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Shuttle Integration Status

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ABSTRACT

As the Space Shuttle nears its first flight, the systems activity is changing its emphasis to concentrate on certification of the flight system and potential growth into the future. In this paper I would like to explain how we have approached the certification of the Shuttle system and then later describe recent activities which will enhance the capability of the Shuttle during the operational time period.

SYSTEMS CERTIFICATION METHODOLOGY

The Shuttle system certification, as we have defined it, is comprised of two major activities. One is the verification of the adequacy of the design and the second is the proper accomplishment of the certification of the particular flight end items that will be used for the first missions. The end item certification, which consists of the manufacturing inspection, factory acceptance test, and then checkout at the launch site, is being planned and conducted much as it has been on previous NASA programs and will not be discussed in any detail here. The Space Shuttle is, however, much more complex than previous NASA programs. This is a result of the integrated nature of the vehicle where many functional systems go across element interfaces. This means that much of the design verification must be planned and/or conducted at the system level.

Figure 1 is a figurative display of the logic flow that we have used to develop the overall verification program. The left-hand portion shows the systems specification which defines the vehicle requirements and below it are the verification responsibilities which have been identified and assigned to individual elements or combined elements for each of the functional requirements in the system spec. These two volumes lead to the Shuttle Master Verification Plan, which is made up of a volume for the combined elements and individual volumes for each of the projects within the program. The combined element volume contains an overall description of the verification program and is divided, from a system standpoint, into 15 individual disciplines that we will talk more about later. The volumes for the individual elements contain all of the verification requirements to properly satisfy that element's end item specification and, in addition, describe those systems level verification requirements which have been assigned to that specific element. As a cross-check of the overall content in the verification program, logic diagrams have been prepared for each of the major functional areas of the vehicle. Individual items required to verify these functional areas have been defined and cross-checked to make sure they are contained in one of the Master Verification Plans. In those cases where a hole is found, then that particular requirement has been assigned to one or more of the disciplines in the combined element volume, or assigned to one of the five elements. Each of the blocks has then been broken down to specific activities required to accomplish that particular block. All of the data required to be supplied to those activities and the products of those activities have been defined. Definitions of these activities are contained in an automated data file which we call a VIS (verification information system) file. This allows us to track the satisfactory accomplishment of the program from several different viewpoints. The schedule portions of those activities that are assigned to the combined elements are shown on the master engineering schedules depicted here as the engineering plan.

Figure 2 shows a matrix approach which also has been used to cross-check the basic systems. Here, the specification requirements are listed down the ordinate, and the technical discipline areas and elements involved in the satisfaction of each of the requirements are listed across the abscissa at the top. As indicated by the intersecting arrows, several technical areas may be required to satisfy a single specification requirement. Each intersection of the arrows represents one of the product activities that we talked about back in figure 1. They are, in fact, the level of detail that we define and track in the verification program.

The VIS file for each of the technical areas has been baselined in the program and we are presently managing and tracking approximately 1500 product activities in the combined systems area alone. A listing of 15 technical disciplines that we have used to define the program is shown on figure 3. Two areas will be described in a little more detail to better illustrate the activities involved.

STRUCTURAL DYNAMICS

The first area I would like to discuss is that of structural dynamics. On figure 4 is seen a grossly simplified version of the verification logic net for this area. The main flow through the logic net for the structures program, as shown by the bold line, starts on the left and proceeds from the requirements through the Master Verification Plan into the integrated structural math modeling activity. While the construction of the system structural math model is a systems level responsibility, there are very significant inputs from each of the elements, including the mobile launch platform which is used in lift-off loads calculations. Each of the element's math models is updated as information is obtained from structural tests of the elements. Structural data from combined systems tests, such as the main propulsion test article resonant survey which was conducted on the main propulsion test article, are also fed into the math model. The math models are then used to generate loads inputs at the element interfaces, and these are used by the elements for evaluation of their structural capability. In addition, the structural math models are used by several other disciplines in their verification program and, in turn, these disciplines are used to support the structural verification. Representative of these are pogo, flutter, thermodynamics, and structural dynamics of the umbilicals at the launch and landing site. A major factor in the structural verification program is the conduct of the full-scale mated vehicle ground vibration test program, which has recently been completed at the Marshall Space Flight Center. Figure 5 is a photograph of the test article in its stacked position for the lift-off portion of the test. Shuttle vehicle modal data were obtained from this test article for mass loading conditions corresponding to five different times during the launch profile. These modal data have been used for an update of the integrated math models and are now being fed back into the systems load assessment and will, in fact, have a significant input on the placards and constraints for the early portion of the flight test program. During the flight test program itself, we will obtain additional information needed to verify the adequacy of the vehicle for operational use. Specific flight test requirements have been defined for all of the flight test program and each of these flight test requirements has been assigned to one of these specific missions in the first six flights. As the flight information becomes available, the constraints and placards will be updated and the restrictions reduced so that near the end of the flight test program the vehicle will be demonstrating a significant portion of its total structural capability.

MAIN PROPULSION

The other technical area I would like to discuss briefly is the MPS (main propulsion system). The Shuttle MPS is an integrated system which spans across three flight elements plus the associated launch facility systems which serve to prepare the vehicle for flight. The three major flight elements are the ET (external tank), the Orbiter, and the SSME (Space Shuttle Main Engines). The system is shown pictorially in figure 6. The MPS is divided into several interrelated systems, all of which cut across the interfaces between the flight and ground elements to perform specific functions in the integrated system. Figure 7 is a schematic representation of the main propulsion systems. The MPS is further subdivided as follows:

a. Propulsion Loading System - This system loads propellants onboard within designated launch timelines. Considerations include limiting peak tank pressures during facility/vehicle chilldown, avoidance of geysering conditions in LO_2 system, maintenance of proper LO_2 tank pressure, and attainment of the required loaded mass within acceptable loading errors.

b. LO$_2$ and LH$_2$ Preconditioning Systems - These systems provide suitable temperatures at the SSME inlets and throughout the propellant feed systems to satisfy engine start requirements. Considerations include propellant conditions as delivered from the facility, heat loads in the three major flight elements, combined resistance of flight and ground fluid systems, recirculation pump performance, antigeyser system performance, and transient pressures in the ET ullage after loading.

c. Helium and Nitrogen Pneumatic Systems - These systems provide in-flight helium for valve actuation and purging services for the engines and the Orbiter components. Nitrogen purging for the engines during ground operations is also provided. The airborne helium system provides pressure for expulsion of residual propellants from the Orbiter after engine cutoff and maintains a positive pressure within the fluid system during reentry and landing operations. Considerations include facility storage conditions and flow capacity, engine purge requirements, performance characteristics of Orbiter pneumatic components, and heat transfer during preflight and flight operations.

d. Pressurization System - This system provides ET ullage pressure to support engine start requirements, ullage pressure for detanking operations, and ullage pressure throughout boost to maintain the proper engine suction pressure. Considerations include facility storage conditions supplied by the engines, ET structural and safety limits, heat transfer effects, and component performance parameters.

e. Propellant Feed System - This system transports the propellants from the ET to the engines during boost. Prevalves are incorporated to isolate deactivated engines, and disconnects are provided to permit separation of the feedlines between the ET and the Orbiter. The propellant feed system performance, in conjunction with the pressurization system and the hydrostatic head of the propellants, helps assure adequate pressure at the engine inlets during boost. Considerations include engine steady-state flow requirements, engine startup and shutdown flow transients, propellant temperature stratification, launch acceleration, and pressure drop characteristics for lines and components in the ET and the Orbiter.

The MPS verification involves a combination of analyses and tests to assure that the design is capable of satisfying the system performance requirements for all Shuttle missions. A major result of system verification will be a math model which will be used to predict system performance. This requires an in-depth understanding of the individual elements plus an understanding of the mutual interactions between them. Data obtained from an integrated test program result in a greater understanding of these interactions, thereby permitting a progressive improvement in the performance predictions. The basic verification flow chart is shown on figure 8.

The analysis block of figure 8 is further amplified by the network shown in figure 9. This analysis network shows the flow of test data and analysis results from the major element contractors and test/launch sites into the integrated performance analysis and finally into the flight operations. Each analysis output is supported by a matrix of supporting information and data from the major elements and test/launch sites. The elements of this matrix are contained in the VIS file described earlier. The periodic updates of the integrated propulsion performance predictions reflect the increased maturity as integrated system test data are progressively obtained and assessed.

The MPTA (main propulsion test article) is the principal tool for development and verification of the integrated MPS. Figure 10 is a photograph of the MPTA which is located at NSTL (National Space Technology Laboratory) in Mississippi. The MPTA test program is the first opportunity to test the integrated MPS, consisting of the three major flight elements, in essentially a flight configuration. Ground support equipment and facility systems are the same or as closely approximate those that will be used in the flight program. Extensive special instrumentation has been added to the MPTA to permit more detailed analysis and assessment than would be possible with flight instrumentation alone. The MPTA program to date has completed two tanking tests and four static firing tests. Information gained during this initial test series has verified the basic design of the integrated MPS as well as demonstrated compatibility of the interfacing flight and ground systems.

The progressive resolution of problems and the refinement of operating procedures for MPTA during the initial series of tests culminated in a near-perfect fourth static firing. Although many critical MPTA program objectives remain to be accomplished, the initial series of tests has already made significant contributions toward the verification of the integrated MPS and the development of the Shuttle transportation system.

As illustrated by these two examples, the verification approach for the Shuttle system is considered to be a logical and effective means to demonstrate compliance with design requirements, maturity of design, and readiness for flight. Through cooperative efforts of the several contractors and the cognizant NASA centers, many of the major verification objectives have been accomplished and a detailed plan is available to monitor the accomplishment of the remaining activity.

THRUST AUGMENTATION

A review of projected Shuttle performance requirements and predicted capability was conducted early in 1978 and revealed that the Shuttle needed a significant increase in capability to satisfy the growing user desires. Comparison of the original mission requirements with Shuttle capability disclosed negative payload margins which could be resolved by implementing previously identified weight savings on the Orbiter and ET; however, the new mission requirements of 32,000 pounds in a polar orbit, combined with a desired 3,000 pound allowance for future weight growth, was beyond satisfying with weight reduction programs alone. In addition, as the Space Program grows in maturity, there is a possibility of requirements that demand still greater capability. Therefore, NASA, with support from the Air Force and its contractors, began investigation of various methods of improving Shuttle ascent performance.

In the early phase of the study, a wide variety of options was analyzed. Some of the candidates considered were: sub-cooling the liquid oxygen and hydrogen for use in the Orbiter main engines; enlarging the SRBs in both length and/or diameter; new propellants in the SRBs; and additional solid rocket motors attached to either the SRBs or the aft end of the ET. Payload lift capability and major performance characteristics of all options were determined to permit initial elimination of the least desirable. All but two options were eliminated because of excessive cost, questionable state-of-the-art capability, or insufficient performance improvement. The two options which were selected for more detailed study were: solid rocket motors attached to the SRBs (called SRB strap-ons) and solid rockets attached to the aft end of the ET (ET strap-ons).

Each option was then subdivided to give two different levels of lift capability as depicted in figure 11. Options 2A and 4A were sized to meet Mission 4 requirements plus growth allowance, and options 2B and 4B were designed to provide approximately 15,000 pounds payload above that.

Option 2A utilizes two solid rocket motors (one per SRB) 90 inches in diameter and 486 inches long. Each motor contains 105,000 pounds of propellant and develops a maximum of 1.36 million pounds thrust. These strap-ons are ignited at lift-off, burn for 30 seconds, and are jettisoned shortly after they burn out. No recovery of the spent motors cases is planned. The main SRM requires a mandrel redesign to change its thrust time history as well as a reduction in propellant burn rate to stay within the vehicle strength capability. Thrust histories of both the SRM and the strap-on motor are carefully tailored to achieve maximum efficiency without violating existing critical load criteria.

Option 2B utilizes four solid rocket motors (two for each SRB) which are 109 inches in diameter and 471 inches long. Propellant weight for each motor is 181,000 pounds, maximum thrust 1.0 million pounds, and burn time 75 seconds. These data indicate that an SRB strap-on configuration with this payload capability could not be made as efficient as option 2A without violating the existing load criteria. Consequently, the strap-on burn time had to be stretched out and, as a result, the propellant weight increased as compared to 2A. Two of the strap-on motors are ignited at T-0 while ignition of the other two is delayed 5 seconds to lessen demands on the launch mount exhaust ducts. After burnout of the second set of motors, each pair is jettisoned as a package and is not recovered.

Option 4A consists of two solid rocket motors attached to the aft end of the ET. The motors are made from a 160-inch long segment of the main SRM motor case and the overall length is 297 inches. The motors contain 218,000 pounds of propellant. Strap-on ignition occurs at lift-off and the magnitude and shape of the thrust/time curve is chosen to minimize in-flight loads and resultant weight impacts. No change to the SRB thrust history is required. The strap-on motors are designed to essentially lift their own mass until after SRB burnout and separation. The burn time of 165 seconds (40 seconds longer than the SRB) then permits additional impulse to be imparted to the vehicle without danger of violating critical loads. After burnout, the strap-ons are jettisoned as a package. Although some analysis of recovery of the spent motors was conducted, this was not a prime consideration and the payload capability shown in figure 11 does not include any provisions for strap-on motor recovery. Option 4B uses four of the same motors operated in the same manner as option 4A.

Total program cost estimates indicated very little difference between options 2A and 4A and between 2B and 4B. However, one major contributor to option 2As cost was the redevelopment and requalification necessitated by the change in the existing SRMs thrust-time history. Data developed during the study indicated that this cost could be made to approach zero if the change to the SRM was limited to a small burn rate change and some sacrifice in cost-per-flight (i.e., increased strap-on motor size) was permitted. The decision, therefore, was made to adopt a version of option 2A based on those guidelines. This option became known as option 2C. Later analysis has validated this decision. Its characteristics, as presently understood, are shown in figure 12. Analysis of this configuration is not complete at this time but present indications are that a payload of 35,000 pounds in a polar orbit can be achieved with very little impact to the basic SRM. Initial operational capability for option 2C is presently planned for June 1984 at VAFB and June 1985 at KSC.

After selecting option 2C for near-term growth, potential for future growth capability was considered. Some preliminary analysis showed that a version of option 4 could be added to option 2C to give a payload capability equal to option 4B but at reduced cost. The use of option 2C with a smaller version of option 4B would also permit delayed ignition of the ET strap-on motors and thus avoid the extensive changes to the launch mount exhaust ducts that would otherwise be required. Therefore, ET strap-ons, in conjunction with option 2C, are favored as the long-range growth configuration.

Figure 13 shows a few of the possible applications for the improved performance. The left side of the figure shows the relationship between payload weight and circular orbital altitude for the baseline Shuttle and the four options. It is apparent that for a given orbital altitude the growth version of the Shuttle would permit a significant increase in payload weight although at the lower altitudes the payload would be limited by the 65,000 pound maximum capability of the Orbiter. Alternatively, for a given payload, the growth capability would permit addition of payload bay OMS (orbital maneuvering system) propellant kits and attainment of higher altitudes. The right-hand side of figure 13 shows how orbital inclination can be increased with increased lift capability. For example, for a given payload and altitude, options 2A and 4A could increase orbital inclination up to 24 degrees. Another possibility would be to use the extra capability for yaw steering to provide wider launch windows for faster rendezvous with previously launched satellites.

In summary, the current NASA proposal is to (1) implement option 2C immediately for an initial operational capability of June 1984; (2) perform the preliminary engineering effort required to ensure the capability of incorporating ET strap-on motors for still greater capability at a later date; and (3) design and build the VAFB launch mount to withstand launch loads from option 2C with allowance for the addition of the ET strap-on motors.

This study and subsequent decisions show that the Space Shuttle is a very versatile system and will be able to provide a significant growth potential for future space missions.

INTEGRATED SYSTEM VERIFICATION

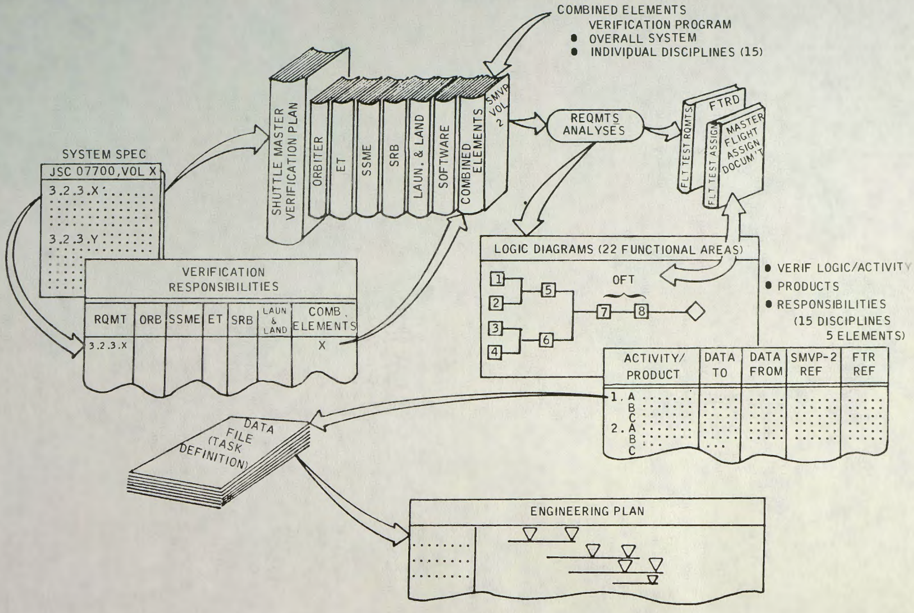
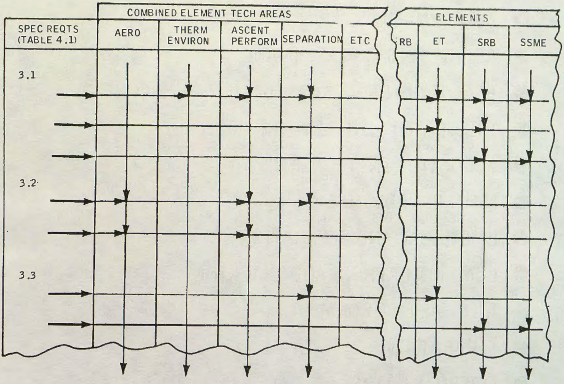


Figure 1.

VERIFICATION INTEGRATION
(COMBINED ELEMENT)



PRODUCTS:

IVLN'S

- REQT GROUPS
- VCN'S

VIS

- NUGGET DEF
- T/M RESP
- STATUS

PRODUCTS:

SMVP-II DISCIPLINE SUMMARY PLANS

- SYSTEM VERIFICATION NETWORKS
- VERIF RESPONSIBILITY SUMMARIES

ELEMENT VERIF PLANS

- SMVP-III (ORB)
- SMVP-IV (SRB)
- SMVP-V (ET)
- SMVP-VI (SSME)
- SMVP-VIII (L&LS)

Figure 2.

SHUTTLE VERIFICATION SYSTEM DISCIPLINES

- AERODYNAMICS
- ASCENT FLIGHT PERFORMANCE
- ASCENT GUIDANCE, NAVIGATION, AND CONTROL
- INTEGRATED VEHICLE MATH MODEL
- ACOUSTICS ENVIRONMENT
- MAIN PROPULSION
- UMBILICAL AND SEPARATION
- COMMUNICATIONS AND TRACKING
- THERMAL ENVIRONMENT
- SEPARATION
- EXTERNAL LOADS
- POGO DYNAMICS
- FLUTTER
- AVIONICS AND SOFTWARE
- HYDRAULICS

Figure 3.

SYSTEMS INTEGRATION VERIFICATION LOGIC NETWORK STRUCTURES

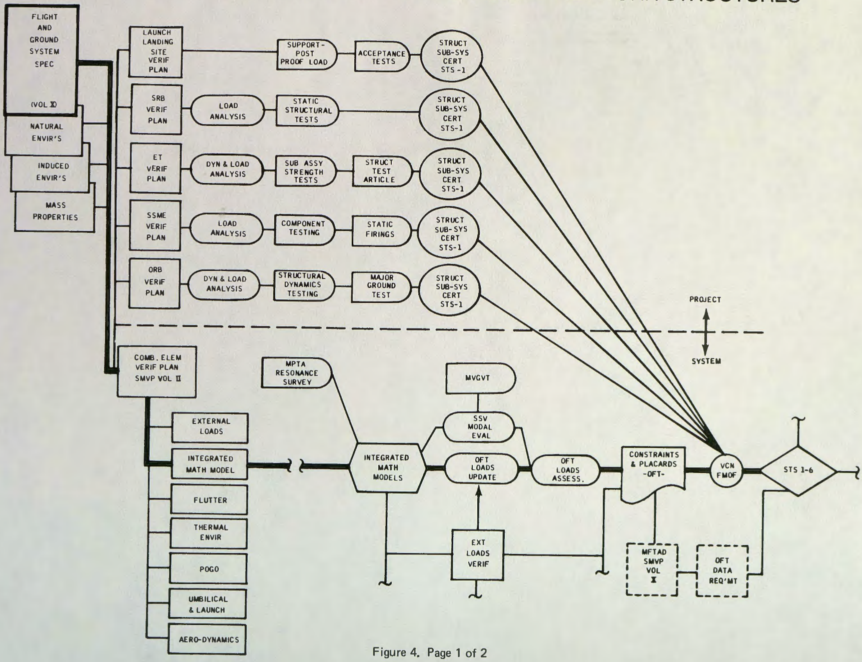


Figure 4. Page 1 of 2

SYSTEMS INTEGRATION VERIFICATION LOGIC NETWORK
STRUCTURES

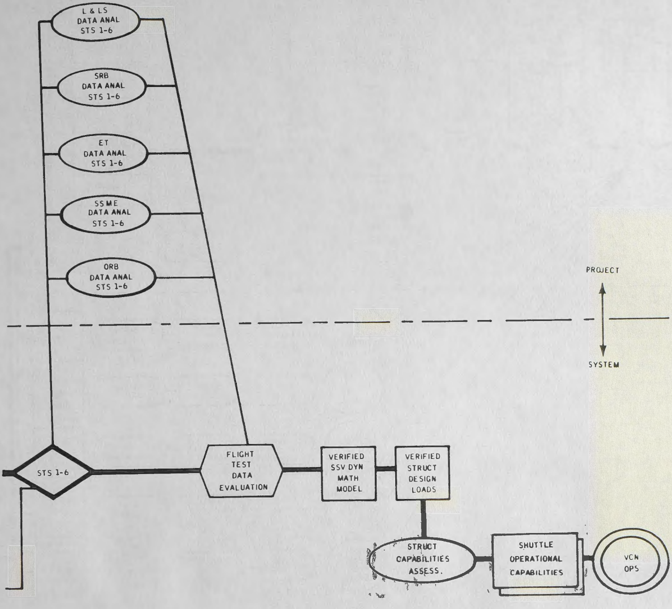
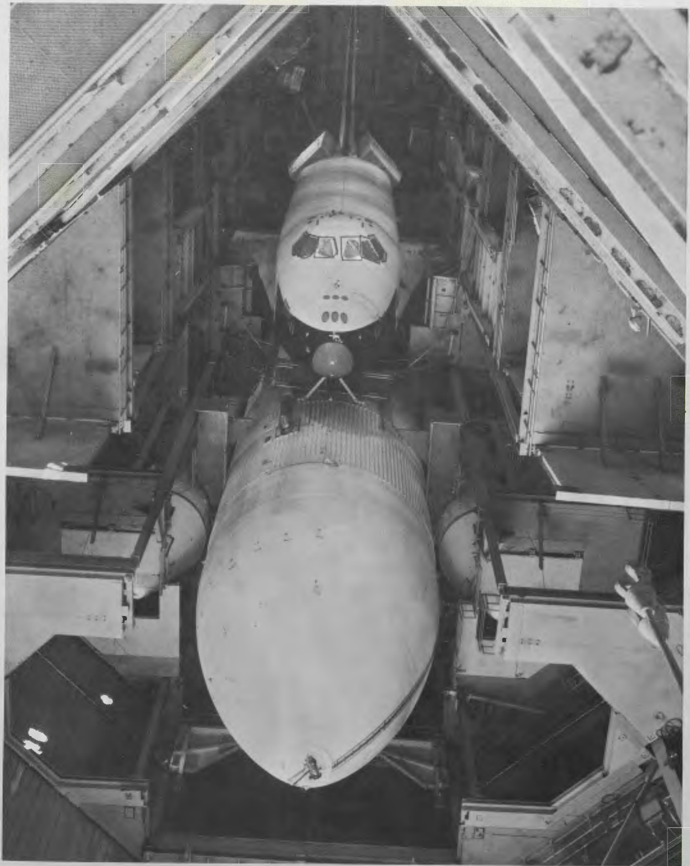


Figure 4. Page 2 of 2



Mated Lift Off Configuration in Test Stand

Figure 5.

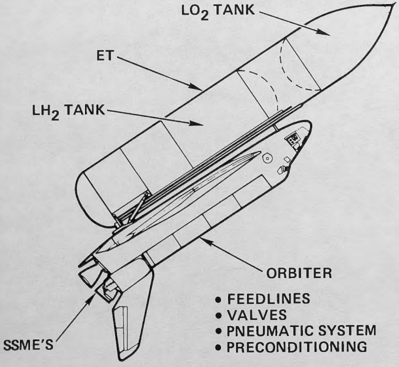


Figure 6. Main Propulsion System

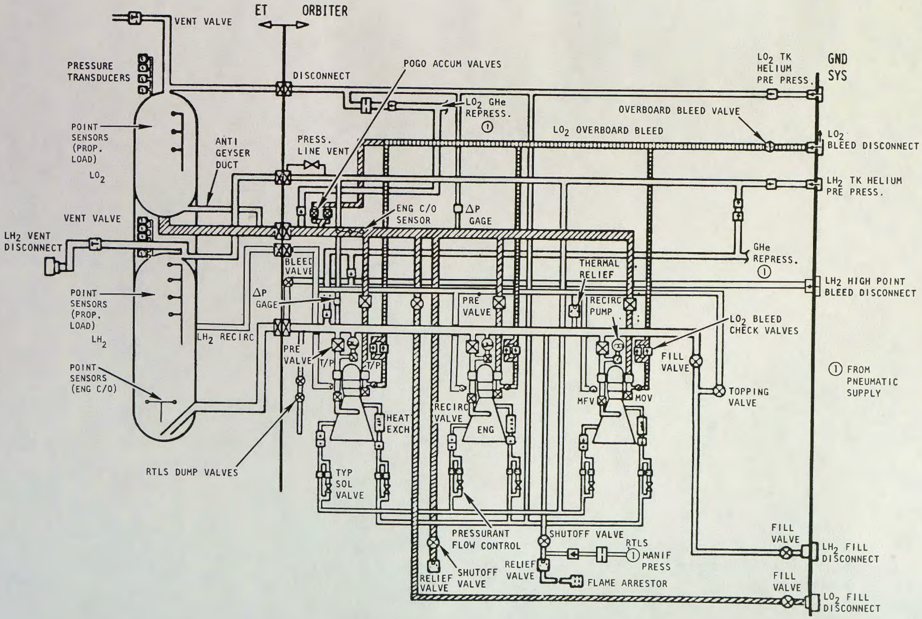


Figure 7. Main Propulsion System Schematic (Fluid)

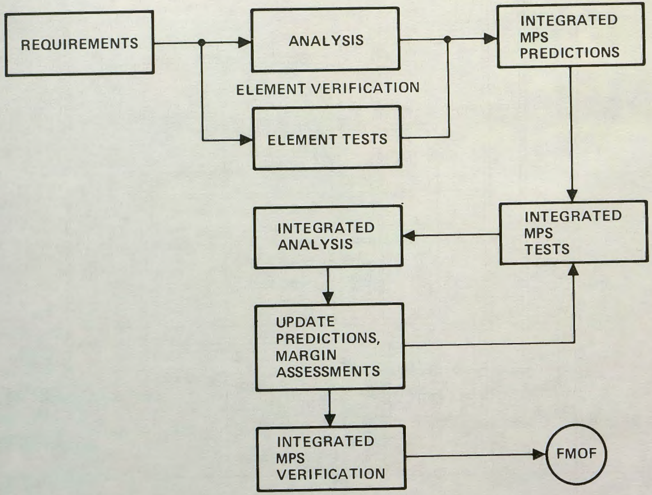


Figure 8. MPS Verification Approach

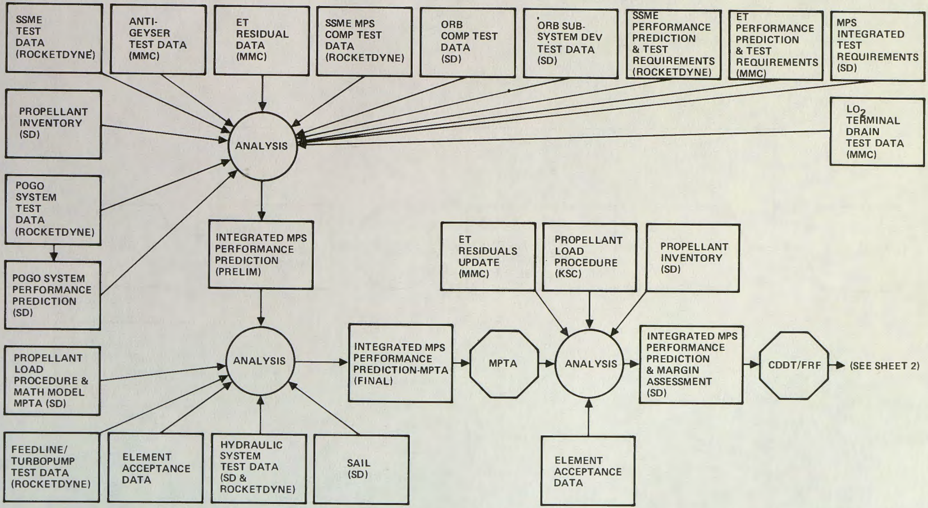


Figure 9. Integrated MPS Verification Analysis Network (Sheet 1 of 2)

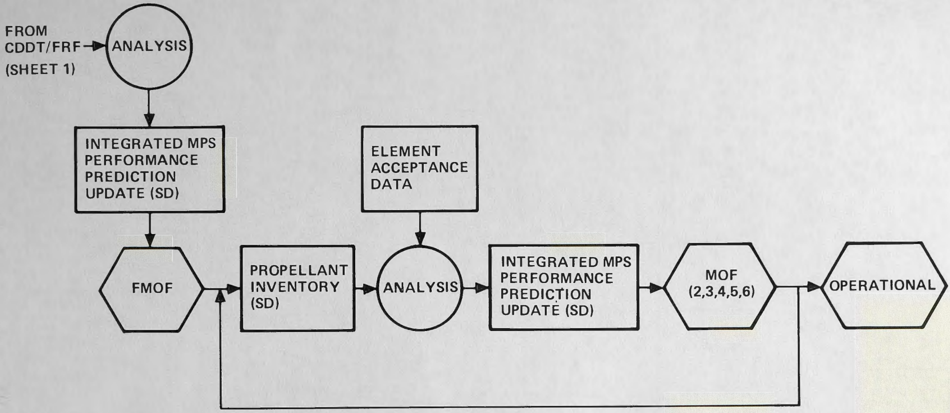
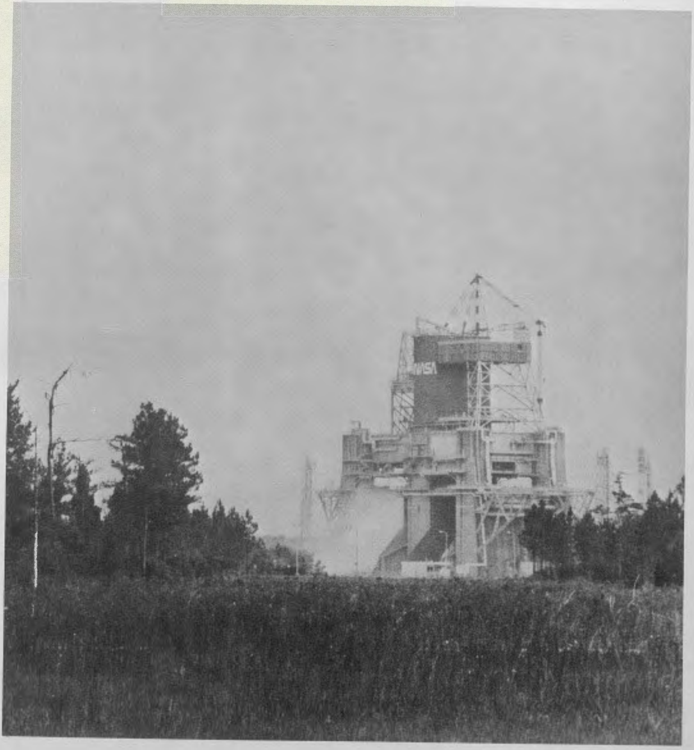


Figure 9. Integrated MPS Verification Analysis Network (Sheet 2 of 2)



MPT Static Test Firing No. 3

Figure 10.

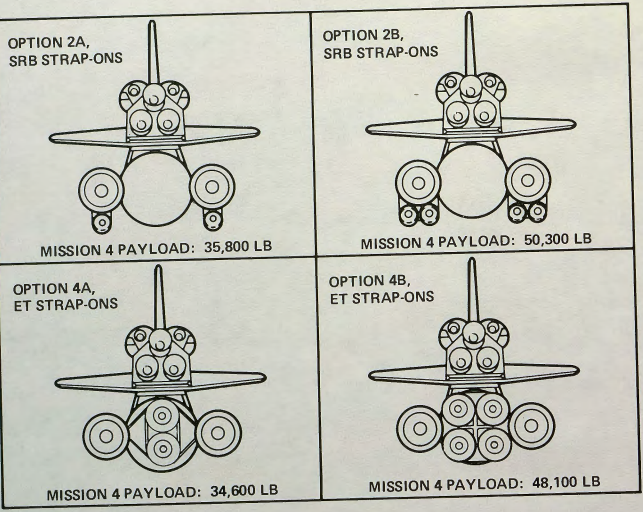
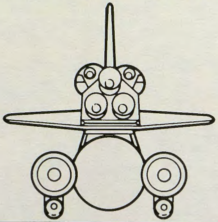


Figure 11. Thrust Augmentation Options Studied

OPTION 2C, SRB STRAP-ONS

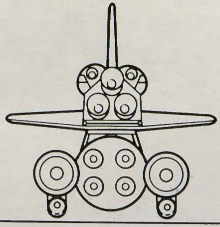


IMMEDIATE IMPLEMENTATION

CHARACTERISTICS – (PRELIMINARY)
- PAYLOAD: 35,000 LB (MISSION 4)
- STRAP-ON PROP WT: 120-160K LB
- 90-120 OD X 340-390 LONG
- MAX THRUST: 0.6-1.3M LB
- BURN TIME: 60-80 SEC
- SRM BURN RATE DELTA: 0-5% REDUCT

IOC –
- VAFB: JUN, 1984
- KSC: JUN, 1985

GROWTH OPTION, ET STRAP-ONS



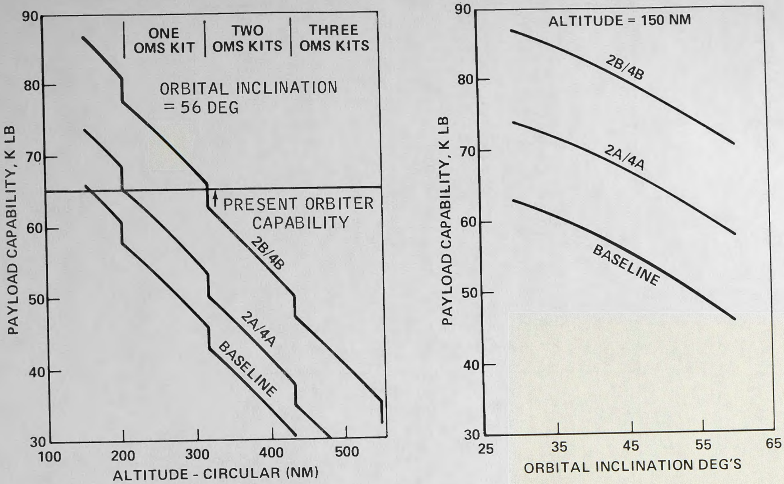
POTENTIAL FUTURE IMPLEMENTATION

CHARACTERISTICS –
- PAYLOAD: $\approx$ 50,000 LB (MISSION 4)
- OTHER: TBD

GROUND RULES –
- MIN DESIGN EFFORT TO ENSURE CAPABILITY FOR LATER IMPLEMENTATION
- DESIGN VAFB LAUNCH MOUNT FOR LIFT-OFF LOADS
- NO OTHER PROVISIONS AT PRESENT

Figure 12. Thrust Augmentation Option Decisions

ESTIMATED GROWTH OPTION DELIVERY CAPABILITY AT ETR



POTENTIAL APPLICATIONS

- HEAVIER PAYLOADS
- HIGHER INCLINDATIONS - NONPLANAR
- LARGER OMS LOADS - HIGHER ALTITUDES
- LAUNCH WINDOW YAW STEERING - FAST RENDEZVOUS

Figure 13. Potential ETR Applications for Growth Capability