), is scheduled to be certified in 1997. All components are currently in development testing except for the HPFTP which has been deferred by Congressional mandate. It had been hoped that the work on the HPFTP could restart during FY 1994, but as of the date of this writing, no authorization has been forthcoming. This jeopardizes the ability to have the Block II changes certified by the planned date. As a result, the safety benefits of the Block II component changes will likely be delayed beyond 1997 and may not be available for the first Space Station construction build.

The Block I changes have completed 16 development tests in engines in full-up Block I configuration. There are no major technical issues for the powerhead or the heat exchanger. The alternate HPOTP has progressed well in its development and has accumulated over 36,000 seconds of test time of which over 5,000 seconds have been at full power (109%). The introduction of silicon nitride balls in the pump end ball bearing has eliminated this bearing's problems. There is still a propensity for the turbopump to exhibit synchronous vibration sensitivity, but it is believed that tightening clearance specifications in the bearing mounts will go far towards rectifying the situation. Cracking has occurred in the turnaround duct casting and the turbine inlet housing. Detail design changes have been incorporated to reduce the number and severity of the cracks generated. It is believed that the situation is under control with adequate fracture life achieved.

The development of the LTMCC for the Block II engine is proceeding well. Thirty-four tests of the LTMCC have been completed with no significant anomalies encountered. The baseline design comprises the current Naraloy-Z liner with cast inlet and outlet manifolds. Two other approaches to the construction of the chamber are under consideration. One is that of the Marshall Space Flight Center (MSFC) Propulsion Laboratory comprising a one-piece structural casting (manifolds and throat section) with a "platelet" fabricated liner. The other is a Rocketdyne proposal employing a three-piece casting and the standard liner insert. Early in 1995, hot fire test results as well as demonstrated manufacturing schedule and cost benefits will be used to make a final decision as to which of the three approaches will be taken.

As noted above, the alternate HPFTP development is still on hold but some 27 engine-level tests have been conducted on the Technology Test Bed facility at MSFC. An acceptable start/shutdown sequence has been developed on the engine, and the pump has been operated to 109% power level and to well below the allowable minimum net positive suction pressure at the inlet. In view of the sheetmetal cracking problem of the Phase II HPFTP, restarting the development is urgent.

The SSME controller monitors the status of the engine during countdown and flight by sensing engine conditions through signals from a variety of temperature, pressure, position, and propellant flow transducers. It takes these inputs and, via a set of algorithms in its software, determines the "health" of the engine system. If it determines that an anomalous condition exists (e.g., violation of a "redline"), it will inhibit engine ignition or shut down an engine either on-pad or in flight in accordance with the logic of its programmed algorithms. Although some engine failure modes (such as a turbine blade breaking off) propagate too quickly for any remedial action to be taken, many modes can be sensed or predicted rapidly enough to prevent a catastrophic engine failure.

The effectiveness of any such monitoring system may be expressed in terms of the extent to which it correctly classifies the state or "health" of the system being monitored. Both false alarms (a healthy engine being classified as unhealthy) and false positives (a failure being classified as healthy) are to be avoided, of course. With most monitoring systems, there is a tradeoff between false alarms and false positive rates. The more sensitive the monitoring system is made in an attempt to correctly identify real failures, the more prone it becomes to false alarms.

The SSME controller system employs sensors of old technology (which are prone to failure as noted earlier), and its computer capacity precludes the incorporation of more capable algorithms and decision rules that are possible with more state-of-the-art technology. As a result, the probabilities of shutting down a healthy engine or failure to detect an engine anomaly are higher than necessary. Updating the sensors, controller hardware, and algorithms should provide cost-effective risk reduction.

SOLID ROCKET MOTORS

Ref: Finding #19

The aft skirt of the Redesigned Solid Rocket Motor (RSRM) failed at a 1.28 factor of safety (FOS) during a Static Test Article (STA-3) full-scale static test. The addition of an external bracket had been proposed to modify the aft skirt for the now canceled Advanced Solid Rocket Motor (ASRM) in order to achieve the design FOS requirement of 1.4. The installation of the external bracket for the ASRM was to be fully evaluated during the STA-4 static test. Since cancellation of the ASRM and STA-4 test, it has been proposed to use the external bracket to reinforce the aft skirt of the RSRM.

An 11-inch segment of an aft skirt will be used in a specimen test to determine the effectiveness of the external bracket modification in reducing the overall bending stress of the skirt. The first test was planned for October 1993, but was delayed at the time of this writing until January 1994 because of unforeseen slippage in the fabrication of the test fixtures and test articles. Implementation into the fleet will be based on these test results and funding.

The first specimen test will provide insight as to whether the input loads at the ends and top of the test article are such that the strains in the critical weld correspond to those found during the STA-3 static test. If the strains and boundary conditions cannot be duplicated, other means of testing should be evaluated. Alternatively, the existing

1.28-demonstrated FOS could be accepted because the probability that 1.28 times design limit load will be exceeded is extremely remote.

Ref: Finding #20

A single crack was detected in a forward case segment (S/N 55) after the STS-54 flight. The case segment had been flown four times and had been proof tested successfully during refurbishment. Other cracks have been found in RSRM casings, but this is the first time a crack had been found in a forward segment.

It was determined that the crack occurred during the manufacturing heat treatment process because of an inclusion in the parent material. The crack size was 0.27 inches long by 0.10 inches deep. It was located 10 inches from the clevis end and oriented longitudinally on the inner diameter of the case. This is the only membrane crack found in approximately 600 pieces of hardware that have been manufactured. The crack was less than half the critical flaw size.

The detectable magnetic particle threshold is approximately 0.250 inches long by 0.125 inches deep. Hence, a 0.27-inch-long crack in the inner wall of the case was in the detectable range for normal refurbishment inspections. Therefore, the inspection plan for the case should be re-examined to verify the minimum size crack that can be detected by X-ray and magnetic particle inspection.

Ref: Finding #21

With cancellation of the ASRM, it is logical to explore the inclusion in the RSRM of applicable design features that were planned for the ASRM. These candidate changes include redesigned aft case stiffener rings, case-to-nozzle joint redesign, the new nozzle design, and the use of hydroxyl-terminated polybutadiene (HTPB) propellant. These changes have the potential to increase reliability and/or performance if applied to the RSRM.

Ref: Finding #22

Analysis of telemetered chamber pressure data from the right-hand RSRM of the STS-54 flight revealed a short duration perturbation of 13 psi at 67 seconds into the flight. The 13 psi is equivalent to a thrust change of slightly more than 54,000 pounds. A perturbation of this magnitude was higher than had been recently observed. Therefore, a thorough investigation was initiated. The investigation covered reviews of the pressure data from previous flights, the composition of the propellant in the particular motor as compared with earlier motors, manufacturing history, solid propellant combustion processes, flight dynamics, integrated vehicle stability, and control factors as well as structural margins throughout the Space Shuttle system. Meetings of NASA and industrial specialists in solid rocket motor combustion phenomena were convened to address the issue. Test programs to verify some of the hypotheses of the origin of the perturbation put forward during the reviews were undertaken. The investigations and reviews were very thorough, and some aspects continue.

The review of the chamber pressure histories of all Space Shuttle solid rocket motors flown and tested on the ground (a total of 145 motors) indicated that perturbations or "spikes" of approximately 1- to 2-second duration have occurred in every one of them. The "spikes" average between 5 and 7 psi superimposed on a base pressure of about 670 psi. There were a number at about 10 psi, with a few, including STS-54, at about 13 psi. The spikes occurred on one or both of the motors of a flight set with no preferential side. However, during most flights there were perturbations on only a single motor. Flight data also show that the perturbations occur between 65 and 75 seconds into the burn. Statistical analyses of these data indicated that the 3-sigma excursion would be about 20 psi.

All manufacturing processes, propellant chemistry, and control data indicate that the right-hand STS-54 motor was within the specification requirements. Vehicle dynamics and control analyses indicated that the thrust perturbations were well within the control capability of the flight control system even under greater than 3-sigma excursions in pressure. Similarly, structural analyses indicated that none of the established structural margin (factor of safety) requirements would be violated under such pressure excursions.

A number of hypotheses as to the cause of the perturbations were put forward. Among the most plausible were: (1) the shedding of parts of the castable inhibitor located between the segments of the motors as the burn progresses, resulting in partial blockage of the grain bore or the nozzle throat as the parts are expelled, and (2) accumulation and expulsion of slag (aluminum oxide) generated during combustion, resulting in partial blockage of the bore or nozzle throat. The bounding excursion of pressure that could be postulated was 31 psi, equivalent to 124,000 pounds of thrust (this is the value used in the analyses noted above).

Static tests of motors on the ground showed the presence of spikes such as those experienced in flight. Real-time radiography showed no evidence of breakup of the castable inhibitor, but did show evidence of a higher-density medium (slag) at the aft end of the motor. An increase of combustion chamber pressure "roughness" after 50 seconds of burn was evidenced in radiographic, calorimetric, strain gage, and pressure gage data. Emission data from the exit plume taken by radiometers correlate with pressure data and also are indicative of a more dense fluid (slag) being ejected during a perturbation. In another test in which the nozzle was vectored, pressure perturbations corresponded to the two nozzle vectoring events at 68 and 74 seconds, respectively.

Analytical modeling of the inhibitor breakup hypothesis yielded a requirement of inhibitor fragments of some 12-14 square feet in area to provide a pressure perturbation of the magnitude observed. The generation of fragments of this magnitude is difficult to support. The hypothesis of slag expulsion is supported by the following: (1) the generation of slag has been confirmed experimentally; (2) an annular "reservoir" is generated around the submerged portion of the SRM nozzle by completion of the combustion of the propellant in that volume at about 60 seconds into the burn, allowing for the collection of slag in this volume; (3) the burn rate of the grain shifts from regressive to progressive in the 50-55-second timeframe (this is conducive to the generation of roughness in the combustion process); (4) the SSMEs are throttling up in the 50-second timeframe, providing a source of external acceleration; and (5) there is a vehicle pitch maneuver at about 65 seconds (a standard event) that would result in the "tilting" of the annular "saucer" and expulsion of the liquid slag that had been collected.

Although the slag expulsion hypothesis is supported by the data obtained to date and is a reasonable causal chain, additional testing, data review, and analysis continue as of this writing. The investigation of the phenomenon has been, and continues to be, thorough and objective. More important, all indications are that Space Shuttle safety is not compromised even under the worst-case perturbations that can be supported by available data.

EXTERNAL TANK

Ref: Finding #23

A Super Light Weight External Tank (SLWT) has been proposed for the Space Shuttle to provide additional payload performance. Present estimates are that up to 8,000 pounds of additional payload can be gained. The SLWT replaces 2219 aluminum with 2195 and 2090 Aluminum-Lithium (Al-Li) alloys. The Al-Li alloy has improved fracture toughness, stress corrosion resistance, stiffness, and strength. The SLWT also includes a redesign of the liquid hydrogen tank to employ an orthogrid (square waffle) structure and tailoring of the thermal protection system insulation on the inter-tank to reduce weight. The use of Al-Li accounts for approximately half of the potential weight reduction because of its increased strength and decreased density. The structural and insulation changes account for the balance.

The welding processes for the Al-Li alloys are similar to those used for 2219 aluminum. Even with the thinner skins, the decision has been made to leave the weld lands at the current thickness, which simplifies tooling aspects of the change and results in a stronger tank. With the marked increase in fracture toughness, especially at cryogenic temperatures, and the same weld lands, the critical flaw sizes should be greater than for the current lightweight tank.

To determine the effect of the increased stiffness of the tank on the Space Shuttle system, 12 ground and flight load conditions have been analyzed. The preliminary results show the loads to be within the presently defined envelope.

The entire program, including manufacturing procedures, weight reduction estimates and test plans, appears reasonable. With cancellation of the ASRM, the increased payload possible from the SLWT will be valuable for the Space Station in its new, high inclination orbit. However, the total system impacts of the SLWT need to be carefully examined.

LOGISTICS AND SUPPORT

Ref: Findings #24 through #27

The logistics and support programs for the Orbiter and other principal project elements—SSME, RSRM, and External Tank (ET)—all appear to be in satisfactory condition. Some lingering effects of the introduction of Orbiter OV-105 (Endeavour) have been overcome, and measurement of the principal tracking parameters of cannibalization, fill rates, zero balance, and repair turnaround time show satisfactory-to-excellent trends. In the parameter of "pending loss of repair/spare," there is some concern about certain subcontractors' capability or willingness to continue maintenance or overhaul support. About 80 contractors are being monitored in this context, and alternative solutions are being sought where necessary.

More specifically, cannibalization affecting the Orbiter and the STS-54 through -57 launches has been minimal, reflecting very favorably upon the efficiency of the controls instituted over the past 3 or 4 years. There are, however, some significant problems, such as the unreliability of the IAPU. The SSME is also having its share of problems in particular with the availability of high pressure oxygen and fuel turbopumps, engine nozzles, and valves.

Repair Turnaround Time (RTAT), which has a major effect upon spares availability, tends to fluctuate with the experiences of launch demands for components and the workload at the NASA Shuttle Logistics Depot (NSLD). A major part of the RTAT problem involves work at the Original Equipment Manufacturers (OEMs).

On the management and administrative control front, the logistics and support system within NASA and its contractors has been excellent, and its control, trend reporting, and audit systems appear to be functioning well. Interrelationships, as evidenced by the half-yearly Integrated Logistics Panel (ILP) reports, show that the major contractors' Integrated Logistics Systems (ILS) programs comport well with those of the principal NASA Centers—KSC, Johnson Space Center (JSC), and MSFC. Inventory management systems such as the Kennedy Inventory Management System (KIMS) are being constantly updated and performance measuring methods such as the Maintenance Trend Analysis Report (MTAR) provide good visibility into the effectiveness of the support.

Frequent audit examinations and analyses are conducted, and the entire program is well monitored. One especially commendable attitude on the part of the KSC ILS management is the interest in recruiting and training bright young people as analysts and statisticians and the encouragement thus afforded towards career paths in logistics.

The ILP is the most important coordinating activity linking the project elements of the Space Shuttle program. The ILP, which serves as a forum for periodic review, meets at a selected NASA Center every 6 months. It is an invaluable source of knowledge about the entire logistics program, and provides cross-fertilization of ideas and standardization of techniques among NASA Centers and their contractors. The ILP activity should be continued without diminishment or reduction in the frequency of its meetings. It is the one central source of knowledge of the interrelationship of the entire logistics and support organization.

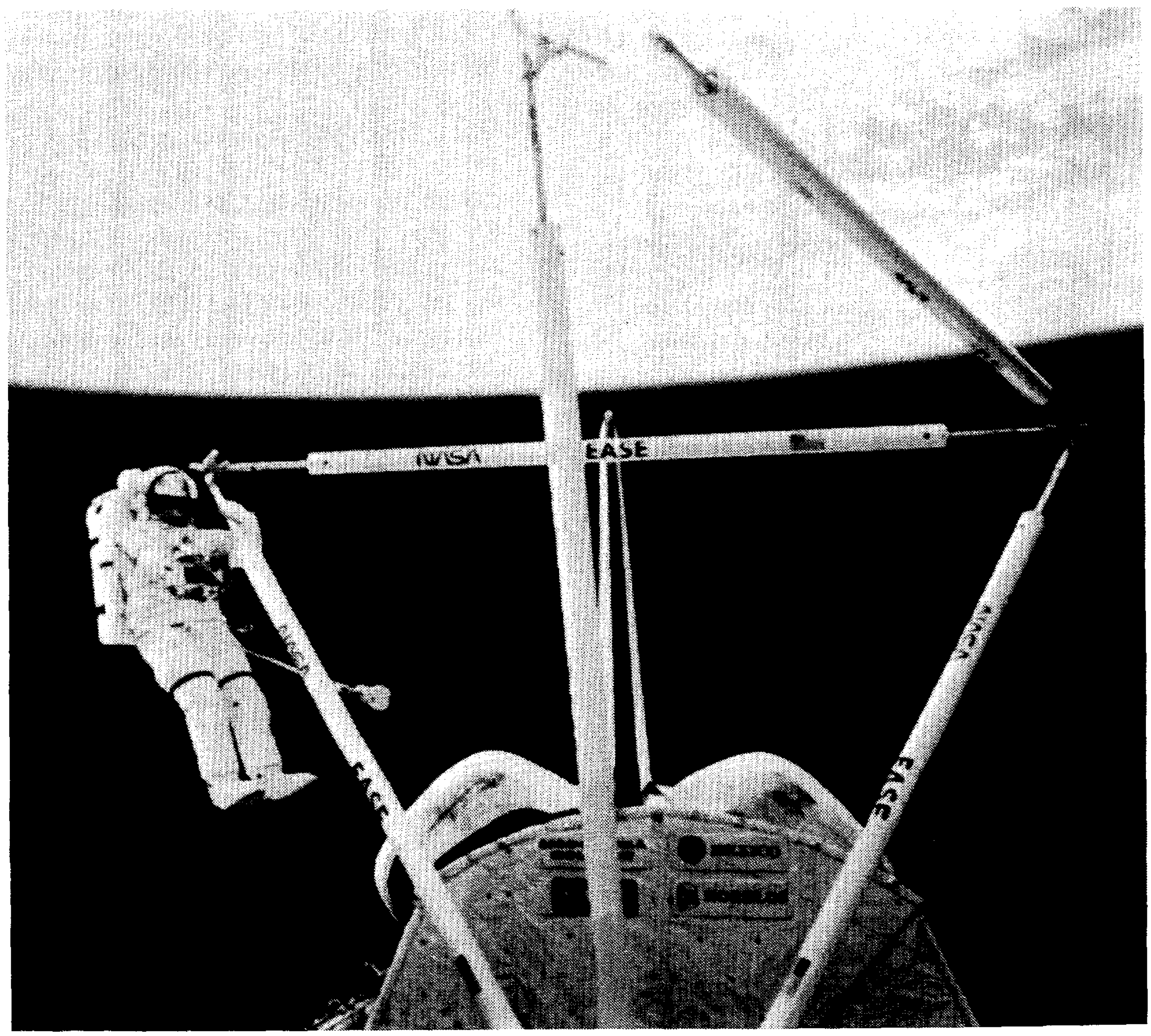
Cannibalization of built-up spare SSMEs is now a significant problem. Seven HPFTPs and seven HPOTPs were required to complete the build of available spare engines at the time of this writing. Engine nozzles are also in short supply. It should be noted that the manufacturers have already instituted action to correct many of these issues. It is essential to reinforce the ongoing recovery program to ensure better SSME component availability in the future.

The *Vision 2000* program, which has been subscribed to by key personnel at the manned Space Flight Centers, outlines Space Shuttle program organization and activities to the end of the century and beyond. It is, in effect, a "manifesto" for future management approaches and procedures, the underlying purpose being that of major cost reductions brought about by organizational realignments and the elimination of duplication.

While these reductions are obviously necessary to meet the funding available, they are going to be particularly harrowing for the logistics community, principally because of the increasing age of the Orbiter structures, engines, and components and the concomitant need for increased maintenance attention. Component obsolescence is also a major factor entailing more — not less — expenditure to meet the launch requirements. The present logistics system has been arrived at over a period of more than 12 years, and, in spite of certain inevitable shortcomings, is working remarkably well. It would therefore appear prudent to avoid any precipitous or arbitrary cutbacks that might imperil the overall logistics system.

The NSLD continues to evolve as an essential part of the Space Shuttle program. It has added some advanced equipment and has provided the skills, together with the necessary training of personnel, for the overhaul, checkout, and failure identification of some 4,500 line items. Not only is the NSLD a guarantee of continued support of component overhaul when the OEM is unable or unwilling to offer a satisfactory program, but it is also highly cost effective, in part because of its close proximity to the launch site.

One of the activities in the logistics field which has recently attained prominence is that of Just-in-Time (JIT) manufacturing and shelf stocking. This concept, which involves deferring restocking certain items until they are needed, offers many cost-effective advantages and is now widely used in the auto manufacturing and other production-line related activities. With careful control, JIT can be a valuable cost-saving technique for NASA, although its use should be confined to relatively easily available hardware type items or readily repairable components.



C. AERONAUTICS

Ref: Finding #28

The Dryden Flight Research Facility (DFRF) is about to begin extensive testing of the Perseus Unmanned Aerial Vehicle (UAV). The Perseus is designed for high altitude and long-duration observation missions. The Perseus testing raises an issue of range safety. The flight termination system is a parachute that is deployed on command. The vehicle is then lowered to the ground by the parachute. The initial three flights are limited to 3,000 feet above ground level. The flight path is planned to be over Rogers Dry Lake (Edwards), avoiding approach patterns to the main runways. In addition, these flight boundaries are reduced for the case of wind drift for 30 knots from the 3,000-foot altitude. Control of the termination system would be by NASA, as it should be. Test flights would be controlled by the contractor and monitored by NASA. This procedure is probably adequate for the low-altitude flights, but a different approach must be developed for the high-altitude flights (probably above 10,000 feet) when wind drift can be quite high. The area around Dryden is no longer the totally barren territory it has been in the past. Dryden is depending on the contractor to bring in a proposal for flight safety in this part of the program which they would review and approve.

At present, DFRF does not have a range safety policy for UAV flights similar to other unmanned test facilities. In earlier unmanned vehicle testing activity at DFRF, individual cases were evaluated and negotiated. If unmanned flights are to be continued at DFRF, there is a need for an overall range safety policy that includes definition of the areas, risk assessment, type of flight termination, and range safety displays and controls. In the case of Perseus, NASA has some control over the project. DFRF is concerned that there are other projects where DFRF is simply providing housekeeping with no control over the project, including safety. This situation cannot be tolerated without either NASA or the Air Force having control of range safety. This issue should be addressed as part of the DFRF Range Safety Policy. The Director of DFRF has recently established a committee under the Chief Engineer to develop a UAV range safety policy.

Ref: Findings #29 through #30

NASA's flight research facilities are among the finest in the world. During the past year, the Panel visited only DFRF which has undertaken, with great success, some of the most challenging and high-risk flight projects ever initiated with a commendable safety record. This has led to the designation of DFRF as an independent center.

DFRF is currently engaged in a number of interesting projects, one of which involves post-stall flights. This is a unique flight regime made possible by advances in aircraft and engine technology and can only be researched adequately in free flight.

Other programs of importance to the future of the nation's commercial and military aviation stature involve total integration of power and flight controls, boundary layer transition studies, and sonic boom studies. In the interest of keeping the United States competitive in the world aircraft market, it is essential to maintain the flight research capability at NASA's research centers. The use of flight readiness reviews for programs and technical briefings before each test flight at DFRF is an excellent way to minimize test flight risk.

Much progress has been made in the various DFRF flight research programs over the past year. As part of the propulsion control aircraft (F-15) program, a landing was made on April 21, 1993, using only propulsion control. This work is very important from a safety standpoint and should be continued. Aircraft of the future may be ***designed*** with characteristics that enhance propulsion control power. This will allow for possible landings with structural damage, combat damage, or a faulty aerodynamic control system.

The performance-seeking, propulsion-controlled testing is not directly related to safety. It does, however, offer excellent potential for efficiency gain in civil and military aircraft operations. The multi-axis thrust vectoring nozzle research should add enormous impetus to both the propulsion-controlled and performance-enhancing research efforts.

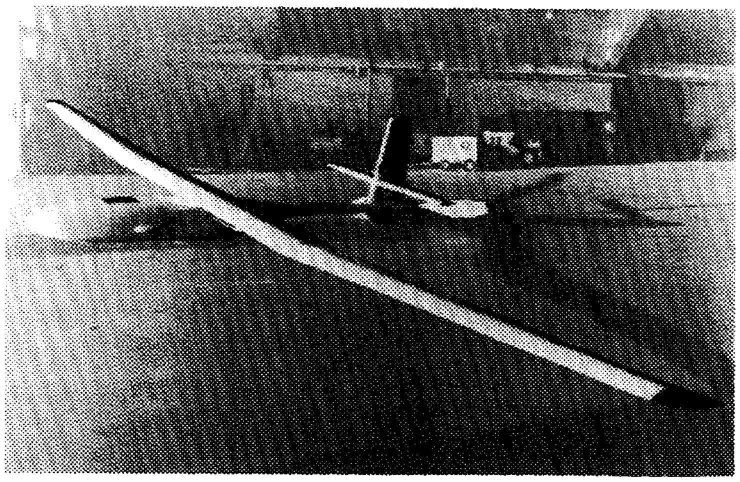
The X-31 aircraft exhibited undesirable stability characteristics at higher subsonic speeds and was therefore limited well short of the full maneuvering design envelope. Also, an unexpected departure was experienced during a high alpha test. This departure could not be duplicated or explained by analysis but is an excellent example of the necessity of flight testing. Another potential safety issue is an insufficient quantity of hydrazine to run emergency power unit (which furnishes flight electrical power and therefore controls power in the event of an engine failure) long enough to return to the Edwards runway from the test site. If the aircraft cannot make the runway, the pilot must bail out. This situation represents a risk that has been deemed acceptable by the program.

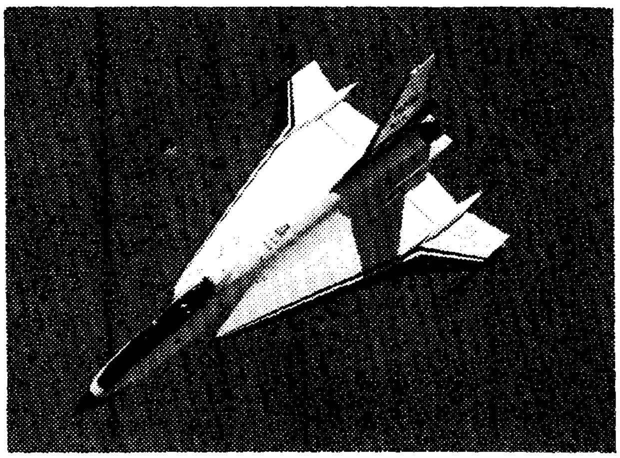
DFRF should evaluate the specific program objectives that can be uniquely performed by the X-31 and cannot be performed by the F-18 or F-15 vectored thrust aircraft. The results of this study should be the basis of continued testing of the X-31 and the continued acceptance of risk. The F-18 High Angle of Attack Research Vehicle (HARV), another thrust vectoring program, has completed over 82 flights with successful maneuvers up to 70° angle of attack. The software programming of the flight control system has the potential to contribute significantly to the design of advanced flight control laws for future aircraft. The HARV program provides a good example of risk analysis and rational risk acceptance. The possibility of spin chute interference with thrust vectoring equipment is an example of a risk that was properly assessed and accepted.

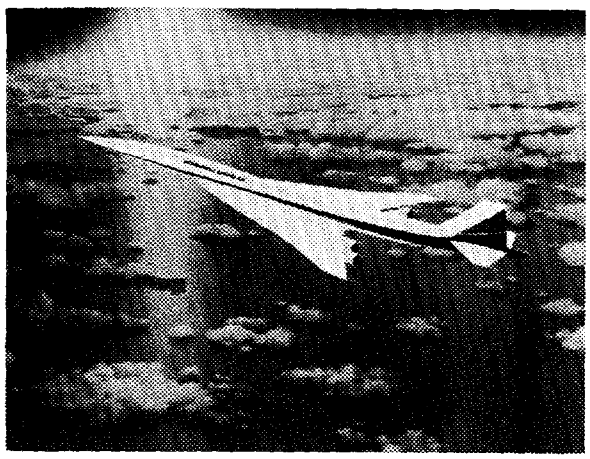
The F-16XL supersonic laminar flow control program is another example of the systematic approach that Dryden follows to control the inherent risks connected with experimental flying. The Dryden *Basic Operations Manual* clearly identifies a procedure to be followed for identifying hazards and taking the necessary actions to reduce them to an acceptable level, up to and including a redesign of the system.

The CV-990 Space Shuttle tire test program is progressing well. Many taxi tests preceded the initial flights, and six flights had been accomplished at the time of the Panel's review in August. A primary concern of the Panel had been a braking problem during a rejected takeoff and subsequent fire that destroyed a previously-owned NASA 990 aircraft. A decision was made to carry no fuel in the center tanks — ones likely to be struck in the event of a test gear or CV-990 gear failure. Also, "armor plating" and automatic failure detection hardware and software have been incorporated in the system.

Another of the unique programs ongoing at DFRF is the SR-71 flight program, which had completed 28 flights (both SR-71A and SR-71B models) at the time of this writing. There are a number of science payloads and experiments that the aircraft are now testing or have plans for testing. The aircraft has unique capability for high-altitude (84,000 feet) and high-speed (Mach 3) flight and should prove invaluable for testing sonic boom theories and codes needed to design an acceptable high-speed civil transport aircraft. This use of the SR-71 aircraft should be viewed as a flying laboratory and funded as a unique national asset. Other programs reviewed during the visit to Dryden include the Small High Altitude Science Aircraft (SHASA), the Perseus UAV, and the Advanced Actuation/Fiber Optics Systems.







D. OTHER

Ref: Finding #31

NASA programs have long had a significant dependence on software processes. That dependence is now increasing rapidly, and will continue to do so for the foreseeable future. With the increasing capabilities of computer systems and their decreasing cost, weight, space and power consumption, many more functions are being controlled through software, and the size and complexity of the software is correspondingly greater. In addition, and at least partially as a result of the widespread increase in software control of devices and functionality, computer and software systems increasingly need to be interoperable, not only within NASA, but with other agencies and commercial and academic organizations that will use or create space system data. The multi-national Space Station program, including the Russians, may place particular demands on interoperability because the Russian computing capability and philosophy differ from NASA's.

NASA's past approach to software development has been to incorporate it within the individual programs, allowing them to determine their own requirements and development, verification, and validation procedures. In the future, this mode of operation will be increasingly less satisfactory as the complexity of NASA's computer systems and the need for interoperability grow. It is timely to examine closely the overall structure and management of software processes within NASA.

The need for a more comprehensive view of software development processes has been cited by several different organizations over the past several years, including the Aerospace Safety Advisory Panel (ASAP), the General Accounting Office, and most recently, a subcommittee of the National Research Council. These groups have called for a variety of improvements to the software development process, including software hazard analyses, independent verification and validation, more central oversight and planning, and a variety of other potential improvements.

Most of the recommended changes in software policy to date have been made in the name of safety within the scope of a single program, e.g., Space Shuttle. The emerging demands for interoperability and the ability even to achieve the necessary functionality dictate a broader safety need that even more strongly argues for greater centralization of software policy setting. Interoperability will require coordination among programs on such matters as data definitions, representations, and access. This cannot be done within the scope of independent program management structures, but will require some central coordination.

NASA does not now have the overall management policies, procedures, or organizational structure in place to deal with these broad issues. Although relevant work, e.g., a software assurance plan and software development guidelines, has been in work for some time, progress has been slow and still does not fully address all of the broad Agencywide software issues. In view of growing needs for interoperability along with continuing needs for software safety assurance, this is an important limitation.

Recently, however, NASA has indicated a consideration of an internal effort to develop the needed polices, guidelines, and