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ORBIT TRANSFER ROCKET ENGINE TECHNOLOGY PROGRAM

AUTOMATED PREFLIGHT METHODS CONCEPT DEFINITION
TASK E.7

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16. Abstract

Orbit transfer engine preflight requirements were defined and a range of possible preflight methods were proposed. Critical issues and benefits were also identified for each method and technology readiness and development costs addressed.

It would be advantageous in a space based setting to minimize or entirely eliminate preflight engine checkouts requiring manual/extravehicular interaction with the hardware. Extravehicular activity not only introduces added safety risks for the astronauts, but is extremely costly.

In this study the possibility of automating these checkouts.was investigated. The minimum requirements in terms of information and processing necessary to assess the engine's integrity and readiness to perform its mission were first defined. A variety of ways of remotely obtaining that information, spanning a range of method sophistications were then generated. The sophistication of these approaches varied from a simple preliminary power up, where the engine is fired up for a short time, to the most advanced approach where the sensor and operational history data system alone indicates engine integrity. The critical issues and benefits of each of these methods were also identified, outlined, and prioritized.

The technology readiness of these automated preflight methods were then rated on a NASA Office of Exploration Scale used for comparing technology options for future mission choices. Finally estimates were made of the remaining cost to advance the technology for each method to a level where the system validation models have been demonstrated in a simulated environment.

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FOREWORD

The work reported herein was conducted by Advanced Programs and Engineering personnel of Rocketdyne, a division of Rockwell International Corporation, under Contract NAS3-23773 from December 1989 to April 1991. M. Millis, Lewis Research Center, was the NASA Project Manager. Mr. R. Pauckert was the Rocketdyne Project Manager, and T. Harmon was the Project Engineer. A. Martinez was responsible for the technical direction of the effort while C. Erickson, D. Hertzberg, K. Kramer, C. Meisl, and N. Gustafson made important technical contributions to the program. Secretarial support was provided by D. Senit.

INTRODUCTION

A space based chemical propulsion system capable of multiple starts and varied mission scenarios will require extensive preflight checkouts to assure crew safety and mission success. An automated approach for a space based system is highly desirable from the standpoint of feasibility. Performing preflight checkouts manually using modified ground-based techniques would require costly EVA and result in prohibitively high mission costs while also compromising reliability and safety.

Approaches to automating preflight readiness checkouts depend heavily on condition monitoring technology to provide the information required to assess the engine's readiness to fire. Condition monitoring sensors permit remote monitoring of critical components as the engine fires during normal operation. Based on the flight data obtained from these sensors, an assessment can be made on the condition or health of a particular component which in turn dictates the need for maintenance procedures or replacement.

OBJECTIVES

The objective of this study is to suggest and evaluate various methods of preflight readiness checkouts in the context of a space-based system. Where required, methods will incorporate advanced Integrated Control and Health Monitoring (ICHM) technologies enabling rapid and remote engine turnaround. Specific objectives of this task as defined by five separate subtasks in the statement of work (SOW) are summarized in Table 1.

SUMMARY OF ACCOMPLISHMENTS

Preflight readiness verification requirements were established for the engine. Requirements were based on previous logistics studies including the preliminary failure modes and effects analysis (Ref. 1) and the flow task analysis report. This report was generated in support of a prior NASA technology task (Ref. 2) to establish the operational flow of the engine and identify the applicable maintenance tasks for both current and advanced technologies. The operational flow tasks of interest to this study are those executed after delivery to the space station and before return to earth. Maintenance tasks were reviewed in light of the SSME

Statement of Work Objectives

- Specify OTV engine preflight requirements.
- Suggest a range of possible preflight methods.
- Identify critical issues and benefits for each method.
- Estimate technology readiness for each method.
- Estimate the remaining development cost for each method.

Table 1

Operations and Maintenance Requirements and Specifications Document (OMRSD - Ref. 3) which reflects the current inspection and checkout philosophy evolving from the Challenger incident. Thirty six preflight readiness verification requirements were identified for the engine. Requirements include 14 functional checks, 10 leak checks, 10 inspections, and 2 servicing tasks.

Several approaches for remotely performing readiness checkouts in space were outlined for each preflight requirement. The range of approaches reflect a variety of method sophistications. Three approaches for remotely obtaining data were considered - Preliminary power-up in which the engine is fired for a short time to acquire real time data, Automated component pre-cycling in which engine components are cycled in an inert gas medium to assess component integrity without hot firing the engine, and Automated static checkout in which an analysis of historical data and static checks are used to assess the engine's readiness to fire without the cycling of any components.

Where practical, alternate component designs were suggested to reduce criticality of component failure and hence delete or simplify preflight readiness requirements. This was particularly useful in the case of the Lox/H2 heat exchanger, in which a robust design was suggested to reduce the possibility of failure and eliminate the need for leak checks. Alternate designs were also suggested for the turbopump bearings and combustion/propellant systems joints.

Issues and benefits were generated for applicable preflight checkout approaches. Sensors and flight hardware, alternate component designs, and individual approaches were addressed separately. Issues and benefits were categorized into space basing, vehicle/infrastructure, and engine system impacts.

The technology readiness levels of the three preflight checkout methods were also evaluated. The scale used for comparing the methods was that used by the NASA office of exploration for evaluating options for future mission choices.

Estimates were also made for the remaining cost to advance the technology for each method to a level where the system validation models have been demonstrated in a simulated environment.

TECHNICAL DISCUSSION

SUBTASK 1 - Specification of Engine Preflight Requirements

Subtask 1 entailed the definition of the preflight readiness verification requirements for a space based engine. These requirements are the information and processing necessary to access the engine's integrity and readiness to perform its mission. The preflight requirements were generated by review and update of several completed studies. One of the primary sources was a similar study conducted under the Orbit Transfer Rocket Technology Program contract in 1987. In a subtask of the Advanced Engine Study (Ref. 4), maintenance and verification checks were identified for the space based engine.

In that effort a review of the Space Shuttle Main Engine (SSME) operations and maintenance manual was conducted with two purposes in mind: (1) to begin to outline the overall maintenance procedures for the engine, and (2) to identify technology requirements for streamlining space based operations. The original SSME document contained the requirements and specifications for the SSME at the organizational level (installed engines). Routine maintenance requirements (after each engine firing), periodic maintenance requirements (time/cycle oriented), and contingency requirements (unscheduled to isolate/rectify a condition) were covered.

It was then determined whether the individual tasks would be affected by an advanced integrated control and health monitoring (ICHM) system incorporating advanced sensors.

In order to update and expand the work completed under the Advanced Engine Study, additional documents were reviewed and integrated into the current study. These documents included:

a. Operation and Maintenance Requirements and Specifications Document (OMRSD) for processing the SSME during STS launch operations at KSC. This OMRSD reflects the current inspection and checkout philosophy evolving from the Challenger incident (Ref. 3)

b. RL10 Liquid Rocket Engine Service Manual prepared by United Technologies, Pratt and Whitney Aircraft Group (Ref. 5)

c. Preliminary Failure Modes and Effects Analysis (FMEA) for the OTVE (Ref. 1)

d. RL10 FMEA for Apollo missions (Ref. 6).

The results of this review constitute a current baseline list of preflight requirements. These redefined requirements for the engine in an operational space environment are presented in Table 2. These requirements are primarily based on Criticality 1 failure (major uncontained damage to an engine subsystem or component resulting in widespread engine damage) and Criticality 2 failure (significant contained damage to a vital engine subsystem or component sufficient to render it inoperative or its continued operation hazardous) modes identified in the OTVE FMEA.

Table 2 lists the preflight requirements to be performed between each engine start and also those requirements that are to be performed periodically at an interval to be determined as designs mature. The periodic requirements are those associated with damage, erosion, etc., that will propagate with time.

A total of thirty-six checkouts falling into four separate categories were identified. These included fourteen functional checks, ten leak checks, ten inspections, and two servicing tasks.

After a review of the available documentation, it was determined that additional information is required in order to substantiate the need for, or the possible deletion of, some of the requirements. These areas of concern are:

(a) Hazards associated with simultaneously leaking hydrogen and oxygen in a space environment; how quickly do propellants dissipate in a space environment, and what combination of leakage rates constitute a hazardous combustible mixture? Additionally, some leak test requirements may be mission dependent; i.e., because of the possibility of hydrogen and oxygen combustion, more in-depth leak tests should be performed for engine starts in close proximity to the engine docking facility, than in a free space environment.
(b) More information is needed on the dissipation characteristics of water in a space-based environment to support the engine drying requirements listed in Table 2.
(c) More information is needed on the probability of damage from debris, etc. in orbit and on the protection the vehicle affords the engine relative to encapsulation.

OTV Preflight Requirements

Functional Checks

1. Valve Actuator Check
2. Sensor Checkout/Calibration
3. Pneumatic Component Checkout
4. Operational Sequence Test (FRT)
5. Control System Redundancy Verification
6. Controller Memory Verification
7. Contoller Pressurizatiion Verification
8. HPOTP Torque Check
9. HPFTP Torque Check
10. LPOTP Torque Check
11. LPFTP Torque Check
12. Turbopump Axial Shaft Travel Check
13. *Extendible Nozzle Travel Check*
14. Igniter Operation

Servicing Tasks

1. Combustion Zone Drying
   a. Igniter Valves
   b. P_c Sensors
2. HPOTP Lox/Turbine Drive Gas Seal Pre-Start Purge

Inspections

1. Exterior of Components for Damage/Security, etc.
2. T/C Assembly for Evidence of Coolant Passage Blockage
3. HPFTP Turbine Wheel/Blades for Cracks, Fatigue, and Damage
4. HPOTP Turbine Wheel/Blades for Cracks, Fatigue, and Damage
5. LPFTP Turbine Wheel/Blades for Cracks, Fatigue, and Damage
6. LPOTP Turbine Wheel/Blades for Cracks, Fatigue, and Damage
7. HPOTP Bearings for Damage
8. T/C Assembly Injector Faceplate, Igniter, and Lox Post Tips for Erosion, *Burning, and Contamination.*
9. Gimbal Bearings and TVC Attach Points for Evidence of Bearing Seizure and Fatigue.
10. Heat Exchanger for Cracks, Evidence of Wear, and Damage

Leak Checks

1. HPOTP Primary Lox Seal
2. HPOTP Lox/Turbine Drive Gas Seal
3. Oxidizer Inlet Valve and MOV Ball Seals
4. Fuel Inlet Valve and MFV Ball Seals
5. Propellant Valves Primary Shaft Seals
6. Pneumatic Control Assembly Internal Seals
7. Heat Exchanger Coil Leak Test
8. *Heat Exchanger Coil Proof Test*
9. Thrust Chamber Assembly Outer Walls
10. Combustion and Propellant System Joints

Table 2

(d) Criticality assignments in the FMEA (Ref. 1) dated 2-22-85 should be reviewed/revised to reflect the current philosophies established after the Challenger incident. (Refer to the SSME FMEA).

This information may be acquired through quantitative modeling (i.e., item a), or by performing additional qualitative studies. Acquiring this information was beyond the scope of this task. Nevertheless, it is recommended that these issues be studied in subsequent tasks since they could impact the development and operation of the ICHM system.

Additional documentation substantiating these conclusions is presented in Appendix 1 and include:

Part A - Lists the SSME OMRSD and/or the OTVE FMEA failure mode references that were used to establish pre-flight requirements.

Part B - Defines the FMEA failure mode criticality assignments.

Part C - Comprehensive list of SSME OMRSD currently used to process the SSME/Shuttle at KSC and alternate landing sites. Entries in the column marked "OTV APPLIC - FUTURE" will be made after the engine component design becomes more firm.

Part D - Summary of RL-10 prelaunch checks extracted from the RL-10 service manual. It is assumed that these requirements are for ground launch activities and are for unmanned launch operations. This document was superficial and did not contain sufficient detail to influence the preflights methods study. The summary is provided for information only.

SUBTASK 2 - Generation of Range of Possible Preflight Methods

Introduction

The objective of Subtask 2 was to generate automated methods to accomplish the preflight checkouts identified in Subtask 1. Three sets of methods were generated, each reflecting a checkout philosophy which progressively relies on more ICHM monitored status checking of the component and system physical status, and less on component dynamic functional tests. The three levels of ICHM sophistication are reflected in the means by which the required data are remotely obtained. The methods include the following:

(1) Preliminary power-up where the engine is fired for a short time (tankhead idle and a brief transition to pump idle). This represents the lowest level of ICHM sophistication.

(2) Automated component pre-cycling where critical portions of the engine are physically cycled and monitored (such as pressurizing lines and spinning turbopumps). This represents an intermediate level of ICHM sophistication.

(3) Automated static checkout where the sensors and operational data history are sophisticated enough to indicate engine integrity and readiness to fire without the need to cycle any part of the engine. This is the ultimate goal for preflight checkouts.

Preliminary Power-up

The preliminary power-up technique assumes required information is obtained through system operation. System conditions during the preliminary power-up phase permit detection of critical failures without catastrophic results, and subsequently permit safe shutdown of the engine. However, stress and pressure related potential failures might not be detectable. The engine system modes of operation which occur as part of the preliminary power-up phase include prestart, engine start, tank head idle, and pump idle mode. A brief description of each mode is provided below.

(1) Prestart: The controller performs a self-test and checkout of the ICHM. At the end of this phase, system temperatures are checked to assure that conditions are normal for engine start. A start-enable signal is sent to the vehicle.

(2) Engine Start: The inlet valves are opened and propellants dropped to the main valves. The main fuel valve (MFV) is then opened. Hydrogen flows through the system, vaporizes, and enters the main injector. The gaseous oxidizer valve is then opened to circulate oxygen through the GOX heat exchanger and into the main injector. The igniter valves are then opened, the igniter sparks, and ignition is established in the augmented spark igniter. This initiates Tank Head Idle mode.

(3) Tank Head Idle: Operation continues chilldown to thermally condition the engine system and provide some passive regulation of mixture ratio swings via H2 to O2 heat transfer. Transition to the next phase, pump idle mode, is determined by the appropriate component and propellant feed temperatures.

(4) Pump Idle: Transition to pump idle begins as the controller opens the turbine shutoff valve. The main oxidizer valve (MOV) is ramped open approximately 40%. The oxidizer turbine bypass valve (OTBV) and the turbine bypass valve (TBV) are ramped closed 92% and 85% respectively. Closure of the turbine bypass valves increase hydrogen flow through the turbines which initiates pumping. The high pressure oxidizer pump discharge pressure rises and the gaseous oxidizer valve (GOV) is closed. Gaseous hydrogen and oxygen pass through the fuel tank check valve (FTCV), and the oxidizer tank check valve (OTCV) to the respective tanks elevating tank pressure and NPSH. The injector primes and combustion boosts the vaporization rate of the fuel in the cooling jacket providing additional power to the turbines. At the appropriate chamber pressure (approximately 8%), the controller initiates active control of mixture ratio and chamber pressure.

Advanced Design Recommendations

While determining preflight checkout methods, the possibility of deleting certain checkouts by incorporating advanced designs was considered. Advanced design features which may be available for proposed missions include hydrostatic bearings, which exhibit negligible wear, and welded joints, which reduce the overall number of leakage paths. A more complete list of advanced design recommendations is presented in Table 3. These features were not included in the OTVE preliminary design.

Advanced Design Features Recommended To Simplify Preflight Checkouts

- Welded engine system with the exception of inlet/outlet turbopump interface joints
- Robust heat exchanger design - Seamless heat exchanger design
- Robust thrust chamber design
- Hydrostatic bearings
- Addition of labyrinth seals and more durable seal materials to minimize seal wear and leakage

Table 3

Sensors

The type and projected availability of sensors had a significant impact on the preflight checkout methods which were ultimately recommended. Where applicable, both current and advanced sensors were considered in the various approaches. Current ICHM sensor requirements were defined in the concurrent Task E.6 - ICHM Definition study (Ref. 7). These current ICHM measurements identified in E.6 are presented in Table 4.

Advanced sensor availability for the Lunar and Mars missions is shown in Table 5. Advanced sensors for the engine were determined in an earlier technology task (Advanced Engine Study Task D.1/D.3, Jan. 1986 - Ref. 8). Advanced sensor availability may also impact the nature of the checkout itself. For example, in the case of turbine wheel/blade inspection, remotely obtained blade fatigue data coupled with a life prediction model and trend analysis form the basis for an assessment of turbine condition. This differs from a manual boroscopic inspection which requires disassembly and does not lend itself to simple automation.

Groundrules and Assumptions

The groundrules as specified by NASA in the contract were:

(1) Hydrogen/oxygen expander cycle
(2) Space based
(3) Man Rated
(4) Designed for 100 starts/4 hours of operation (safety factor = 4)
(5) No EVA available for preflight checks
(6) Start cycle - tankhead start (providing propellant settling and chilldown of components for thermal conditioning), pumped idle operation required for autogeneous tank pressurization
(7) Preflight Checkout Technology development to readiness level 6

Current Technology
ICHM Measurements

- Static Pressure
- Static Temperature
- Flow (Turbine flowmeter)
- Speed
- Modulating Valve Displacement (continuous)
- Shutoff Valve Displacement (on/off)
- Acceleration

Table 4

Advanced Instrumentation Availability

Advanced Sensor/Hardware	Availability* Technology Level 6 by 1996	Availability* Technology Level 4 by 1996
Ultrasonic Mass Flowmeter	X	
Fiberoptic Deflectometer	X	
Optical Leak Detection System	X	
Exo-Electron Fatigue Detector		X
Isotope Wear Detector	X	
Plume Spectrometer	X	
Ferromagnetic Torque Meter	X	
Automated Visual Inspection	X	

* Based on current and projected funding levels

Table 5

Additional groundrules adopted which were not specifically stated in the contract were:

(1) The following launch scenarios were applicable:
   (a) Space station
   (b) Lunar surface
   (c) Martian surface
   (d) Planetary orbit - selected as most stringent

(2) Engine system assumptions:
   (a) Valves are electrically actuated with redundant motors
   (b) Pneumatic system consists of LOX pump intermediate seal purge and injector shutdown purge

The OTV preliminary design incorporated an intermediate seal purge on the MK-49 Lox turbopump. The purpose of this purge is to assure that no intermixing of the GH_2 and Lox occur, thus preventing potentially dangerous combustible mixtures from forming. The injector shutdown purge is performed to expel any residual propellants from the injector and combustion chamber. This process also is to prevent the accumulation of a potentially explosive mixture. In a space based setting, the residual propellants would most likely diffuse rapidly to the surrounding vacuum of space. A detailed design and mass transfer analysis need to be conducted to verify this preliminary conclusion.

Methods

The approach taken in subtask 2 was to generate a range of preflight methods expanding the NASA suggested approaches into a detailed matrix to satisfy all preflight requirements. Based on the range of approaches, a preliminary recommendation of a particular approach for performing each check was made. Several advanced design concepts were also identified and are recommended to possibly reduce the number of checks. Sensors required for the preflight checkout approaches were identified and a preliminary assessment was made on the availability of sensors. A detailed table of the approaches developed in this subtask is presented in Appendix 2. The table in this appendix includes the approach for each of the three methods as applied to each preflight check required, the current and advanced hardware if needed, the recommended approach, and comments.

A condensed version of Appendix 2 is provided in Table 6. This summary presents the preflight checks required and the recommended approach for accomplishing them.

A brief overview of the individual preflight checks will now be provided.

Functional Checks

Of the 14 checks specified, eight are currently automated and in use on operational engine systems and require little additional technology for implementation. Most are static checks which are driven by software. Precycling of valve actuators is necessary to assure system integrity. These engine valves are cycled before the upstream propellant shutoff valves at the exit of the supply tanks have been opened. Therefore, no propellant flow is required for this functional check.

Torque checks for all pumps can be performed in a similar manner using the automated component pre-cycling approach. Because of the extremely small breakaway torque values, this check may require the development of highly accurate sensors and special checkout procedures.

The turbopump axial shaft travel check may be substituted with other means of determining bearing health such as data from the bearing vibrational spectrum to indicate wear. There is also a possibility of deleting this check based on the use of hydrostatic bearings.

The extendible nozzle travel check will rely on data from any nozzle deployment/retraction during a previous mission. This is to avoid any additional cycling which may cause undue wear to the actuator mechanism.

Leak checks

Turbopump and valve seal leakage can be monitored in flight with pressure transducers at the seal drain cavities. Leakage past valve ball seals can be monitored with external skin temperature sensors located just downstream of the ball. Valve shaft seal leakage can be monitored through the port just beyond the dynamic shaft seals.

Preflight Checks and Recommended Methods

Functional Checks	Method*
1. Valve Actuator Check	B
2. Sensor Checkout/Calibration	C
3. Pneumatic Component Checkout	C
4. Operational Sequence Test (FRT)	B
5. Control System Redundancy Verification	C
6. Controller Memory Verification	C
7. Controller Pressurization Verification	C
8. HPOTP Torque Check	B
9. HPFTP Torque Check	B
10. LPOTP Torque Check	B
11. LPFTP Torque Check	B
12. Turbopump Axial Shaft Travel Check	C
13. Extendible Nozzle Travel Check	B
14. Igniter Operation	B
Leak Checks	**Method***
1. HPOTP Primary Lox Seal	C
2. HPOTP Lox/Turbine Drive Gas Seal	C
3. Oxidizer Inlet Valve and MOV Ball Seals	C
4. Fuel Inlet Valve and MFV Ball Seals	C
5. Propellant Valves Primary Shaft Seals	C
6. Pneumatic Control Assembly Internal Seals	C
7. Heat Exchanger Coil Leak Test	B
8. Heat Exchanger Coil Proof Test	B
9. Thrust Chamber Assembly Outer Walls	C
10. Combustion and Propellant System Joints	C

* A = Preliminary power-up
B = Component Precycling
C = Automatic Static Checkout
(Detailed description of approaches in Appendix 2)

Table 6

Preflight Checks and Recommended Methods (continued)

Inspections	Method*
1. Exterior of Components for Damage/Security, etc.	C
2. T/C Assembly for Evidence of Coolant Passage Blockage	C
3. HPFTP Turbine Wheel/Blades for Cracks, Fatigue and Damage	C
4. HPOTP Turbine Wheel/Blades for Cracks, Fatigue and Damage	C
5. LPFTP Turbine Wheel/Blades for Cracks, Fatigue and Damage	C
6. LPOTP Turbine Wheel/Blades for Cracks, Fatigue and Damage	C
7. HPOTP Bearings for Damage	C
8. T/C Assembly Injector Faceplate, Igniter, and Lox Post Tips for Erosion, Burning, and Contamination	C
9. Gimbal Bearings and TVC Attach Points for Evidence of Bearing Seizure and Fatigue	B
10. Heat Exchanger for Cracks, Evidence of Wear, and Damage	C

Servicing Tasks	Method*
1. Combustion Zone Drying	B
a. Igniter Valves	
b. P_C Sensors	
2. HPOTP Lox/Turbine Drive Gas Seal Pre-Start Purge	B

* A = Preliminary power-up
B = Component Precycling
C = Automatic Static Checkout
(Detailed description of approaches in Appendix 2)

Table 6 (continued)

The heat exchanger is difficult to leak check since small internal leakage is difficult to detect remotely. Small undetectable leaks may develop into significantly larger leaks during full power operation; actual heat exchanger operating conditions may be difficult to simulate. A highly robust heat exchanger design is recommended as a means of deleting this check.

Hot gas system leaks may be difficult to detect since no throat plug is available. Remote in-flight leak detection techniques present a viable option. Some leakage paths could be eliminated by welding combustion system joints.

Inspections

Remote high resolution visual techniques and thermally sensitive surface coatings (for the detection of hot spots) is a viable solution for exterior inspections. However, these techniques may be difficult to implement inside of the main combustion chamber because of inaccessibility and incompatibility of the coating with combustion products.

Turbine rotating element inspection can be accomplished by monitoring blade/disc fatigue and bearing wear. The blade/disc fatigue can be inferred from historical thermal data provided by optical pyrometers. Damage and fatigue is a function of both thermal transients and extended exposure to elevated temperature while under dynamic stress. Wear of the roller element bearings featured in the OTVE preliminary design would be monitored by isotopic wear detectors and fiberoptic deflectometers. Exhaust plume analysis may also be used to detect degradation.

Condition of the gimbal bearing and Thrust Vector Control (TVC) attach points can be deleted by using robust gimbal bearing design.

Servicing tasks

Drying of igniter and Pc sensors may not be required in a vacuum, but if needed, can be accomplished with an inert gas purge.

SUBTASK 3 - Issues and Benefits

The objective of Subtask 3 was to identify the issues and benefits associated with the range of automated preflight checkout methods developed in subtask 2. This task served the purpose of identifying technology areas and potential approaches for automating preflight checkouts, while providing a basis for more detailed preflight method definition studies.

The approach taken is illustrated in Figure 1. Each preflight checkout method was viewed as a composite of (1) the general approach and methodology of each suggested method, (2) the sensors which provide the required data, and (3) any alternate component designs considered to simplify or eliminate that particular preflight requirement. By viewing preflight checkouts in this manner, issues and benefits of each suggested method for satisfying preflight requirements were thoroughly identified.

As described above, three general approaches were considered in satisfying each preflight requirement. These approaches included preliminary power up, automated component precycling, and automated static checkout. Issues and benefits relating to each of these approaches were identified in a general sense as well as specifically in the context of the preflight requirements they satisfy. Issues and benefits were also identified for each sensor considered for preflight checkouts and for any alternate design recommendation where applicable. Where feasible, issues were categorized into space basing issues, vehicle / infrastructure issues, and system issues.

The results of subtask 3 are contained in Appendix 3 where a complete set of issues and benefits are presented. Part A of Appendix 3 identifies general issues and benefits for each of the three approaches listed above, Part B considers the range of methods suggested for satisfying each preflight requirement. Each entry in part B contains references to other applicable issues and benefits, specifically, issues relating to the general approach used (i.e., preliminary power up, component precycling, or static check), sensors and hardware considered for that particular method, and related alternate design recommendations where applicable. Preflight requirements that would be impacted by alternate design recommendations include heat exchanger leak checks and inspections, turbopump bearing checkouts, and hot gas system checkouts. ICHM sensor/hardware issues are identified in part C, and alternate design issues are discussed in part D of Appendix 3.

Issues and Benefits - Approach

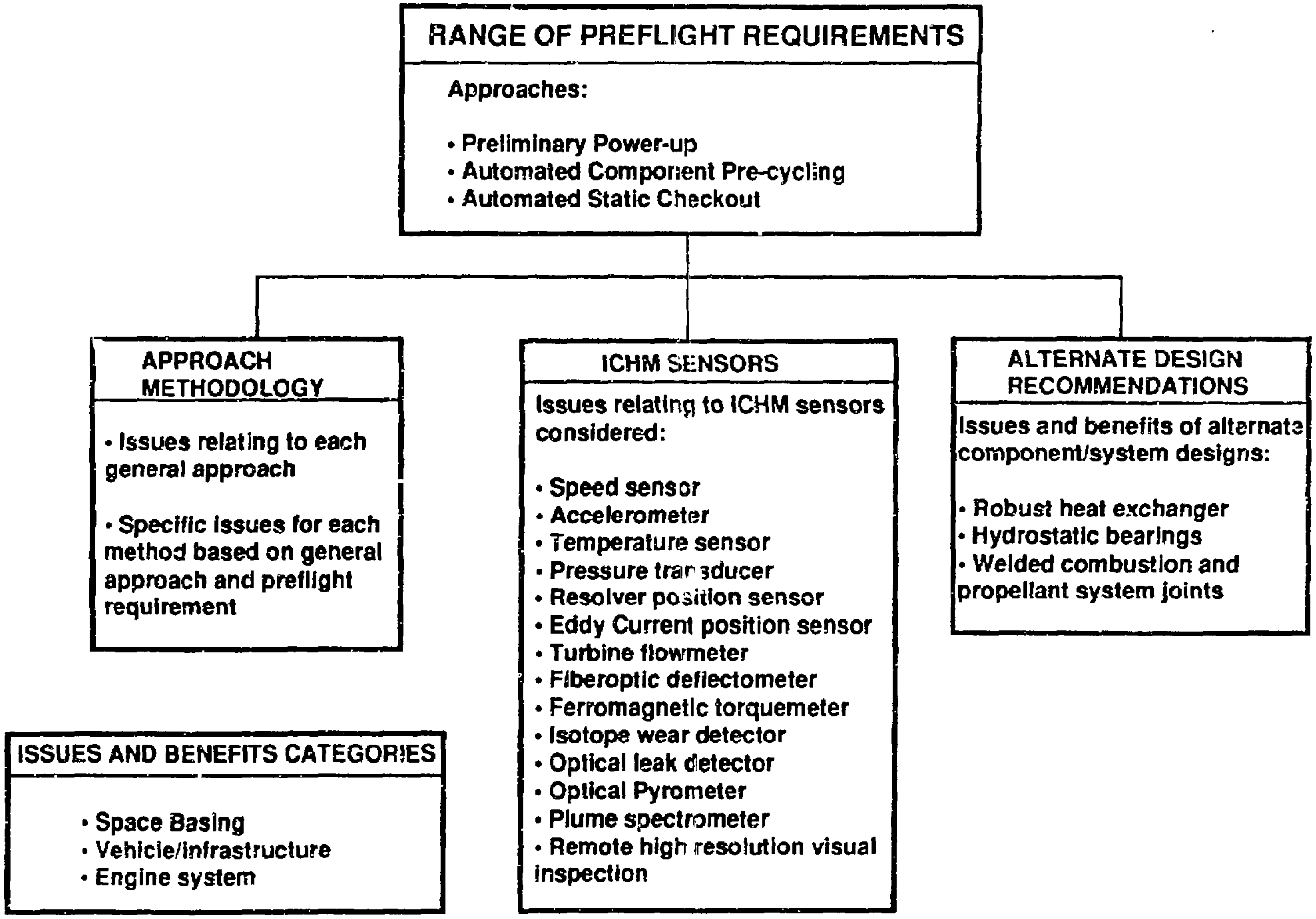


Figure 1

The scope of the methods presently used for satisfying preflight requirements will need to change as a result of the advanced ICHM sensors being considered. This applies particularly to visual inspections and leak checks - two of the most commonly practiced means of determining flight readiness - which would not be feasible in space using conventional ground based methods. Flight readiness assessments made on the basis of an operational history data base seem to be the simplest and safest approach, yet critical issues still need to be resolved. Of particular importance is a means to adequately monitor degradation of certain components during idle periods in space.

The issues identified for each automated preflight method reflected the current state of ICHM technology based on inputs provided by Rocketdyne experts. As ICHM development continues, some issues will be resolved while others will surface. Based on the evolving nature of the ICHM system and that of chemical transfer propulsion in general, it is recommended that this task be revisited as the ICHM definition firms.

SUBTASK 4 - Technology Readiness Assessment

In subtask 4, the technology readiness levels of the three preflight checkout methods defined in subtask 2 were evaluated. These are the preliminary power-up, automated component precycling, and automatic static checkout methods. Appendix 4 lists the 36 individual checkouts identified in subtask 1 to be accomplished by these methods for a successful preflight complete engine checkout. Appendix 4 also lists the sensors required for each of the three methods to complete these tests. Although the methods are fundamentally different, in many cases they use the same means to evaluate engine conditions. This table also gives the technology readiness of each of the sensors, allowing easy determination of overall method technology readiness as a sum of component readiness. The sensor readiness levels for the first six sensors were obtained from previous ICHM studies. Technology readiness rationales for the remaining seven sensors were established in conjunction with current E.6 efforts. A summary of the type and number of sensors used for each of the three methods is provided in Table 7.

Appendix 4 includes many checkout tasks from subtask 1 for which sensors were not required or are not applicable. Of those, the following checkout tasks do not require sensors: 1.2, 1.5, 1.6, 1.14, 4.1 and 4.2.

For steps 3.3, 3.4, 3.5, and 3.6, the turbine wheel and blade checks, there is no way at present to satisfactorily determine wear or damage using the automated component precycling method. In this case either the statistical techniques of the automated static checkout, application of a low life limit, or a preliminary power-up would have to be used to determine the turbine readiness.

It should be noted that components other than sensors needed for these methods are not included in Appendix 4. Among them are the engine controller, automation and control software, and a pressurized inert gas system for the precycling approach. These components, although integral parts of the preflight methods, are extensions of current, proven elements assumed to already exist in the engine system. They will, nevertheless, require significant development to incorporate the specific preflight functions and will be included in the overall method readiness assessment.

Required Sensors for Preflight Engine Checkout Methods

Method	Accelerometer (7)	Temperature Sensor (7)	Pressure Transducer (4)	Resolver Position Sensor (4)	Eddy Current Position Sensor (5)	Fuel Turbine Flowmeter (7)	Ferromagnetic Torquemeter (5)	Isotope Wear Detector (4)	Optical Leak Detector (4)	Optical Pyrometer (5)	Plume Spectrometer (4)	Remote High Resolution Visual (4)	Fiberoptic Deflectometer (5)	Total
	Number Of Sensors Needed													
Preliminary Power Up	1	6	4	3	8	0	4	2	2	4	1	1	2	38
Automated Component Precycling	1	3	6	3	8	1	4	2	2	0	0	1	1	32
Automatic Static Checkout	1	6	4	3	8	0	4	2	2	4	1	1	2	38

(Technology Readiness Level) — Type Of Sensor

Table 7

Table 8 gives three indexes to show the level of technology readiness for each of the methods. The average readiness level of the sensors for each method along with the minimum level of sensor readiness is shown. The overall system readiness for each method is also given with the following rationales:

Preliminary Power-up: Level 5. There are many procedures perfo med to date which demonstrate elements of this method. Current engines such as the SSME and RS-27 are test fired before vehicle installation to check engine operation and performance against nominal values. The SSME block two controller performs a similar checkout of all systems without starting the engine before each firing. The J-2 was also fired, shut down and then fired again in an environment similar to that of a space based engine. In addition, the proposed advanced sensors have been demonstrated in ground tests. Together with component refinement, the efforts remaining are systems integration and validation.

Automated Component Precycling: Level 4. As with the previous method, all sensors have been ground tested in some form, but require varying degrees of further development. Evaluating engine readiness using cold flow tests is presently performed on components in preassembly ground tests only. This method would require the design of a substantially larger pressurized gas system with accompanying valves, engine ports and control system plus the design of a shaft drive mechanism.

Automatic Static Checkout: Level 4. This method is presently performed on most engines using available sensors; the only difference being the checkout is not done on board the vehicle. Measurements are remotely checked against the family of data for that engine type, and when possible against that engine's own previous data. Automating and moving these functions to the controller and further developing the designated sensors are efforts yet required to implement this method.

Table 8. Method Readiness Assessment

	Average Sensor Readiness	Minimum Sensor Readiness	Overall System Readiness
Preliminary Power Up	5.0	4	5
Automated Component Pre-cycling	4.9	4	4
Automatic Static Checkout	5.0	4	4

SUBTASK 5 - Remaining Development Cost for Automated Preflight Checkout Methods

This section describes the remaining development cost for each of the three preflight checkout categories; i.e., (1) Preliminary power-up (engine fired for short time), (2) Automated pre-cycling (cycling certain individual engine components without firing the engine), and (3) Automated static checkout (without cycling or hot firing engine). "Remaining" costs are understood to cover those costs which are required to bring the sensors and associated computer hardware and software to Technology Readiness Level 6, and to develop and demonstrate the entire automated preflight checkout process and system in a test bed engine (AETB). Activities which lead to a space flight ready system (Technology Readiness Level 7), i.e., qualification and reliability demonstration of the integrated automated preflight checkout system are excluded from the development cost reported in this section. Technical Readiness Levels definitions are listed in Table 9.

Groundrules and Assumptions

For definition purposes, "preflight checkout" was defined as that part of a space-based mission timeline which encompasses both engine preflight condition and engine postflight condition assessment. The mission time difference between postflight and preflight may be short, several days, or long, a year or more. Both checkout conditions will draw heavily on data accumulated by the ICHM during the actual flight phase. These data are assumed to be stored and processed by a ground-based maintenance data base. Table 10 lists additional operational requirements above those mentioned in Subtask 2 which implicitly affect the automated preflight checkout method development program and cost. Table 11 lists all other groundrules and assumptions used in establishing the cost estimates.

Technology Readiness Levels: Definition	
Level 7	System validation model demonstrated in space; system ready for space-based applications
Level 6	System validation model demonstrated in simulated environment; test of an equivalent of the final system configuration
Level 5	Component and/or breadboard demonstrated in relevant environment
Level 4	Component and/or breadboard demonstrated in laboratory
Level 3	Analytical and experimental proof-of-concept for critical function and/or characteristic; conceptual design test
Level 2	Technology concept/application formulated; conceptual design drafted
Level 1	Basic principles observed and reported

Table 9

Important Operational Requirements

- Fail operational/fail safe
- High reliability
- Service free life for 100 starts and four hours
- Entire engine is Orbital Replacement Unit (ORU), except: sensors can be replaced at space base by EVA or robotic
- Extendable nozzle
- 10:1 to 20:1 continuously throttleable

Table 10

Costing Groundrules and Assumptions

- Development program covers all phases of automated preflight checkout from advanced sensor development to system validation in terrestrial simulation of actual flight environment in advanced expander test bed (AETB).
- Development program includes the cost of a comprehensive maintenance data base, though this data base will also be required for the flight parameter data analysis.
- Already spent technology acquisition costs for sensors and software not considered (relatively small sunk costs).
- All costs in 1991 constant dollars.
- Sensor, software and computer costs are incremental above those reported in Task E.6 for a minimal ICHM system ($46M).
- All costs are Rough Order of Magnitude (ROM), based on analogies, parametrics and expert information, not on detailed program schedules and manpower loadings.

Table 11

Approach

There are many alternative preflight checkout development programs possible since three candidate checkout methods have been identified, for 36 measurement parameters with several sensor alternatives of different technology readiness levels. In order to reduce this large number of possible development programs to a manageable size, the following approach was taken, illustrated in Figure 2. Two engine design alternatives were postulated:

(1) An advanced engine is optimized for space based operations and as many design precautions as possible have been taken to minimize the necessary amount of preflight condition monitoring. These include, e.g., hydrostatic bearings on both turbopumps, an external tubular, seamless, weldless heat exchanger and welded engine component interfaces. This approach assumes a design philosophy which is analogous to that of the ALS booster engine concept, i.e., optimization of the engine design with respect to operability with performance as a close but secondary design criterion. It was further assumed that two approaches are feasible: one maximizing the use of current state-of-the-art sensors, the second one maximizing the use of advanced sensors. Current sensors may be somewhat limited in their attributes such as life expectancy, drift characteristics, reliability, repeatability, measurement directness, etc. Advanced sensors will have improved such attributes. In addition, non-intrusiveness and new direct measurement capabilities, as described in the previous section of this report and in the appendices, will be available.

(2) The engine is not optimized for space base operations, but rather a modification of a ground based engine (such as an RL-10 derivative). It may have features like ball or roller bearings, a heat exchanger with welds in the coils, and flanged engine component interfaces. This design approach necessitates a maximum amount of preflight checkout operations. As in Alternative (1), it was also assumed that either a maximum number of current sensors, or a maximum number of advanced sensors can be used. In this design approach, the engine will need some modifications to accommodate the turbopump spin-up for preflight torque measurement, and for checking turbopump seals with inert gas.

Development Program as a Function of Engine Design Approach

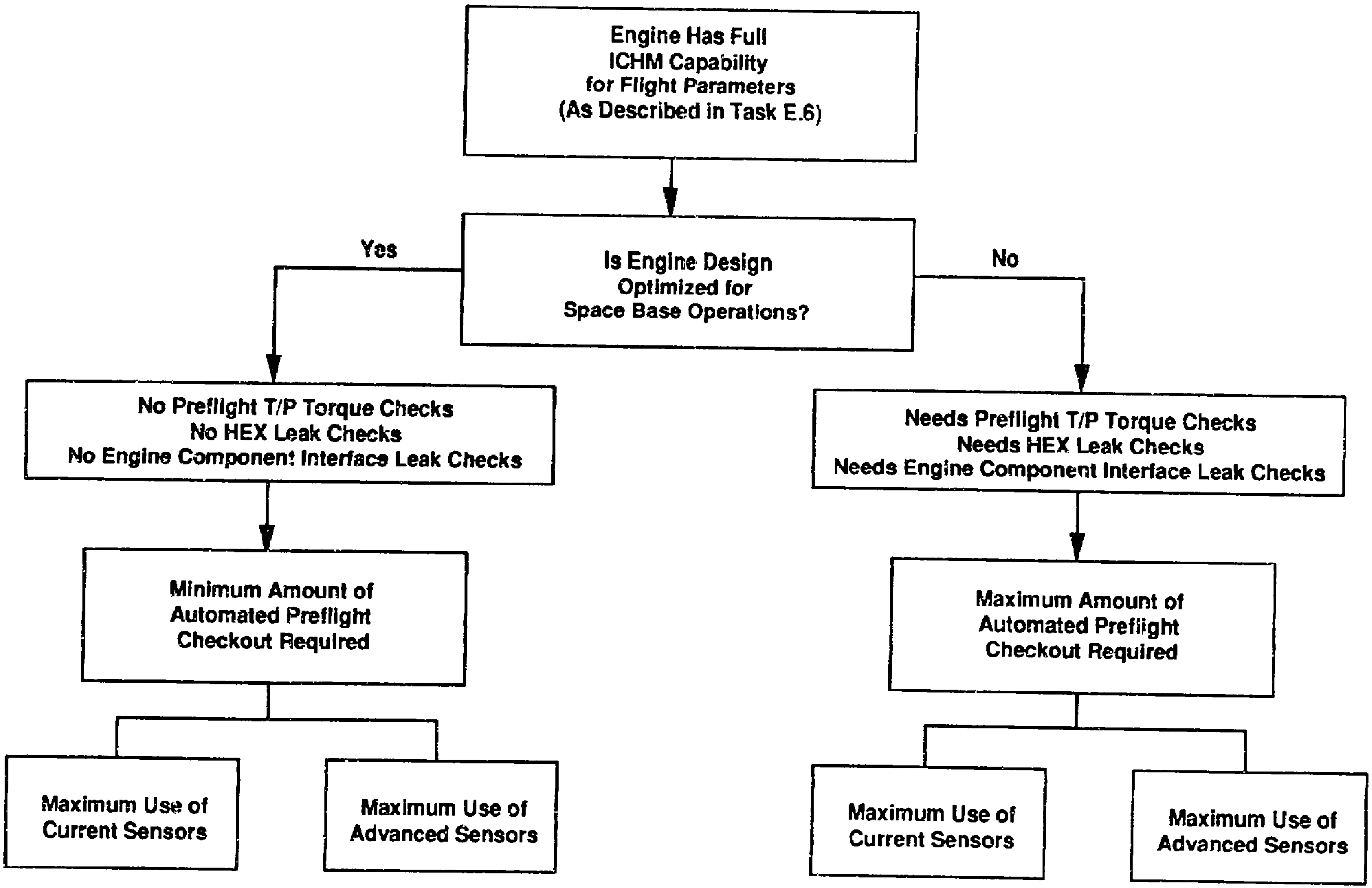


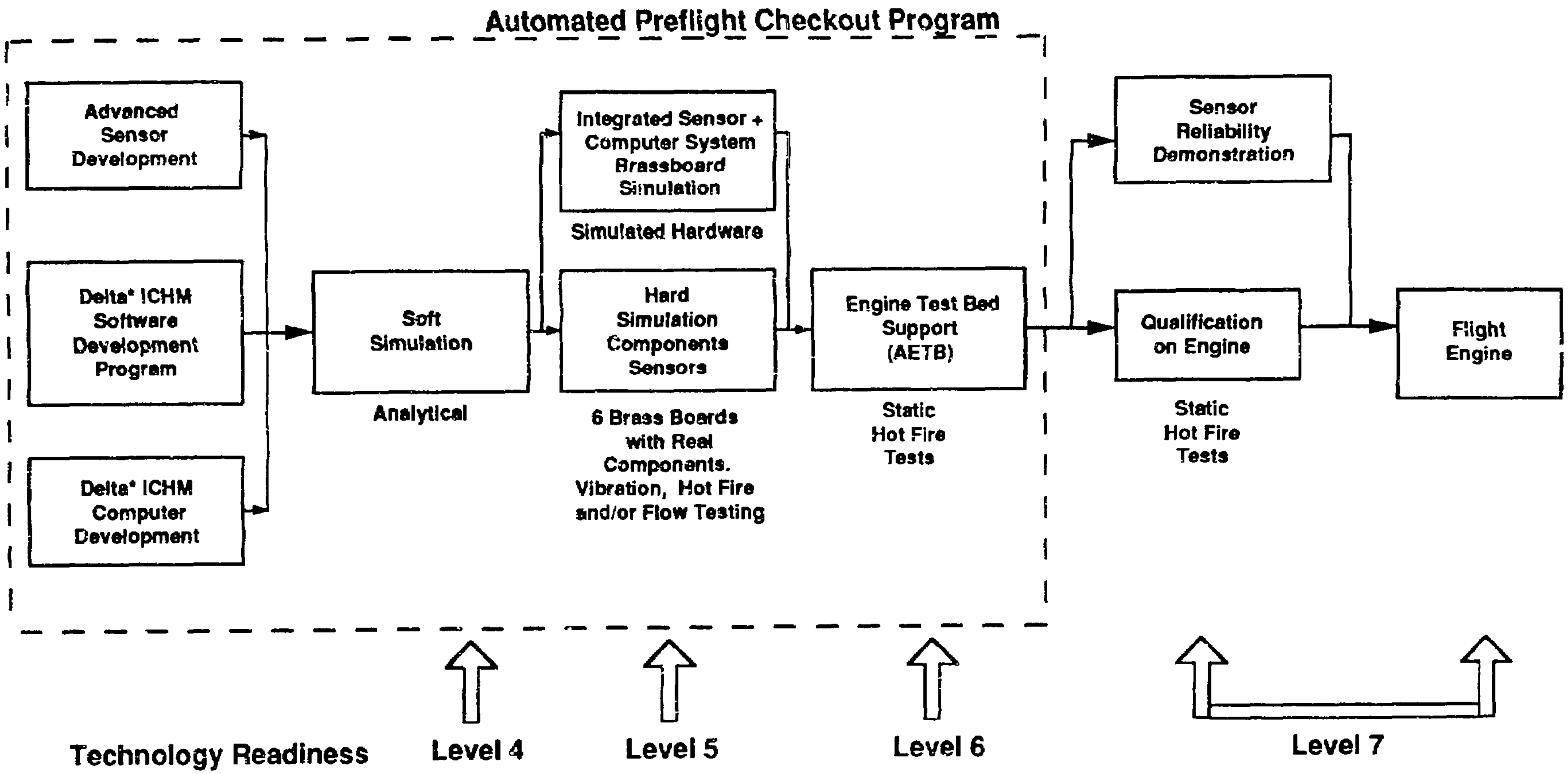
Figure 2

Figure 3 presents the "building blocks" of a generic development program for the automated preflight checkout methods. The development cost of each building block was determined. For the case in which advanced sensors are used, the program starts with sensor development to advance the sensor technologies to readiness level 6, system validation model demonstrated in simulated environment, i.e., one level before validation in space. Parallel with the sensor technology, the computer hardware and software has to be developed. The computer hardware includes memory and processors in addition to those identified for flight parameter measurements in Task E.6. The software includes the processing logic and algorithms for the preflight checkout sensors, and a (presumably ground based) centralized maintenance data base for engine history information. It will accumulate all flight, preflight and postflight data, and will be used for trend analysis and statistical process control techniques as the basis for maintenance actions. The software costs were determined as those in addition to Task E.6 software costs. The cost estimates of Task E.6 did not include development of a centralized maintenance data base.

Sensors and software have to be integrated into a preflight checkout system and "tested" in an engine. This can be best accomplished first in a "Soft Simulation" (i.e., analytical) task. In this task all engine parameters and sensor parameters will be simulated by time dependent functions and algorithms. This could be performed with support of Rocketdyne's transient engine performance model which encompasses analytical representation of engine hardware. Engine component and sensor failures can be introduced into a Monte Carlo-type soft simulation in order to understand the time and functional interdependencies of the sensor/software/engine component system.

The next set of activities, shown in parallel in Figure 3, are "Hard Simulation" and "Integrated Sensor/Computer System Brassboard Simulation." The Hard Simulation of engine components and preflight checkout sensors involves instrumenting real engine components with real sensors required for preflight checkout, and testing the engine components by flow testing (turbopumps, valves, pneumatic subsystem) or hot firing (main combustion chamber with nozzle, gimbal/TVC). Vibration testing (shaker table) may also be required. The engine components should be of flight configuration, but need not be the same as those for an OTVE or STVE. These component and sensor tests will be performed using six separate component brass boards and will establish the viability of the sensors in an engine component environment.

Development Program Logic for Automated Preflight Checkout



* "Delta" means additional development over that discussed in Task E.6 for the ICHM

Figure 3

The next task, "Integrated Sensor/Computer System Brassboard Simulation" includes real sensors and processors, prototype software and a suitable existing computer platform. The engine components will be simulated by digital or analog signals driving the sensors or processors. This simulation will address systems aspects of the automated preflight checkout method, sensor time behavior, real processor characteristics, data base functioning, etc.

The final task of the development program consists of instrumenting an engine with sensors, integrating all preflight checkout sensors, software and computer with the engine and flight ICHM system, and statically hotfiring the engine (e.g. the Advanced Expander Test Bed [AETB]). Successful completion of this task will establish the system validation in simulated (i.e. ground) environment. For this task, only that cost was estimated which is due to contractor instrumentation, software and systems engineering support, while engine testing costs (both labor, hardware and propellants) are assumed to be government furnished.

Sensor reliability demonstration and qualification of the engine/sensor/ computer/software system are considered to be outside technology level 6 and constitute necessary tasks for advancing to level 7. The costs of these tasks were, therefore, not determined.

Figure 4 is a generic program schedule for the preflight checkout method tasks discussed above, to establish the timeframe of activities. Development costs were based on this schedule. The schedule (4 years to first AETB test) is consistent with a reasonably paced development program and would allow time for integration of the automated preflight checkout system with an engine ready for an Initial Operating Capability (IOC) near the end of the decade.

Development Program Cost Evaluation

After dividing the development program into 7 tasks, the cost of each task was determined separately, based on parametrics, analysis, modification of Task E.6 costs and some preliminary manpower loading estimates.

Generic Development Schedule for Automated Preflight Checkout Program

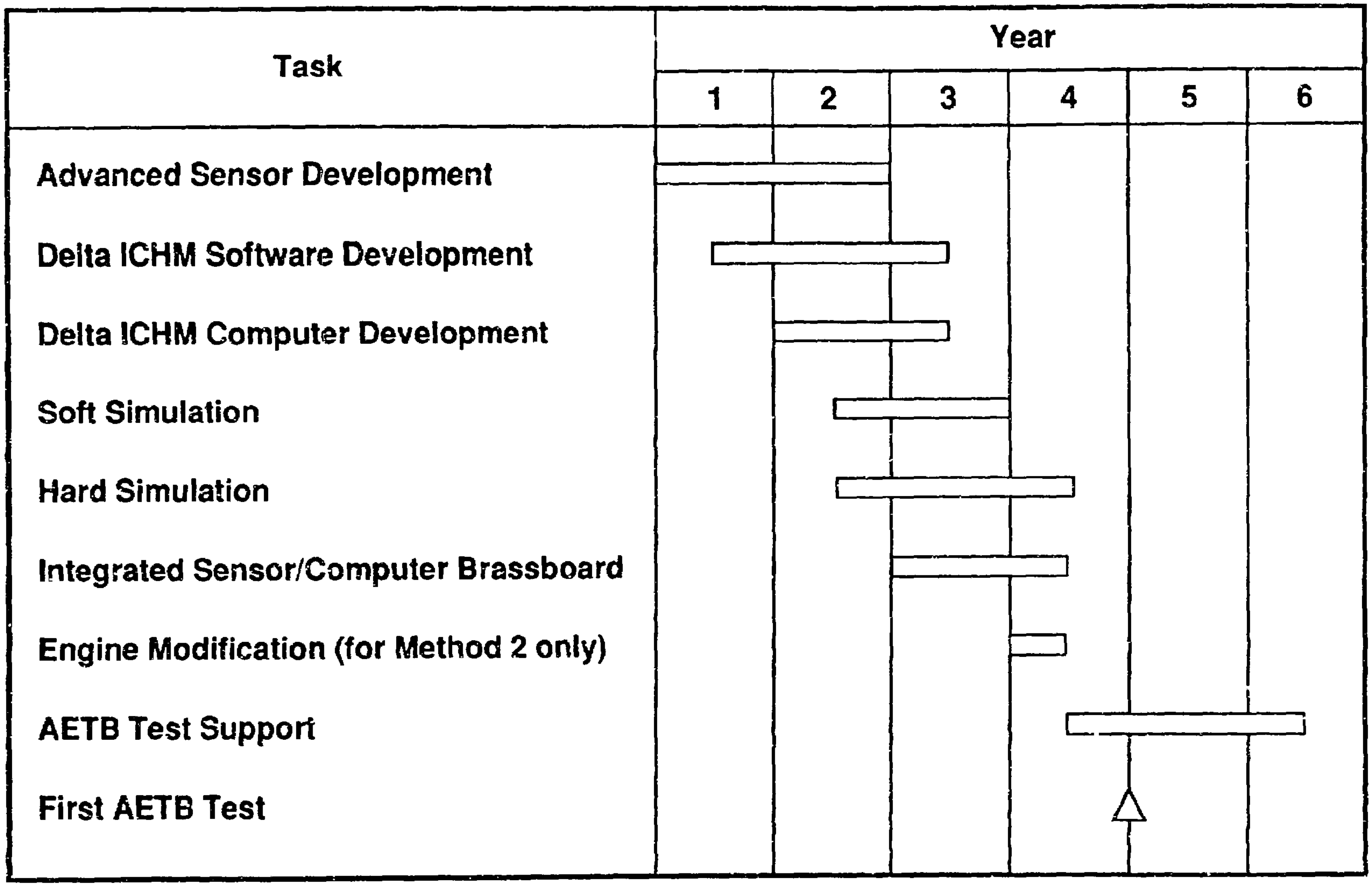


Figure 4

The logic for sensor development costs is as follows: Current technology ICHM sensors (see Table 4) need a minimum of development, and a nominal cost of $0.5M was assumed for the sum of all sensors. This was based on the cost estimate provided in Task E.6. Advanced sensors (see Appendix 4) currently at a technology level of 4 were estimated to require $1M for each type to bring them to level 6. Sensors currently at level 5 were estimated to require $0.5M for each type to bring them to level 6. These approximate, averaged costs were based on extensive discussions with instrumentation experts.

The development rationales for the other tasks shown in Figure 2, plus required engine modifications for Category 2 (component precycling), are listed in Table 12. The costs of the individual development tasks are summarized in Table 13.

Development Program Costs for Each Preflight Checkout Method

As discussed previously, the preflight development costs were determined for two alternatives: (1) an advanced design engine optimized for space based operations, and (2) an engine with minimum modifications to an existing ground based engine.

(1) Engine Optimized for Space Basing

For this alternative, the design assumptions shown in Table 3 are presumed to be incorporated into the engine. The following engine preflight checkout requirements can be eliminated (see also Table 2):

Development Cost Estimate

Task	Task Cost Elements	Cost (1991M$)	Rationale
1. Sensor Development	• Current state-of-the-art sensors	0.5	Adaptation of existing sensor suite, see Task E.6. Sum of advanced sensor development costs for sensors shown in Appendix 4, using rule described in text.
	• Advanced state-of-the-art sensors	8.0	
2. Delta Software Development	• Maintenance Data Base		
	• Space Base Optimized Engine Design	3.5	3000 Source Line of Code (SLOC) (average of 17 military ground and mobile data bases, non-ADA) x 7.6 hrs/SLOC for manned flight related computers x 2.0 (complexity factor for ADA).
	• Non-Space Base Optimized Engine	4.5	30% more SLOC than above due to more sensors, more data reduction and data storage.
	• Process Software		
	• Space Base Optimized Engine	2.4	16,000 man hours (from Task E.6 for pre-start operations) x 2 (complexity factor to account for more extensive checkout processes).
	• Non-Space Base Optimized Engine	3.6	50% more SLOC than above due to more sensors, and more complex process logic.
3. Delta Computer Hardware Development	• Labor	2.5	354,000 man hours (from Task E.6 for ICHM computer) x 0.1 (10% delta cost for additional capability).
4. Soft Simulation (Analytical Tool)	• Labor	0.6	Development and documentation of a complete simulation analysis tool where all sensors and engine components are simulated by characteristics functions. Possible use of "Transient Engine Model." 2 man years.
	• Software	0.1	Simulation software shell and training.

Table 12

Development Cost Estimate (continued)

Task	Task Cost Elements	Cost (1991M$)	Rationale
5. Hard Simulation (Component Brassboards)			Sensors mounted on engine components, tested by cold flow, vibration and/or test fire.
Lox Turbopump	Test Labor	0.2	(20 tests/3 tests/wk) x 10 EP x 40 hrs/wk
Fuel Turbopump		0.2	(20 tests/3 tests/wk) x 10 EP x 40 hrs/wk
Main Combustion Chamber and Extendable Nozzle		0.8	(40 tests/3 tests/wk) x 20 EP x 40 hrs/wk
Valves		0.2	(8 valves x 10 tests/valve/5 tests/wk) x 5 EP x 40 hrs/wk
Pneumatic Subsystem		0.05	(10 tests/3 tests/wk) x 5 EP x 40 hrs/wk
Gimbal/TVC		0.05	(10 tests/3 tests/wk) x 5 EP x 40 hrs/wk
6 Component Brassboards	Engineering and Management Labor	3.0	2 yrs x 10 EP x 2000 hr/yr
6 Component Brassboards	Hardware	3.5	Cost of 70% of new OTVE 0.7 x $5M
6. Integrated Sensor/Computer System Brassboard			System Integration of actual sensors and simulated engine component hardware
Sensors	Hardware	0.6	40 sensors at $15K/sensor in the average
Engine Component Simulation	Software	0.2	Equivalent to "Transient Engine Model," 2000 man hrs
Computer	Hardware	0.5	Engineering estimate of special purpose computer
Sensor/Component integration	Software	1.2	50% of item 2 process software
Brassboard Test and Design	Labor	1.5	1 yr x 10 EP x 2000 hr/yr
7. OTVE Modification			Turbine spin and seal inert gas supply subsystem
Valves and Press. Tanks	Hardware	0.3	5% of OTVE First Unit Cost, 0.05 x $6M
Design, Test and Checkout	Labor	2.0	1% of OTVE DDT&E core effort, 0.01 x $200M
8. AETB Test Support	Labor	2.4	2 yrs x 8 EP (Instrumentation, software and systems engineers)

Note: EP = equivalent person

Table 12 (continued)

Summary of Development Cost Elements by Task*

		(M$, 91)
Sensor Development		0.5 to 8.0
Delta Software Development		
Maintenance Data Base	• Optimized engine	3.5
	• Not optimized engine	4.6
Process Software	• Optimized engine	2.4
	• Not optimized engine	3.6
Delta Computer Hardware Development		2.5
Soft Simulation		0.7
Hard Simulation		8.0
Integrated Sensor/Computer System Brassboard		4.0
OTVE Modification (for Cat. 2 only)		2.3
AETB Test Support		2.4

* These costs are not additive. The proper elements are combined for 4 different cases as shown in Table 14.

Table 13

- Functional Checks
    - HPOTP Torque Check
    - HPFTP Torque Check
    - LPOTP Torque Check
    - LPFTP Torque Check
    - Turbopump axial shaft travel

- Leak Checks
    - HPOTP Primary Lox Seal
    - HPOTP Lox/Turbine Drive Gas Seal
    - Heat Exchange Coil Leak Test
    - Heat Exchange Coil Proof Test
    - Component Interface Joints (but not engine/vehicle fluid interfaces)

- Inspections
    - HPOTP Bearings for Damage
    - Heat Exchanger for Cracks, Evidence of Wear and Damage

- Servicing Tasks - None to be eliminated

(2) Engine not Optimized for Space Basing

This assumes that an engine with a basically ground based design concept, such as the current RL-10, is used for space based operations. In this instance, all or most of the 36 preflight checkout parameters listed in Table 2 need to be addressed.

The development program costs for the two engine design alternatives are summarized in Table 13. The total program costs range from about $26M to $35M. This range is relatively small due to the fact that a large part of the costs are contained in software, hardware simulation and brassboard efforts which were assumed to be basically invariant to the selection of particular sensor concepts. Software costs for engines which are optimized for space basing are different than those for engines not optimized for space basing. The maintenance data base software for non-optimized engines was assumed to be 30% larger, and the process software 50% larger compared to those for optimized engines. The 30% increase is due to the larger amount of sensors and the associated larger data base requirement for maintenance. The 50% increase is also partly due to the higher amount of sensors, and partly because of the additional more complex process logic requirements. A more detailed development program analysis, however, may show more differentiation, especially with regard to sensor algorithm software. The cases which use advanced state-of-the-art sensors are more costly than those with existing qualified sensors; however, the capability, quality and reliability of the preflight checkout information is also higher for these cases. The use of current state-of-the-art sensors may lead to higher operating costs (due to lower sensor life and reliability expectations) and to lower quality information (due to more reliance on trend analysis instead of direct measurements).

Preflight checkout Category 2 (automated precycling) for engines which are not optimized for space base operations may introduce substantial reliability and safety issues connected with the addition of valves, lines, inert gas tanks, etc. which may degrade the overall reliability and safety and may also lead to larger life cycle costs.

All development program costs shown in Table 14 are in addition to those which were given for Task E.6, as previously noted.

Development Program Costs (M$, 91)

	Engine Optimized for Space Base Operations: Max. Use of Current Sensors (Cat. 1, 2, 3)	Engine Optimized for Space Base Operations: Max. Use of Advanced Sensors (Cat. 1)	Engine Optimized for Space Base Operations: Max. Use of Advanced Sensors (Cat. 2, 3)	Engine Not Optimized for Space Base Operations: Max. Use of Current Sensors (Cat. 1)	Engine Not Optimized for Space Base Operations: Max. Use of Current Sensors (Cat. 2)	Engine Not Optimized for Space Base Operations: Max. Use of Current Sensors (Cat. 3)	Engine Not Optimized for Space Base Operations: Max. Use of Advanced Sensors (Cat. 1)	Engine Not Optimized for Space Base Operations: Max. Use of Advanced Sensors (Cat. 2)	Engine Not Optimized for Space Base Operations: Max. Use of Advanced Sensors (Cat. 3)
Sensors	2.5	4.0	5.5	5.5	1.5	2.5	7.5	6.5	5.5
Δ Software	← 5.9	—	→	←	—	— 8.2	—	—	→
Δ Computer	← 2.4	—	→	←	—	— 2.4	—	—	→
Soft Simulation	← 0.7	—	→	←	—	— 0.7	—	—	→
Hard Simulation	← 8.0	—	→	←	—	— 8.0	—	—	→
Integrated Brassboard	← 4.0	—	→	←	—	— 4.0	—	—	→
Engine Modifications	← —	—	→	—	2.3	—	—	2.3	—
AETB Test Supp.	← 2.4	—	→	←	—	— 2.4	—	—	→
Total	$25.9M	$27.4M	$28.9M	$31.2M	$29.5M	$28.2M	$33.2M	$34.5M	$31.2M

Note: Preflight checkout category (1) = preliminary power up, (2) = automated precycling, (3) = automated static checkout

Table 14

References

1. Preliminary Failure Modes and Effects Analysis (FMEA) for the OTVE, Internal Letter No. 85-005, Rocketdyne, 1985.

2. Integrated Control and Health Monitoring Task E.1, Orbit Transfer Rocket Engine Technology Program, NAS3-23773, Rocketdyne, 1985.

3. SSME Operations Maintenance Requirements and Specifications Document (OMRSD), V41 File III, Rocketdyne, 1989.

4. Advanced Engine Study Task D.4, Orbit Transfer Rocket Engine Technology Program, NAS3-23773, Rocketdyne, 1987.

5. RL10 Liquid Rocket Engine Service Manual, Pratt and Whitney Aircraft Group, 1982.

6. RL10 FMEA for Apollo missions, NASA Document No. N7477935, NASA, 1964.

7. Definition, Technology Readiness and Development Cost of the Orbit Transfer Vehicle Engine Integrated Control and Health Monitoring System Elements Task E.6, Orbit Transfer Technology Program, NAS3-23773, Rocketdyne, 1991.

8. Advanced Engine Study Task D.1/D.3, Orbit Transfer Rocket Engine Technology Program, NAS3-23773, Rocketdyne, 1986.

Appendix 1

OTVE Preflight Requirements (References)

Part A

OTVE PREFLIGHT REQUIREMENTS – REFERENCES (Sheet 1 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
FUNCTIONAL CHECKS							
1. Valve actuators checkout	X		V41AS0.010	1	050501	2/B	
					050502	2/B	
					050601	2/B	
					050602	2/B	
					060103	2/B	
					060108	1	
					060502	2/B	
					060503	2/B	
					060504	1/B	
					060505	1	
					060509	1	
					070103	2/B	
					070502	2/B	
					070503	2/B	
					070504	2/B	
					080201	–	
					080202	–	
					080203	–	
					040202	2/B	
2. Sensor checkout/calibration	X		V41AQ0.010	1	(NOTES)		No FMEA data available.
3. Pneumatic component checkout	X		V41AS0.020	1	050306 (NOTES)	1M	See valve actuator checkout.
4. Operational sequence check (FRT)	X		V41AS0.030	1	--		
5. Control system redundancy verification	X		V41AN0.030	1	--		
6. Controller memory verification	X		V41AV0.010	–	--		

Part A

OTVE PREFLIGHT REQUIREMENTS - REFERENCES (Sheet 2 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
FUNCTIONAL CHECKS (continued)							
7. Controller pressurization verification	X		V41AN0.040	1	--		
8. HPOTP torque check	X		V41BS0.040	1	050302	2/B	
					050303	1/A	
					050304	1/C	
					060302	2/B	
					060303	2/B	
					060304	2/C	
					060306	2	
					060307	1	
9. HPFTP torque check	X		V41BS0.020	1	050202	2/B	
					050203	1/A	
					050204	1/C	
					070302	2/B	
					070303	1/A	
					070304	1/C	
					070306	1	
10. LPOTP torque check	X		V41BS0.030	1	050402	2	
					050403	1/A	
					050404	2/C	
					050406	1	
					060202	2/B	
					060203	2/B	
					060204	2/C	
					060206	2	
					060207	1	

Part A

OTVE PREFLIGHT REQUIREMENTS - REFERENCES (Sheet 3 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
FUNCTIONAL CHECKS (continued)							
11. LPFTP torque check	X		V41BS0.010	1	050102 050103 050104 070202 070203 070204 070206	2/B 2/B 2/C 2/B 2/B 2/C 2	
12. Turbopump axial shaft travel check	X		V41BS0.032 V41BS0.044 V41BS0.020	1 1 1	(NOTES)		See FMEA reference for turbopump torque checks.
13. Extendable nozzle travel check	X		--	-	020502	2	
14. Igniter operation	X		V41AQ0.010	1	040101	3M	

Part A

OTVE PREFLIGHT REQUIREMENTS - REFERENCES (Sheet 4 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
LEAK CHECKS							
1. HPOTP primary LOX seal	X		V41BQ0.110	1	060302	2	
2. HPOTP LOX/turbine drive gas seal (intermediate seal)	X		(NOTES)	-	050306	1M	SSME monitors intermediate seal pressure.
3. Oxidizer inlet valve and MOV ball seals	X		V41BQ0.120	1	060506 060507 060104 060105 060106	2/B 2 3 3 3	
4. Fuel inlet valve and MFV ball seals	X		V41BQ0.010	1	070104 070105 070106	3 3 3	
5. Propellant valves primary shaft seals	X		V41BQ0.020 V41BQ0.040	1 1	-- --	- -	
6. Pneumatic control assembly internal seals	X		V41BQ0.090 V41BQ0.091	1R 1	-- --	- -	
7. Heat exchanger coils leak test	X		V41BPB.020	1	--	-	
8. Heat exchanger coils proof test		X	V41BPB.030	1	--	-	Frequency of test TBD.
9. Thrust chamber assembly outer wall	X		V41BQ0.160	1	020202	1M	
10. Combustion and propellant system joints	X		V41AY0.221	1	020201 020301 020401	1/A 1/A 2/B	

Part A

OTVE PREFLIGHT REQUIREMENTS - REFERENCES (Sheet 5 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
INSPECTIONS							
1. Exterior of components for damage, security, clearances, etc.	X		V41BU0.030	1	--	-	More information needed on probability of damage from orbital debris, etc.
2. TC assembly for evidence of coolant passage blockage (hot spots)	X		--	-	030101 030102	1B 1	
3. HPFTP turbine wheel/blades for cracks, fatigue, and damage		X	V41BS0.080	1	050205	1	Frequency of inspection TBD.
4. LPFTP turbine wheel/blades for cracks, fatigue, and damage		X	--	-	050105	2	Frequency of inspection TBD.
5. HPOTP turbine wheel/blades for cracks, fatigue, and damage		X	V41BS0.082	1	050305	1	Frequency of inspection TBD.
6. LPOTP turbine area for evidence of fatigue or damage		X	--	-	050405	2	Frequency of inspection TBD.
7. HPOTP bearings for damage		X	V41BS0.082	1	060303 060304	1A 1C	Frequency of inspection TBD.
8. TC assembly injector faceplate, igniter, and LOX post tips for erosion, burning, and contamination	X		V41BU0.040	1	020101 020105	1 2B	
9. Gimbal bearing and TVC attach points for evidence of bearing seizure and fatigue		X	--	-	090301 090304	1/R 1	Frequency of inspection TBD.
10. Heat exchanger for weld cracks, evidence of wear, and damage		X	V41BU0.040 V41BU0.086	1 1	030201	1	Frequency of inspection TBD.

Part A

OTVE PREFLIGHT REQUIREMENTS – REFERENCES (Sheet 6 of 6)

OTVE PREFLIGHT REQUIREMENTS			REFERENCES				NOTES
			SSME OMRSD		OTVE FMEA		
REQUIREMENT	Routine	Periodic (TBD)	REF. NO.	CRIT.	REF. NO.	CRIT.	
SERVICING							
1. Combustion zone drying							
a. Igniter valves	X		--	-	040202 040302	2/B 3	
b. P_c sensors	X		V41CB0.080	1	--	-	
2. Purge HPOTP LOX/turbine drive gas seal (intermediate seal) pre-start	X		S00FA0.210J	1	050306	1M	

Part B

BASIC FAILURE MODE EFFECTS AND CRITICALITY

Criticality Number	Engine Effect	Vehicle Effect	Mission Effect
1	Major uncontained damage to an engine subsystem or component resulting in widespread engine damage.	Significant damage to adjacent equipment and/or vehicle probable.	Mission abort(1) Low probability of vehicle loss, crew death or injury
2	Significant contained damage to a vital engine subsystem or component sufficient to render it inoperative or its continued operation hazardous.	Damage to adjacent equipment or vehicle highly improbable.	Mission abort(1)
3	Performance degradation or notable damage to component/subsystem. Continued operation conditionally acceptable.	None	Mission abort(1) Conditionally dependent
4	Minor failures fully tolerated by continued operation at an acceptable hazard level. Minor propellant leakage from flanged joints.	None	Delay until resolved at mission start
5	Nuisance failures.	None	Correct at next routine maintenance

ICHM MODIFIED FAILURE MODE EFFECTS AND CRITICALITY

Criticality Number	Engine Effect	Vehicle Effect	Mission Effect
A	Safe shutdown of engine before uncontained damage results.	None	Mission abort(1)
B	Safe shutdown of engine before significant contained damage results.	None	Mission abort(1)
C	Reduced power level operation.	None	Mission abort(1) Conditionally dependent
D	Parallel or standby redundant system assumes function; normal engine operation continues.	None	Delay until resolved at mission start

(1) Mission abort for criticality 1 through 3 and A through C failures applies only on outbound phases prior to OTV payload disposition. After abort, emphasis is placed on safe return of the vehicle/crew regardless of payload disposition.

NOTE: Basic failure modes requiring multiple failures to produce the specified criticality are indicated by a suffixed M after the criticality number.

Part C
SSME OMRSD (Sheet 1 of 11)

CRITICALITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	FUNCTIONAL CHECKS						
-	Controller memory dump/compare	X	X		X		
1	Valve actuator checkout	X	X		X		
1	Pneumatic component checkout	X	X		X		
1	Sensor checkout	X	X		X		
1	Redundancy verification	X	X		X		
1	Controller heater verification	X	X				
1	Operational sequence check (FRT)	X	X		X		
1	Controller pressurization verification	X	X		X		
3	MFV heater checkout	X					
3	Gimbal electrical bonding test	X					
3	Interface electrical bonding test	X					
3	Gimbal actuator electrical bonding test	X					
1	Controller power/internal temperature verification	X	X				
1	Operational instrumentation verification	X	X				Includes skin temperatures and accelerometers
1	Skin temperature instrument channelization	X					

Part C
SSME OMRSD (Sheet 2 of 11)

CRITICALITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	FUNCTIONAL CHECKS (continued)						
1	LPFTP torque test	X	X		X		
1	HPFTP torque test	X	X		X		
1	LPOTP torque test	X	X		X		
1	LPOTP shaft travel test	X	X		X		
1	HPOTP torque test/impeller lock verification	X	X		X		
1	HPOTP shaft travel test		X		X		
-	HPOTP shaft travel baseline	X					
1	Antiflood valve cracking pressure test		X				
1	Pre-cryogenics load requirements • Load and execute sensor checkout module • Load and execute redundancy checkout module • Load and execute pneumatic checkout module (partial) • Load flight software • Dump and compare controller memory contents		X		X		

Part C
SSME OMRSD (Sheet 3 of 11)

CRITICALITY	REQUIREMENT	SSME APPLICATION: POST-INSTALLATION	SSME APPLICATION: ROUTINE	SSME APPLICATION: PERIODIC	OTV APPLICATION: 1990	OTV APPLICATION: FUTURE	NOTES
	LEAK CHECKS						
1	HPFTP liftoff nose/piston seals	X	X				
1	LPFTP liftoff nose/piston and Naflex seals	X	X				
1	HPOTP primary oxidizer seal		X		X		
1	Heat exchanger coil leak test		X		X		
1	Heat exchanger coil proof test			3500 seconds	X		During HPOTP recycle
1	MFV ball seal	X	X		X		
1	MFV primary shaft seal		X		X		
1	MOV ball seal	X	X		X		
1	MOV primary shaft seal		X		X		
1	FPOV ball seal	X	X				
1	FPOV primary shaft seal		X				
1	OPOV ball seal	X	X				
1	OPOV primary shaft seal		X				
1	CCV primary shaft seal		X				
1	Propellant valve actuators pneumatic seals		X				
1R	Fuel bleed valve seat		X				

Part C

SSME OMRSD (Sheet 4 of 11)

CRITICALITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	LEAK CHECKS (continued)						
1	Oxidizer bleed valve seat		X				
1	Antiflood valve seat/shaft seal		X				
1	Pneumatic control assembly internal seals		X		X		
1	Thrust chamber interior/exterior walls		X		X		
1	MCC-to-nozzle seal		X				
1	MCC liner decay-pressure check		X				
1	Main injector LOX posts		X				Unsupported plugged posts
1	System purge check valves (7)		X				
1	Systems gross leakage (signature leak check)		X				
1	Oxidizer, fuel, hot gas system violated joints	X	X		X		
1	Pneumatic interface connections	X					

Part C
SSME OMRSD (Sheet 5 of 11)

CRITICAL-ITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	INSPECTIONS						
1	Exterior of components for damage, security, clearances, corrosion, etc.	X	X		X		
1	Interior of components (borescope)		X				
	• Main injector faceplate, baffles, injector elements, flow/heatshields, film coolant holes, LOX posts, ASI chambers/orifices, igniters, and LOX dome • Fuel preburner • Oxidizer preburner • Main combustion chamber liner and acoustic chambers • Heat exchanger • Hot gas manifold				X		
1	HPFTP		-	3 starts			Pump removed from engine NOTE: While pump is removed, detailed inspections are conducted on powerhead, MCC injector, and fuel preburner.
	• First- and second-stage turbine blades • Tip seals and platforms • Dampers • Bellows shield (dye penetrant) • Sheet metal, struts, vanes • Coolant orifices				X		

Part C

SSME OMRSD (Sheet 6 of 11)

CRITICAL-ITY	REQUIREMENT	SSME APPLICATION			OIV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	<u>INSPECTIONS</u> (continued)						
1	HPOTP		-	3500 seconds			Pump returned to Rocketdyne for inspection NOTE: While pump is removed, detailed inspections are conducted on powerhead, MCC injector, oxidizer preburner, and heat exchanger.
	• First- and second-stage turbine blades				X		
	• Pump end bearings				X		
1R	Fuel preburner oxidizer ASI orifice		X				
1	Oxidizer preburner LOX posts (eddy current)		-	3,000 seconds			
1	Heat exchanger • Tubes, brackets, turning vanes • Coil eddy-current test • Coil welds (borescope)		-	(see notes)	X		5000 seconds initially, 2400 seconds thereafter Eddy-current testing to detect wall thinning
1R	HPFTP bellows height verification		-	3 starts			Prior to pump installation
1	Hot gas manifold transfer tube liner welds and support pins (dye penetrant)		-	(see notes)			Concurrent with HPFTP and HPOTP removals
1	Fuel preburner LOX post support pins		-	(see notes)			Concurrent with HPOTP removal

Part C

SSME OMRSD (Sheet 7 of 11)

CRITICAL-ITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	<u>INSPECTIONS</u> (continued)						
1	Antiflood valve filter		X				Replace filter after ignition
1R	Sensor (HPFTP and HPOTP discharge temperature) insulation resistance		X				
1	MCC liner surface finish measurement and polishing (post-shutdown)		X				
1	MCC liner polishing (prelaunch)		X				
1	Low-pressure fuel duct helium barrier		X				
1	High-pressure fuel duct alinement		-	(see notes)			Concurrent with HPFTP installation
1	High-pressure fuel duct (dye penetrant)		X				
1	Fuel duct bellows/valve actuator burst diaphragms		X		X (notes)		Assumes burst diaphragms used on OTVE

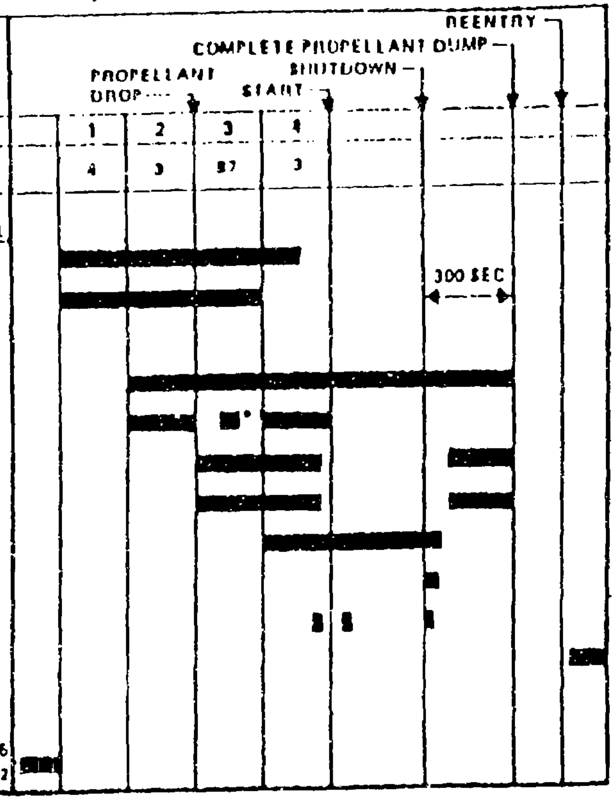
Part C

SSME OMRSD (Sheet 8 of 11)

CRITICAL-ITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	SERVICING						
-	Install protective covers and closures	X	X				
	• Nozzle/MCC						
	• Drain line exits						
	• TC exit						
	• Bellows						
	• MFV heater						
	• Critical sensors						
1	Propellant system drying/verification		X				
	• HPFTP turbine bearing						
	• HPOTP turbine seals/drains						
	• Oxidizer purge system						
	• MCC and nozzle						
	• HPOTP secondary turbine seal pressure sense line						
	• MCC pressure sensors				X		
1	Purges, pre-start		X				See attached purge flow charts
	• Oxidizer dome (GN_2)						
	• HPOTP intermediate seal (GN_2/He)				X		
	• Fuel system (He)						
	• Component fuel drain (He)						
	• Preburner shutdown (He)						
	• LP fuel duct helium barrier (He)						
	• Controller coolant (air/GN_2)						
	• Oxidizer inlet feed system (GN_2/He)						

Part C
SSME OMRSD
(Sheet 9 of 11)

	PRESS (PSIA)	TEMP (°R)	FLOW (SCFM)
PURGE SEQUENCE NO.			
MIN PURGE DURATION (MIN.)			
	DESIGN NOMINAL	DESIGN NOMINAL	DESIGN NOMINAL
GND NITROGEN			
OXIDIZER DOME	600	590	265±20
HPOTP INTERM SEAL	600	600	85±5
VEHICLE HELIUM			
LPFD BARRIER PURGE	750	530	1.2
FUEL SYSTEM PURGE	750	530	126±12
BLEED VALVE ACT	750	530	
COMPONENT FUEL DRAIN	750	530	2±1
HPOTP INTERM SEAL	750	530	280±11
PB SHUTDOWN PURGE	750	530	1050±76
POGO SUPPRESSION	750	530	480±40
OXID INLET FEED SYS	17.7	530	20±5
GND NITROGEN OR HELIUM			
OXID INLET FEED SYS	17.7	530	(He)20±5 (GN_2)17.5±2

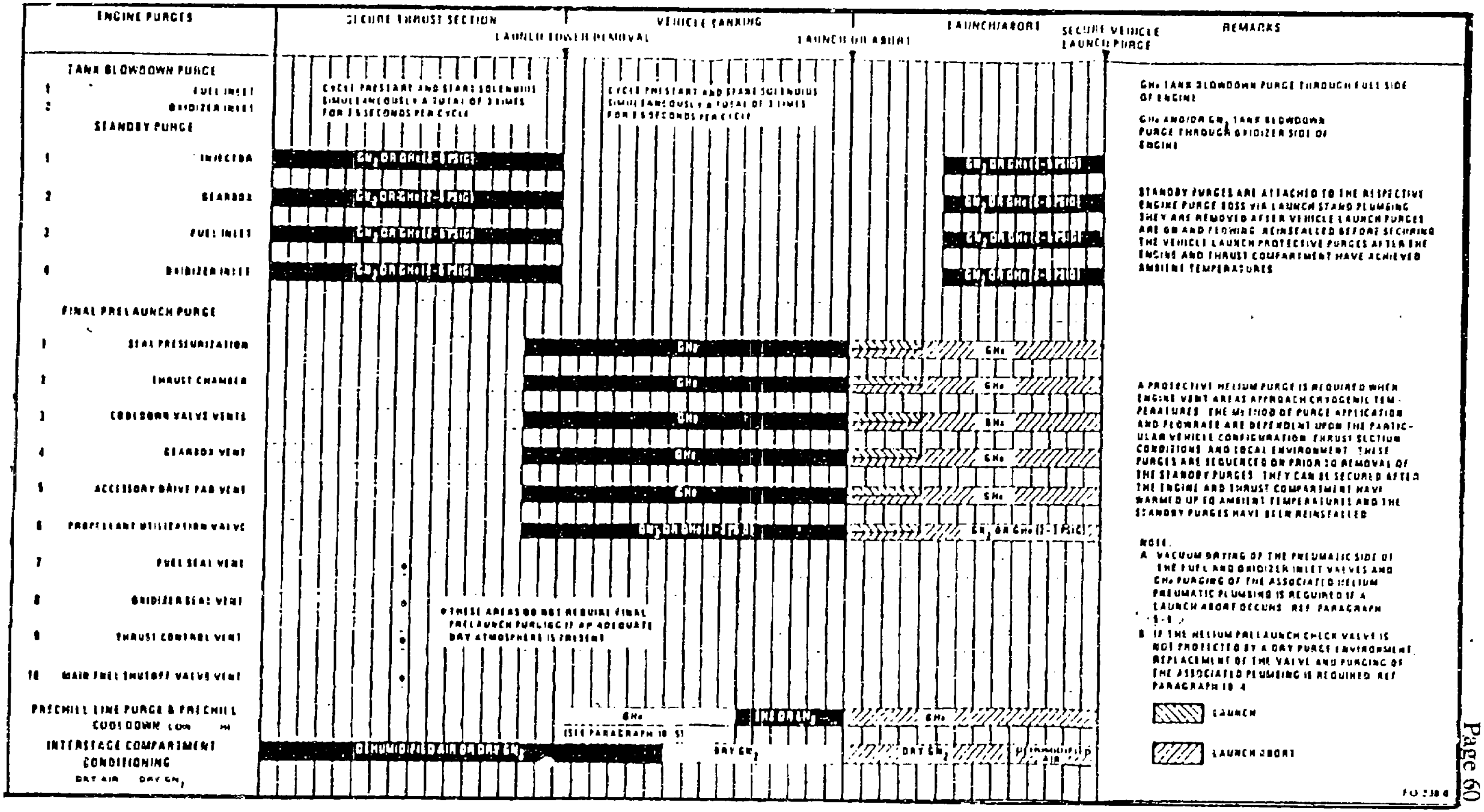


*FUEL SYSTEM PURGE ON 3 MINUTES FOR EACH 60 MINUTES IN PSN 3

SSME Purges

Part C
SSME OMRSD

(Sheet 10 of 11)



RL10 Purges

Part C
SSME OMRSD (Sheet 11 of 11)

CRITICALITY	REQUIREMENT	SSME APPLICATION			OTV APPLICATION		NOTES
		POST-INSTALLATION	ROUTINE	PERIODIC	1990	FUTURE	
	SERVICING						
-	Install environmental closures		X				Post-landing
-	Install ferry flight set o MCC throat closure o Drain line exit closures		-				Prior to orbiter ferry
-	Pressurize propellant and hot gas systems		-				Prior to orbiter ferry
-	Install TC nozzle bumpers		-		X		Post-landing if engines have not been positioned down. Possible application to OTVE in a multi-engine configuration.
	ABORT/RECYCLE REQUIREMENTS						
	All ROUTINE and applicable PERIODIC requirements are required to return the SSMEs to a launch condition.						
	An aborted launch is defined as ignition of propellants in the SSME.						

Part D

RL10 PRELAUNCH CHECKS - SUMMARY

- LEAK AND FUNCTIONAL CHECKS
  - <u>IGNITION SYSTEM</u>
    - ENERGIZE SYSTEM - VISUALLY INSPECT FOR SPARK CONSISTENCY
    - DEFLECTOR TEST - DIAL INDICATOR
  - <u>VALVE ACTUATION</u>
    - SOLENOID VALVES (3) - VERIFY ACTUATION AUDIBLY AND BY TOUCH
    - PROPELLANT VALVES (6) - VERIFY ACTUATION BY TOUCH
  - <u>LEAK CHECKS</u>
    - OXIDIZER FLOW CONTROL AND PURGE CHECK VALVE LEAKAGE
      - IN-LINE FLOWMETER AT TEST FIXTURE
    - OXIDIZER AND FUEL SYSTEM EXTERNAL LEAKAGE
      - LEAK DETECTION SOLUTION
    - HELIUM SYSTEM INTERNAL LEAKAGE
      - IN-LINE FLOWMETER AT SOLENOID VALVE VENTS

- VISUAL INSPECTIONS
  - OBVIOUS DAMAGE AND CONTAMINATION
  - LOOSE CONNECTORS
  - PROTECTIVE COVER, CLOSURE, AND DESICCANT REMOVAL

- SUMMARY
  - TOTALLY MANUAL - NO AUTOMATION
  - REQUIRES SYSTEM VIOLATION AND EXTERNAL HOOKUPS

REFERENCE: RL10 SERVICE MANUAL,
CHANGE 2, 15 NOVEMBER 1984

Appendix 2

OTV Automated Preflight Methods - Approaches

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks

Check	Approach	Sensors /hardware		Selection	Comments
1. Valve Actuator Checkout	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Verify proper valve sequence occurs at power up • Checks performed by sensors and computer **B. Component pre-cycling** • Cycle valves electrically to verify actuator integrity • Performed by sensors and controller **C. Automated static checkout** • Historical data base for every valve • Valve actuation at prior engine operation • Electrical resistance measurements to verify actuator integrity • Performed by sensors and controller	**Current:** LVDT, on/off Position Sensor	**Advanced:**	B	Currently automated on the SSME. A combination of approaches B and C will provide a high degree of confidence.
2. Sensor checkout/ calibration	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Verify nominal sensor data including redundant sensors at power up • Checks performed by sensors and computer **B. Component pre-cycling** • precycling of sensors is considered a static check • approach not applicable to this check **C. Automated static checkout** • Uses historical data base • Sensor outputs from prior engine operation • Programmed inputs to evaluate sensor integrity • Performed by sensors and controller	**Current:**	**Advanced:**	C	Currently automated on the SSME. Note that checkout capability needs to be designed into sensor. Approach C is a valid check and minimizes expended resources.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
3. Pneumatic component checkout	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Verify nominal pneumatic component functioning at power up • Checks performed by sensors and controller **B. Component pre-cycling** • programmed cycling sequence of pneumatic components • performed by sensors and controller **C. Automated static checkout** • Historical data base • pneumatic system operation from prior engine operation.	Current: Pressure transducers, pressurized inert gas source.	Advanced:	C	Currently automated on the SSME. The complexity of this check depends on the pneumatic system. Ideally this would be the lox pump intermediate seal purge and the injector shutdown purge. The checkout may not require anything more than a look at the previous flight's valve actuation and pressure data.
4. Operational sequence test (FRT)	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Verify nominal controller function (valve sequencing) at power up to assess flight readiness • Checks performed by sensors and controller **B. Component pre-cycling** • Verify nominal controller function through cycling of electrical valves and pneumatic system • Check performed by sensors and computer **C. Automated static checkout** • Historical data base • Controller operation from prior engine operation • Static controller electrical check	Current: Pressure transducers, LVDT, on/off position sensor	Advanced:	B	Currently automated on the SSME. Simple sequence check done with computer in combination with past history data would be sufficient.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
5. Control system redundancy verification	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made at pump idle. • Include an interval of redundant controller operation during pump idle mode • Verify nominal controller redundant functions • Checks performed by sensors and controller **B. Component pre-cycling** • Redundant controller functions are checked statically • Approach not applicable to check **C. Automated static checkout** • Historical data base • controller redundancy output from prior engine operation • Programmed inputs to evaluate redundant control system integrity • Performed by sensors and computer	Current:	Advanced:	C	Currently automated on the SSME. Uses an automated self-test.
6. Controller memory verification	**A. Prelim Power Up** • Controller memory check is performed statically • Approach not applicable to check **B. Component pre-cycling** • Controller memory check is performed statically • Approach not applicable to check **C. Automated static checkout** • Historical data base • Verify nominal behavior from prior engine operation • Program to evaluate controller memory integrity • performed by computer	Current:	Advanced:	C	Currently automated on the SSME. Uses an automated self-test.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
7. Controller pressurization verification	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made at pump idle. • Verify that controller casing is pressurized to correct level • Checks performed by sensors **B. Component pre-cycling** • Controller is factory sealed with inert gas at prescribed pressure • Approach not applicable in performing check **C. Automated static checkout** • Historical data base • pressure decay from prior engine operation • pressure measurement prior to flight • performed by sensors and computer	**Current:**	**Advanced:**	C	Currently automated on SSME. Controller will be factory sealed with inert gas. Simply check the internal pressure.
8. HPOTP torque check	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • Evaluate rpm vs. expected rpm at inlet/exit conditions • Requires sensitive torque sensor if torque measured directly • May result in damage or bootstrap to full Pump idle • does not accurately measure breakaway torque • check performed by sensors and computer **B. Component pre-cycling** • Breakaway torque may be measured • Small incremental blasts of inert gas of increasing pressure until breakaway torque is overcome • may require electro mechanical system to torque the shaft • Inert gas spin system required • Performed by sensors and computer • increased weight and complexity **C. Automated static checkout** • Historical data base • Torque during prior engine operation, specifically power down transient to look for shaft hang-up • requires sensitive torque sensor if measured directly • Uses trend analysis	**Current:** Pressure transducer, temperature sensor, speed sensor, flowmeter, pressurized inert gas source.	**Advanced:** Ferromagnetic torquemeter, fiberoptic deflectometer.	B	Use a torque meter and measure torque as the engine powers down from its prior run. This approach on its own however presents a problem with measuring an extremely small breakaway torque which is why approach B is selected.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks (contd)

Check	Approach	Sensors	/hardware	Selection	Comments
9. HPFTP Torque Check	See functional check #8				
10.LPOTP Torque Check -	See functional check #8				
11.LPFTP Torque Check -	See functional check #8				
12. Turbo-pump axial shaft travel check.	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • measure bearing vibrational spectrum • check performed by sensors and computer **B. Component pre-cycling** • Remotely move shaft axially to induce travel • requires mechanical actuation system • performed by sensors and controller • increased weight and complexity **C. Automated static checkout** • Historical data base • Bearing vibrational spectrum at prior engine operation • Real time monitored bearing wear • Uses trend analysis	**Current:** LVDT, accelerometer	**Advanced:** Fiberoptic deflectometer, isotopic wear detector	C	Design bearing with deflectometer if using roller bearings. However, this check may be deleted if hydrostatic bearings are used. These bearings would accumulate negligible wear during start and shutdown. Contact for thrust bearings is minimal since they are used during transient periods only.
13. Extendible Nozzle Travel check	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • monitor excessive vibration at extendible nozzle attach points • check performed by sensors and computer • Extendible nozzle deployed or not deployed during this time **B. Component pre-cycling** • Activate extendible nozzle actuation system • Programmed gimballing sequence may be initiated as dynamic source to check travel • performed by sensors and controller **C. Automated Static Checkout** • Historical data base • Extendible nozzle deployment/retraction at prior engine operation • Verify correct positioning of extendible nozzle in current configuration	**Current:** accelerometer, on/off position sensors	**Advanced:**	B	Should need to extend only when required during mission. Simple alignment sensors will provide necessary data. A robust gimballing mechanism should be employed to permit cycling for checkout purposes.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I. Functional Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
		Current:	Advanced:		
14. Igniter operation - Currently automated	**A. Prelim Power Up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Verify igniter operation at power up • Checks performed by sensors and computer **B. Component pre-cycling** • Cycle igniter to verify integrity • Performed by sensors and controller **C. Automated static checkout** • Historical data base • igniter operation from prior engine starts. • Electrical resistance measurements to verify igniter integrity • Performed by sensors and controller			B	Pre-cycling is the best approach since static electrical check on its own may be misleading. Spark rate and intensity are critical issues because of propellant accumulation.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

II. Leak Checks

Check	Approach	Sensors /hardware		Selection	Comments
1. HPOTP primary Lox seal	**A. Prelim. power-up** • Hardware conditioning has not completely occurred. • Engine Start condition (just prior to Tank head Idle) • Propellant dropped to MOV. • Temperature measured at lox seal drain cavity • Checks performed by sensors and computer **B. Component Pre-cycling** • Lock-up system at MOV and GOV. • Pressurize with inert gas. • Thermodynamic conditions measured at lox seal drain cavity • System lock-up performed by controller • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Lox seal drain cavity temperature and pressure at prior engine operation • Uses trend analysis	**Current:** Pressure transducer, temperature sensor, flowmeter, pressurized inert gas supply	**Advanced:**	C	Drain line pressure monitor is probably all that is needed to show seal degradation.
2. HPOTP inter-mediate seal	**A. Prelim. power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • Temperature measured at intermediate lox seal drain cavity • Checks performed by sensors and computer **B. Component Pre-cycling** • Remotely activate seal purge system • Measure intermediate lox seal supply and drain cavity pressure • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Intermediate Lox seal supply and drain cavity temperatures and pressures at prior engine operation. • Uses trend analysis	**Current:** Pressure transducer, temperature sensor, pressurized inert gas supply	**Advanced:**	C	Can also be checked just prior to start for verification

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

II. Leak Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
3. Main oxidizer valve ball Seals	**A. Prelim. power-up** • Hardware conditioning is occurring. • Check performed when MOV is closed • Measure leakage past MOV ball seal with skin temp sensors • Check performed by sensors and computer **B. Component Pre-cycling** • Assumes purge line added just downstream of Ox. inlet valve. • Lock-up system at MOV and GOV. • Pressurize with inert gas. • Measure leakage past MOV ball seal with skin temp sensors • System lock-up performed by controller • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Leakage past ball seal at prior starts as engine is chilling down. • Check performed by sensors and computer.	**Current:** skin temperature sensor	**Advanced:**	C	Ox. Tank valve is constantly leak checked because Lox propellant is constantly against it. HPOP intermediate seal purge reqd. when propellant introduced into engine. So purge assumption is justified.
4. Main fuel valve ball seal	**A. Prelim. power-up** • Hardware conditioning has not completely occurred. • Engine start condition (just prior to tank head idle) • Propellant dropped to MFV • Measure leakage past MFV ball seal with skin temp sensors • Check performed by sensors and computer **B. Component Pre-cycling** • Check performed prior to engine start • Assumes purge line added just downstream of Fuel inlet valve. • Lock-up system at MFV • Pressurize with inert gas. • Measure leakage past MFV ball seal with skin temp sensors • System lock-up performed by controller • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Leakage past ball seal at prior starts as engine is chilling down. • Check performed by sensors and computer.	**Current:** skin temperature sensors,	**Advanced:**	C	During stand-by or long term storage, propellants are stored in vehicle tanks. The tank [illegible] valve is always self-checked since it will always have a closing pressure or a spring closing force applied.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

II. Leak Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
5. Propellant valve primary shaft seals	**A. Prelim. power-up** • Hardware conditioning has not completely occurred. • Engine start condition (just prior to tank head idle) • Propellant dropped to MFV • Measure leakage of shaft seals by monitoring temperature at dynamic seal port • Check performed by sensors and computer **B. Component Pre-cycling** • Assumes purge line added just downstream of Fuel inlet valve. • Lock-up system at MFV • Pressurize with inert gas. • Measure leakage of shaft seals by monitoring temperature and pressure at dynamic seal port • System lock-up performed by controller • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Leakage past shaft seal at prior starts and shutdowns. • Check performed by sensors and computer.	**Current:** Pressure transducer, temp sensor	**Advanced:**	C	This is generally not a problem due to vacuum environment in space to provide venting - the need for this check needs to be re-assessed.
6. Pneumatic control assembly internal seals	**A. Prelim. power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • Verify nominal pneumatic system supply pressures during power up • Checks performed by sensors and controller **B. Component Pre-cycling** • Check performed prior to engine start • Lock-up pressure in PCA (pneumatic control assy) • May require many pressure transducers and on/off valves • Measure pneumatic system decay • System lock-up performed by controller • Checks performed by sensors and computer **C. Automatic static checkout** • Use historical data base • Monitor pneumatic system operation • Check performed by sensors and computer. • Uses trend analysis - plot increase in leakage rate	**Current:** LVDT, on/off position sensor, pressurized inert gas cource.	**Advanced:**	C	System lock-up with pressure decay will satisfy the requirement in combination with past history data. Note that leakage itself is not the problem since the gas is inert.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

II. Leak Checks (contd)

Check	Approach	Sensors /hardware		Selection	Comments
7. Heat exchanger coil leak test	**A. Prelim. power-up** • Approach not applicable in performing check. • Recommended that check must be performed prior to power up because of dangerous conditions imposed. **B. Component Pre-cycling** • Assumes purge line added just downstream of Ox. inlet valve. • Lock-up system at MOV and GOV. • Pressurize with inert gas. • Monitor pressure decay • System lock-up performed by controller • Checks performed by sensors and computer • May not detect small leaks • Possible checkout isolation valve leakage **C. Automatic static checkout** • Use historical data base • Monitor pressure, temperature and flow conditions at heat exchanger inlet and exits. • Provides data base for Heat exchanger health assessment • Check performed by sensors and computer. • Leak check (specifically small leaks) not accomplished using this method	Current: Pressure transducer, temp sensor, flowmeter	Advanced:	B	The lock-up with pressure decay may be the best approach. However, the leakage may be too small to detect and still presents a dangerous condition. Leakage in the checkout isolation valve may also invalidate the results. This check can be eliminated by utilizing a highly robust heat exchanger design

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

8. Heat exchanger coils proof test	**A. Prelim. power-up** • Approach not applicable in performing check. • Recommended that check must be performed prior to power up because of dangerous conditions imposed. **B. Component Pre-cycling** • Check performed prior to engine start • Assumes purge line added just downstream of Ox. inlet valve. • Lock-up system at MOV, GOV and lox tank check valve. • Pressurize with inert gas to 1.25 times max operating pressure. • Monitor pressure decay • System lock-up performed by controller • Checks performed by sensors and computer • Requires electrically actuated valve in tank pressurization line upstream of tank check valve • May not detect small leaks **C. Automatic static checkout** • Approach not applicable in performing check • Need 1.25 times maximum operating condition to perform proof test • Use historical Data base • Monitor Pressure, temperature, and flow conditions at heat exchanger inlet and exits. • Exhibited anomalies • Provides data base for Heat exchanger health assessment • Check performed by sensors and computer. • Proof test not performed using this method	**Current:** Pressure transducer, temp sensors, flowmeters, pressurized inert gas source.	**Advanced:**	B	The proof test should not be required unless the HPOTP is removed /replaced (this is the case with SSME). May be the fact that this is a space based application is enough to eliminate this check. This needs to be studied further since the requirement may be impacted by differences between SSME and OTV. Note that high pneumatic pressure may cause a problem for MOV and GOV seals. This check should be eliminated by utilizing a highly robust heat exchanger design

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

II. Leak Checks (contd)

Check	Approach	Sensors	/hardware	Selection	Comments
9. Thrust chamber assembly outer walls	**A. Prelim. power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • External leakage directly detectable • Internal leaks (into T/C core) present no problem • Leakage also indicated by performance degradation (Pc vs. flow) • Checks performed by sensors and computer **B. Component Pre-cycling** • Approach not applicable in performing check • System cannot be isolated and pressurized • Throat plug placed using robotic arm seems impractible but is an option • Adds complexity and weight **C. Automatic static checkout** • Use historical data base • External leakage data from previous engine operation • Thrust chamber cooling jacket life prediction model • Uses Trend analysis	**Current:** Pressure transducer, Temp sensor, flowmeters, pressurized inert gas source	**Advanced:** Optical leak detection system	C	Use trend analysis (C); design hardware for slow consistant degradation (if any). Best to eliminate this check and stick with a robust design.
10. Combustion and propellant system joints	**A. Prelim. power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • External leakage directly detectable • Checks performed by sensors and computer **B. Component Pre-cycling** • Approach not applicable in performing check • System cannot be isolated and pressurized • Throat plug placed using robotic arm seems impractible but is an option • Adds complexity and weight **C. Automatic static checkout** • Use historical data base • External leakage data from previous engine operation	**Current:** Pressure transducer, pressurized inert gas suppply.	**Advanced:** Optical leak detection system	C	Optical leak detection may be the best approach (C). Note that SSME checks only disturbed joints. With this groundrule, this check might possibly be eliminated. Detection may be easier by designing system with a minimal number of joints. Also, this check may be eliminated by using welded joints. The system can be welded with the exception of the turbopump interfaces.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

III. Inspections

Check	Approach	Sensors /hardware		Selection	Comments
1. Exterior of components for damage/ security	**A. Preliminary power-up** • Approach not applicable in performing check • Required data consists of visual data only to assess condition of the engine exterior **B. Component pre-cycling** • Approach not applicable in performing check • Required data consists of visual data only to assess condition of the engine exterior **C. Automatic static checkout** •Use of historical data base • Comparison of a series of superimposed images each covering a particular view or angle • Remote real time viewing	**Current:**	**Advanced:** Remote Automated visual inspection system	C	The practicality of the visual inspection system needs to be assessed. Without this system, this check should be eliminated while in free space.
2. Thrust Chamber Assembly for evidence of coolant passage blockage	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Measure pressure drop across cooling jacket. • Check performed by sensors and computer **B. Component pre-cycling** • Requires inert gas flow through hot gas system • Measure pressure drop across cooling jacket. • Check performed by sensors and computer • Requires large volume of inert gas **C. Automatic static checkout** • Use of historical data base • Cooling jacket pressure drop profiles at prior engine operation • Check performed by sensors and computer • Hot spot damage may be seen using remote visual techniques	**Current:** Pressure Transducer, skin temp sensor, pressurized inert gas source	**Advanced:** Remote Automated visual inspection system	C	Delta-P trend analysis is a simple accurate approach. All indicated methods detect general blockage. Detection of individual passage blockage would be difficult and require many sensors or multiple thermal imaging cameras.

O.: AUTOMATED PREFLIGHT METHODS - APPROACHES

III. Inspections (contd)

Check	Approach	Sensors /hardware		Selection	Comments
3. HPFTP turbine wheel/ blades for cracks, fatigue and damage	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle • Measure inlet conditions and RPM and compare to expected RPM those conditions • Measure housing vibration • Check performed by sensors and computer • This approach does not detect fatigue or damage on non-rubbing surfaces **B. Component pre-cycling** • Inert gas spin will not provide realistic conditions to assess turbine wheel/blades for wear and damage • Approach not applicable in performing check **C. Automatic static checkout** • Use of historical data base • Conditions (vibration and thermodynamic) monitored during prior engine operation • Check performed by sensors and computer • Uses trend analysis	Current: Pressure transducer, temp sensor, speed sensor, flowmeter, accelerometer	Advanced: Optical pyrometer	C	The easiest approach would be to go with a high factor of safety/ robust design and look for signs of performance degradation.
4. LPFTP turbine wheel/ blades for cracks, fatigue, and damage	See Inspection #3				
5. HPOTP turbine wheel/ blades for cracks, fatigue, and damage	See Inspection #3				
6. LPOTP turbine wheel/ blades for cracks, fatigue, and damage	See Inspection #3				

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

I... Inspections (contd)

Check	Approach	Sensors	/hardware	Selection	Comments
7.HPOTP Bearings for Damage	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Measure bearing vibrational spectrum at turbine spin-up • Exhaust plume analyzed for contamination • Check performed by sensors and computer **B. Component pre-cycling** • Performed prior to engine start • Measure bearing vibrational spectrum at turbine spin-up • Requires inert gas to spin turbine • Inert gas spin system required • Isolation valves required • Increased weight and complexity **C. Automatic static checkout** • Use of historical data base • Bearing vibration data at prior engine operation • Torque measurements along shut-down transient • Remote bearing wear detection • Check performed by sensors and computer • Uses trend analysis	**Current:** strain gauges,accelerometer,	**Advanced:** fiberoptic deflectometer, plume spectrometer, isotope wear detector, ferromagnetic torque meter	C	This inspection may also be required for the fuel turbopump if the requirement is based on more than the possibility of LOx/H2 mixing. If Hydrostatic bearings are an option, possible requirements for preflight checks on hydrostatic bearings needs to be investigated.
8. TC Assembly injector face plate, igniter and lox post tips for erosion, burning, and contamination.	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Exhaust plume analyzed for contamination • Check performed by sensors and computer • Igniter cycled during functional check • Technique does not provide all data required for inspection • Approach not applicable in performing check **B. Component pre-cycling** • Requires hot firing to aquire data indicating injector and igniter damage • Approach does not employ hot firing • Approach not applicable in performing check **C. Automatic static checkout** • Use of historical data base • Flowrate, Pc, etc. aquired from previous missions to assess combustion efficiency/degradation • Plume spectroscopy data • Checks performed by sensors and computer • Uses Trend analysis • High resolution images to detect damage/degradation	**Current:** Pressure transducer, temperature sensor, flowmeter	**Advanced:** Plume spectrometer, Remote automated visual inspection.	C	Visual inspection seems impractical due to the inaccessibility of the injector and t/c interior to a fixed remote visual system. Performance parameters can be monitored for degradation. Possible design improvements to components may eliminate check.

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

III. Inspections (contd)

Check	Approach	Sensors /hardware		Selection	Comments
9. Gimbal bearing and TVC attach point for evidence of bearing seizure and fatigue.	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • Measure excessive vibration at TVC attach points and gimbal bearing • Check performed by sensors and computer • Technique does not provide all data required for inspection **B. Component pre-cycling** • Gimballing of the engine over the prescribed range will indicate gimbal bearing and TVC attach point damage (see functional check 14). • Check performed by sensors and computer **C. Automatic static checkout** • Use of historical data base • Vibration of gimbal bearing and TVC attach points at previous engine operation • Torque required for gimballing during prior engine operation • High resolution visuals • Verify correct positioning of nozzle • Checks performed by sensors and computer • Trend analysis applicable	**Current:** allignment sensor,acceler ometers	**Advanced:** Remote automated visual inspection	B	Check the gimbal pattern by cycling the nozzle. Torque required to gimbal may be measured using electro-magnetic actuators. Because this involves testing the functioning of the gimballing mechanism, it will be changed to a functional check.
10. Heat exchanger for cracks, evidence of wear, damage	**A. Preliminary power-up** • Hardware conditioning has occurred • Steady state tank head idle conditions achieved • Check made on transient to pump idle. • View surface remotely for presence of hot spots • Requires a thermally sensitive surface coating for hot spot detection **B. Component pre-cycling** • Check performed prior to engine start • Only option is to measure external leakage from heat exchanger to indicate failure • Performed during leak checks • Inert gas required • Approach not applicable in performing check **C. Automatic static checkout** • Use of historical data base • Pressure, temperature and flow monitor [illegible] ger inlet and discharge from prior operation • High resolution views of surface • Requires a thermally sensitive surface coatir [illegible] t spot detection • Checks performed visually • Checks performed by sensors and computer	**Current:** Pressure transducer, temp sensor, flowmeter,pres surized inert gas source	**Advanced:** remote automated visual inspection	C	Performance data can be used to assess heat exchanger health. A robust design rationale can eliminate this check

OTV AUTOMATED PREFLIGHT METHODS - APPROACHES

IV. Servicing Tasks

Check	Approach	Sensors /hardware		Selection	Comments
1. Combustion zone drying of Pc sensors and igniter valves	**A. Preliminary power-up** • This servicing task is done at engine shutdown • Approach not applicable in performing servicing task **B. Component pre-cycling** • Shutdown purge lox from injector • Apply a quick drying blast to remove any water from MCC • Vacuum environment in space is helpful **C. Automatic static checkout** • Approach not applicable in performing servicing task	**Current:** Pressurized inert gas source	**Advanced:**	B	See J-2 space restart data
2. HPOTP Lox Turbine drive gas intermediate seal pre-start purge	**A. Preliminary power-up** • hardware conditioning has occurred • Steady state tank head idle conditions achieved • Purge done as part of normal pre-start procedure • Power up in itself is not a means for performing this task • approach not applicable **B. Component pre-cycling** • Servicing performed as part of normal pre-start procedure • Pressurized inert gas used to purge the seal **C. Automatic static checkout** • Approach not applicable in performing servicing task	**Current:** pressurized inert gas source	**Advanced:**	B	Purge required - See groundrules and assumptions - pneumatic system

Appendix 3

Issues and Benefits of Preflight Methods

Part A - Issues and Benefits of Preflight Methods - General Approach Descriptions

Preflight Checkout	Approach	Issues and Benefits			Comments
		Space Basing	Vehicle/Infrastructure	Engine system	
	Preliminary Power-up	**Issues:** • Deployment of vehicle may result , particularly if preflight checks occur while vehicle is in orbit. • Determination/resolution of problems too late to avoid missing launch window. • Additional checkout hardware will have to be designed to withstand the space environment for long durations. **Benefits:** • Minimum maintenance requirement.	**Issues:** • Use of propellants required to perform checkouts. • Additional propellant may be required to recover the vehicle if deployed unintentionally. • Short fire-up period required - possibly several seconds. **Benefits:** • No requirement for sophisticated condition monitoring sensors and historical data base.	**Issues:** • Start transient conditions are severe. May cause damage to system. Minor damage detectable by other means may otherwise propogate. • May reduce the life of some components due to additional hot firing. **Benefits:** • Actual hot-fire conditions for realistic assessment of engines readiness to fire. • Preliminary power-up approach is part of routine engine start procedure prior to mission. Therefore, this approach can be used redundantly no matter which preflight checkout approach is selcted.	
	Automated Component Pre-cycling	**Issues:** • Additional checkout hardware will have to be designed to withstand the space environment for long durations. • Greatest maintenance requirements. **Benefits:** • Degradation during space storage evaluated.	**Issues:** • Allowable vehicle payload impacted by the weight and volume of mechanical and electrical hardware required for emulating dynamic conditions. This includes a large supply of pressurized inert gas. **Benefits:** • To Be Determined	**Issues:** • Additional hardware may reduce the reliability of the engine and possibly result in additional failure modes. **Benefits:** • Inert conditions for checkouts. • Assessment based on actual cycling of components.	
	Automated Static Checkout	**Issues:** • Condition monitoring sensors will have to be designed to withstand the space environment for long durations. • Degradation of components during downtime just prior to preflight check must be considered in historical database. • Additional checkout hardware will have to be designed to withstand the space environment for long durations. **Benefits:** • Minimum space maintenance.	**Issues:** • Requires extensive data mass storage capabilities which may impact the allowable vehicle payload due to weight and volume. • Requires the most sophisticated integrated control and health monitoring system of all approaches suggested. **Benefits:** • Remaining life prediction based on accurate analytical methods and life prediction models. • Possibly more rapid checkout sequence since performed statically.	**Issues:** • Many sensors will be required for an accurate assessment of engine readiness to fire. • Many condition monitoring sensors are necessarily intrusive. • Sensors will require a high degree of acuracy and reliability for complete condition assessments. **Benefits:** • Component life not impacted by checkout approach since no components are cycled.	

Part B - Issues and Benefits of Preflight Methods - Functional Checks

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
1. Valve actuator Check	a. Prelim. power-up	**Benefits:** • See references	**General Approaches** • Preliminary Power up **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Requires power consumption for actuation. **Benefits:** • Approach can demonstrate full range of actuator operation	**General Approaches** • Automated component precycling **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Does not adequately assess degradation during idle period. • cannot address full range of actuator operation **Benefits:** • Requires minimal power consumption	**General Approaches** • Automated static check **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor **Alternate Design Recommendations** • n/a	
2. Sensor check/calibration.	a. Prelim. power-up	**Issues:** • High risk aproach to sensor check and calibration. • Low level power-up may not provide sufficiently stable operation to allow sensor calibration. **Benefits:** • provides complete end-to-end sensor system checkout • Provides mechanical input required to check dynamic sensors.	**General Approaches** • Preliminary Power up **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Check of dynamic sensors (speed, torque, acceleration, valve postion,etc.) requires additional complexity of actuation systems and power consumption. **Benefits:** • Provides complete end-to-end sensor checkout	**General Approaches** • Automated component pre-cycling **Sensors/Hardware** •n/a **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Only checks sensor elements for continuity, does not identify all sensing element problems. **Benefits:** • Provides sufficient level of confidence for the operational requirements of most systems	**General Approaches** • Automated Static check **Sensors/Hardware** •n/a **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Functional Checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
3. Pneumatic Component checkout	a. Prelim. power-up	**Benefits:** • Provides most complete checkout of system	**General Approaches** • Preliminary Power up **Sensors/Hardware** • Pressure Transducer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Functional checkout requires power consumption for valve actuation. **Benefits:** • provides excellent functional checkout of pneumatic valves and actuators.	**General Approaches** • Automated Component precycling **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Only provides partial system checkout **Benefits:** • Minimum power consumption required	**General Approaches** • Automated static check **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
4. Operational sequence test	a. Prelim. power-up	**Benefits:** • Provides most complete checkout of system	**General Approaches** • Preliminary Power up **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor • Pressure transducer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Requires power consumption for valve actuation **Benefits:** • Provides most complete checkout with minimal risk to engine or vehicle	**General Approaches** • Automated component precycling **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor • Pressure transducer **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Does not provide complete checkout of system **Benefits:** • Requires minimal power consumption	**General Approaches** • Automated static check **Sensors/Hardware** • Resolver Position sensor • Eddy current position sensor • Pressure transducer **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Functional Checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
5. Control systems redundancy check	a. Prelim. power-up	**Issues:** • High risk to engine to investigate system redundancy during engine operation **Benefits:** • See references	**General Approaches** • Preliminary Power up **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	Not Applicable		
	c. Automated static	**Issues:** • Allows verification of electrical systems only **Benefits:** • Provides high level of confidence in system with minimal risk	**General Approaches** • Automated static check **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
6. Controller memory verification	a. Prelim. power-up	Not Applicable		
	b. Automated pre-cycling	Not applicable		
	c. Automated static	**Issues:** • Past history data not required **Benefits:** • Simple electrical check providing high level of confidence for safe operation	**General Approaches** • Automated static checkout **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Functional Checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
7. Controller pressurization verification	a. Prelim. power-up	**Issues:** • Power-up not required - Simple static check may be performed without firing engine. **Benefits:** • see references	**General Approaches** • Preliminary power up **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	Not Applicable	n/a	
	c. Automated static	**Issues:** • Past history data may not be applicable here. Simple static check may be all that is required. **Benefits:** • Simple pressure check is adequate.	**General Approaches** • Automated static checkout **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
8. HPOTP torque check 9. HPFTP torque check 10 . LPOTP Torque check 11. LPFTP torque check.	a. Prelim. power-up	**Issues:** • Breakaway torque can't be measured at spin-up or power down. **Benefits:** • could provide excellent condition evaluation with proper instrumentation.	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Ferromagnetic torquemeter **Alternate Design Recommendations** • Hydrostatic bearings	Modification to the turbopump torque checks would be required to accommodate the use of hydrostatic bearings. This applies to all approaches.
	b. Automated pre-cycling	**Issues:** • Highly sensitive torquemeter required for measurement of small breakaway torque. • Remote spin system would likely be heavy, complex, and require significant power consumption. **Benefits:** • Safest method for providing dynamic evaluation of pump systems.	**General Approaches** • Automated component precycling **Sensors/Hardware** • Ferromagnetic torquemeter **Alternate Design Recommendations** • Hydrostatic bearings	
	c. Automated static	**Issues:** • Not a complete system checkout • Requires extensive statistical data base to justify the use of this approach **Benefits:** • Provides lightest, simplest checkout with little power consumption	**General Approaches** • Automated static checkout **Sensors/Hardware** • Ferromagnetic torquemeter **Alternate Design Recommendations** • Hydrostatic bearings	

Part B - Issues and Benefits of Preflight Methods - Functional Checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
12. axial shaft travel check	a. Prelim. power-up	Issues: • If significant wear present the T/P could be further damaged during power-up Benefits: • Component integrity verified in dynamic hot-fire environment.	General Approaches: • Preliminary power-up. Sensors/Hardware: • Fiberoptic deflectometer. • Isotopic wear detector. Alternate Design Recommendations: • Hydrostatic bearings.	
	b. Automated pre-cycling	Issues: • Extra weight and complexity of mechanical actuation system. Benefits: • Assesses bearing integrity without T/P rotation which could result in damage if bearings are worn.	General Approaches: • Automated component precycling. Sensors/Hardware • Mechanical actuation system. • Displacement sensor. Alternate Design Recommendations: • Hydrostatic bearings.	
	c. Automated static	Issues: • Axial translation during next start transient may not be predictable from previous firing steady state bearing vibration spectrum. • Requires extensive statistical data base. Benefits: • No additional hardware for displacement.	General Approaches: • Automated static checkout. Sensors/Hardware: • Fiberoptic deflectometer. • Isotopic wear detector. Alternate Design Recommendations • Hydrostatic bearings.	
13. extendible nozzle travel check	a. Prelim. power-up	**Issues:** • Check may not require power-up - simple position check during gimballing sequence may be all that is necessary. • Risk and propellant consumption does not justify added fidelity to nozzle travel check **Benefits:** • Vibration magnitude at extendible nozzle attach point may give an accurate assessment of travel. • Provides closest simulation of actual operating conditions.	**General Approaches** • Preliminary power-up **Sensors/Hardware** • Accelerometer • Eddy current position sensor **Alternate Design Recommendations** • n/a	Since gimballing and nozzle extension / retraction will occur for checkout purposes, the actuating and control mechanisms for these processes should be highly robust.
	b. Automated pre-cycling	**Issues:** • Requires robust gimballing mechanism and nozzle actuator mechnism since full range gimballing required for checkout purposes. • requires power consumption for actuation. **Benefits:** • provides greatest confidence for safe operation for any low risk checkout method.	**General Approaches** • Automated Component precycling **Sensors/Hardware** • Accelerometer • Eddy current position sensor **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Does not adequately assess degradation during idle period. **Benefits:** • low power consumption	**General Approaches** • Automated static checkout **Sensors/Hardware** • Accelerometer • Eddy current position sensor **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Functional Checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
14. Igniter operational check	a. Prelim. power-up	**Issues:** • Special preliminary power up verification provides no advantage over verification during operational start-up. **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Igniter must be highly reliable and robust to accomodate many checkout cycles. • spark check requires power consumption **Benefits:** • Allows verification of proper system operation prior to introduction of propellants	**General Approaches** • Automated component precycling **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Continuity and past history may not provide complete assessment. Cycling should be included. **Benefits:** • see references	**General Approaches** • Automated static checkout **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Leak checks

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
1. HPOTP primary Lox seal	a. Prelim. power-up	**Issues:** • Offers no advantage over monitoring redline pressure during operation **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • increases helium consumption required for normal seal operation. **Benefits:** • verifies system operation prior to introduction of propellants	**General Approaches** • Automated component precycling **Sensors/Hardware** • Pressure transducer • Turbine flowmeter **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Does not adequately assess degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static check **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
2. HPOTP intermediate seal	a. Prelim. power-up	**Issues:** • Past history data provides no advantage over monitoring redline pressure during operation. **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Increases helium consumption required for normal seal operation. **Benefits:** • Verifies system operation prior to introduction of propellants	**General Approaches** • Automated component precycling **Sensors/Hardware** • Pressure transducer • Turbine flowmeter **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Does not adequately assess degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static checkout **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Leak checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
3. MOV Ball seals	a. Prelim. power-up	**Issues:** • Seal integrity cannot be thoroughly evaluated during short power-up. **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Inert gas may not give large enough temp difference to be detected by skin temp sensors - cryogenic may be preferable. • Requirement for extra propellant if cryogenics are used. • Difficult to detect small leakage rates due to mild test conditions. **Benefits:** • Simple to perform pressure lock-up and monitor system pressure decay	**General Approaches** • Automated component precycling **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Past history data does not adequately assess degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static check **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
4. MFV Ball seals	a. Prelim. power-up	**Issues:** • seal integrity cannot be thoroughly evaluated during preliminary power-up. **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Assumes purge line added downstream of fuel inlet valve. • Inert gas may not give large enough temp difference to be detected by skin temp sensors - cryogenics may be preferable. • requirement for extra propellants if cryogenics are used. • Difficult to detect small leakage rates **Benefits:** • Simple to perform pressure lock-up and monitor system pressure decay.	**General Approaches** • Automated component precycling **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Past history does not adequately assess degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static checkout **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Leak checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
5. Propellant valve primary shaft seals	a. Prelim. power-up	**Issues:** • offers no advantage over assessment during actual operation **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Assumes purge line added downstream of fuel inlet valve. • may not be able to detect excessive (hazardous) leakage without full power level conditions (flow, pressure, and temperature). • Inert gas may not give large enough temp difference to be detected by skin temp sensors - cryogenics may be preferable. • requirement for extra propellants if cryogencs are used. **Benefits:** • low risk identification of major leaks.	**General Approaches** • Automated component precycling **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Past history data does not adequately assess degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static check **Sensors/Hardware** • Temperature sensor **Alternate Design Recommendations** • n/a	
6. Pneumatic control assembly internal seals.	a. Prelim. power-up	**Issues:** • Short firing period may not provide enough time to detect leakage. • offers no advantage over assessment during actual operation **Benefits:** • see references	**General Approaches** • Preliminary power -up **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Numerous pressure transducers and checkout valves required to thoroughly check system. • may not be able to detect low level leakage **Benefits:** • Longer measurement period may allow small leaks to be accurately detected. • low risk identification of major leaks.	**General Approaches** • Automated component precycling **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Past history data does not adequately assess seal degradation during idle period. **Benefits:** • see references	**General Approaches** • Automated static checkout **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Leak checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
7. Heat exchanger coil leak test	a. prelim-power up	Not applicable		
	b. automated pre-cycling	Issues: • Complexity, weight, and large quantity of inert gas required. • Cannot discern between internal vs external leaks. • May not detect small leaks which could increase during hot-fire conditions. Benefits: • Inert environment provides safe test conditions. • Can detect leaks generated during thermal transient at last engine shutdown (auto static data may not).	General Approaches: • Automated component precycling. Sensors/Hardware • Pressurized inert gas source. • Pressure transducer. Alternate Design Recommended: • Seamless robust heat exchanger design.	
	c. Automated static	Issues • Historical data base may not be capable of predicting sudden catastrophic failures which are not preceded by shifts on operating parameters. • Small leaks may not be detected in this manner. Benefits: • No additional hardware or inert gas required.	General Approaches • Automated static checkout Sensors/Hardware • Existing thermocouples and pressure transducers.	
8. Heat exchanger coil proof test	a. prelim-power up	Not applicable.		
	b. automated pre-cycling	See previous checkout 7.		
	c. Automated static	Not applicable		

Part B - Issues and Benefits of Preflight Methods - Leak checks (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
9. T/C Assembly outer walls	a. Prelim. power-up	**Issues:** • Short firing period may not provide enough time to detect leakage. • Performance degradation may not indicate localized leakage - could be a result of many other factors. **Benefits:** • Provides reasonable simulation of operating thermal environment.	**General Approaches** • Preliminary power-up **Sensors/Hardware** • Optical leak detector • Pressure transducer • Temperature sensor • Turbine flowmeter **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Throat plug required. • System to place and secure throat plug would likely be highly complex and heavy. **Benefits:** • No benefits to this particular approach since pressurizing the hot gas system is not feasible. However, an optical leak detection approach seems promising .	**General Approaches** • Automated component precycling **Sensors/Hardware** • Optical leak detector (for alternate approach) **Alternate Design Recommendations** • n/a	This check could be performed by injecting IR absorbing gas into liner to visually detect external leakage.
	c. Automated static	**Issues:** • Requires development of sensitive optical hardware and physical degradation identification techniques . **Benefits:** • Leakage from prio. operation may be all that is necessary. • does not required additional commodoties or impose risky operation.	**General Approaches** • Automated static checkout **Sensors/Hardware** • Optical leak detector **Alternate Design Recommendations** • n/a	Design should reflect use of hardware with predicatable degradation characteristics which could augment leak detection techniques.
10 . Combustion and propellant system joints.	a. Prelim. power-up	**Issues:** • Short firing period may not provide enough time to detect leakage. **Benefits:** • Provides reasonable simulation of operating thermal environment.	**General Approaches** • Preliminary Power-up **Sensors/Hardware** • Optical leak detector **Alternate Design Recommendations** • Welded combustion and propellant system joints.	
	b. Automated pre-cycling	**Issues:** • Throat plug required. • System to place and secure throat plug would likely be highly complex and heavy. **Benefits:** • No benefits to this particular approach since pressurizing the hot gas system is not feasible. However, an optical leak detection approach seems promising .	**General Approaches** • Automated component pre-cycling **Sensors/Hardware** • Optical leak detector (for alternate approach) **Alternate Design Recommendations** • Welded combustion and propellant system joints.	
	c. Automated static	**Issues:** • Requires development of sensitive optical hardware . **Benefits:** • Leakage from prior operation may be all that is necessary. • does not required additional commodoties or impose risky operation.	**General Approaches** • Automated static check **Sensors/Hardware** • Optical leak detector **Alternate Design Recommendations** • Welded combustion and propellant system joints.	

Part B - Issues and Benefits of Preflight Methods - Inspections

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
1. Exterior of components for damage/security	a. Prelim. power-up	not applicable		
	b. Automated pre-cycling	not applicable		
	c. Automated static	**Issues:** • Accessibility may be a problem for some interior components • requires engine design with optical access **Benefits:** • see references	**General Approaches** • Automated static checkout **Sensors/Hardware** • Remote high resolution visual **Alternate Design Recommendations** • n/a	Prefer to eliminate requirement by robust design in combination with statistical analysis techniques to predict component life.
2. Thrust chamber assembly for evidence of coolant passage blockage.	a. Prelim. power-up	**Issues:** • Short fire-up may not be effective. Accurate assessment may require an interval of steady state operation. • no advantages over monitoring during actual operation **Benefits:** • see references	**General Approaches** • Preliminary power-up **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Very high inert gas pressures may be required to perform check. Implies a massive inert gas tank. • high gas consumption required to identify blockages **Benefits:** • low risk method of identification	**General Approaches** • Automated component precycling **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	
	c. Automated static	**Issues:** • Past history data does not predict sudden, large scale blockage scenarios (i.e. pump seal fragmentation, etc.) **Benefits:** • In-flight monitoring augmented by trend analysis would be a simple and accurate approach. • slow blockage accumulation easily predictable and can be tracked through operation history.	**General Approaches** • Automated static checkout **Sensors/Hardware** • Pressure transducer **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Inspections (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
3. HPFTP turbine wheel/blades for creacks, fatigue, and damage. 4. HPOTP .... 5. LPFTP .... 6. LPOTP	a. Prelim. power-up	**Issues:** • Short fire-up may not be effective. Accurate assessment may require an interval of steady state operation. • puts engine and vehicle at risk if problem exists **Benefits:** • Optical pyrometer is effective for assessing turbine health and may be a more mature technology than exo-electron fatigue det. • most effective method of identifying damage.	**General Approaches** • Preliminary Power-up **Sensors/Hardware** • Ferromagnetic torquemeter • Optical pyrometer • Plume spectrometer **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	not applicable		
	c. Automated static	**Issues:** • can only track slow degradation • Down time degradation may be an issue. Not considered by past history data. **Benefits:** • Past history performance data in combination with trend analysis should provide accurate assessment. • robust design and statistical analysis can sufficiently mitigate the risk of any failure other than slow degradation. • Optical pyrometer is effective for assessing turbine health and may be a mature technology than exo-electron fatigue det.	**General Approaches** • Automated static checkout **Sensors/Hardware** • Ferromagnetic torquemeter • Optical pyrometer • Plume spectrometer **Alternate Design Recommendations** • n/a	A more robust design should be considered to permit predictable slow degradation which lands itself to a life prediction model.
7. HPOTP bearings for damage	a. Prelim. power-up	**Issues:** • Risk engine hardware during power-up if bearings damaged • short power-up not adequate to assess bearing operation **Benefits:** • see references	**General Approaches** • Preliminary Power-up **Sensors/Hardware** • Fiberoptic deflectometer **Alternate Design Recommendations** • Hydrostatic bearings	Check will also include HPFTP bearings. Hydrostatic bearings and their subsystems in both pumps would require inspection and functional checks.
	b. Automated pre-cycling	**Issues:** • Pre-spin hardware greatly adds weight and complexity to pump. **Benefits:** • low risk approach to determine bearing condition • May use same electrical drive hardware as torque checks.	**General Approaches** • Automated component precycling **Sensors/Hardware** • Fiberoptic deflectometer **Alternate Design Recommendations** • Hydrostatic bearings	Since hydrostatic bearings result in minimal wear, this check although complex, would be required less frequently if this alternate design feature was adopted.
	c. Automated static	**Issues:** • does not address sudden bearing degradation **Benefits:** • probably acceptable since most bearing degradation is a slow function of "in operation" time • Zero gravity environment may prevent wear during downtimes and engine start. Downtime degradation may not be an issue in space.	**General Approaches** • Automated static checkout **Sensors/Hardware** • Fiberoptic deflectometer **Alternate Design Recommendations** • Hydrostatic bearings	

Part B - Issues and Benefits of Preflight Methods - Inspections (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
8. T/C assembly injector face plate, igniter, and lox post tips for erosion, burning, and contamination.	a. Prelim. power-up	**Issues:** • Analysis of exhaust plume may not give complete assessment. • risks further hardware damage and produces harsh operating environment for monitoring devices. **Benefits:** • see references	**General Approaches** • Preliminary power-up **Sensors/Hardware** • Plume spectrometer **Alternate Design Recommendations** • n/a	Robust design should be implemented to reduce need for detailed inspection.
	b. Automated pre-cycling	Not applicable		
	c. Automated static	**Issues:** • Injector elements may be inaccessible using current automated visual techniques. Techniques may require enhancements (intrusive fiber optic devices) for inspection purposes. • cannot address sudden failure occuring at end of subsequent operation. **Benefits:** • trend analysis will identify virtially all failures by monitoring typical slow degradation of the injector	**General Approaches** • Automated static checkout **Sensors/Hardware** • Plume spectrometer • remote high resolution visual • Pressure transducer • Turbine flowmeter • Temperature sensor **Alternate Design Recommendations** • n/a	
9. Gimbal bearing and TVC attach points for evidence of bearing seizure and fatigue.	a. Prelim. power-up	**Issues:** • Not a complete check since assessment relies on vibration data alone. • power-up does not significantly alter the operation the gimbal and TVC system. **Benefits:** • see references	**General Approaches** • Preliminary power up **Sensors/Hardware** • Accelerometer **Alternate Design Recommendations** • n/a	This can be combined with the functional check for ext. nozzle travel which involves gimballing and actuation. The nature of this check makes it a functional check.
	b. Automated pre-cycling	**Issues:** • Requires robust gimballing mechanism since full-range gimballing required for checkout purposes. • requires power consumption for actuation **Benefits:** • Gimballing will provides real-time source for required data. • Vibration data combined with verification of gimballing function provides complete assessment of gimbal system.	**General Approaches** Automated component precycling **Sensors/Hardware** • Accelerometer • Eddy current position sensor **Alternate Design Recommendations** • n/a	Robust gimbal bearing and TVC attach points recommended to delete check. Design for uprated thrust to absorb large thrust loads.
	c. Automated static	**Issues:** • does not address idle time degradation of TVC system • Visuals may be a problem due to inaccessibility. • Vibration data plus position data aquired from past history database may not provide enough information for accurate assessment. **Benefits:** • little power consumption	**General Approaches** • Automated static check **Sensors/Hardware** • Accelerometer • Eddy current position sensor • Remote high resolution visual **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Inspections (contd.)

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
10. Heat exchanger for cracks, evidence of wear, and damage.	a. Prelim. power-up	**Issues:** • power-up forces visual inspection sensors to operate in harsh environment unnecessarily • Potential accessibility problems with visual. • Requires development of physical degradation identification techniques and sensitive optical hardware. **Benefits:** • see references	**General Approaches** • Preliminary power up **Sensors/Hardware** • remote high resolution visual **Alternate Design Recommendations** • n/a	Another possible approach is monitoring inlet and exit conditions - this may result in failure during power up. This may be an option with automated static check .
	b. Automated pre-cycling	Not applicable		
	c. Automated static	**Issues:** •Potential accessibility problems with visual. • must design unit for visual accessibility • Requires development of physical degradation identification techniques and sensitive optical hardware. **Benefits:** • Past history data assessment is safest approach	**General Approaches** • Automated static check **Sensors/Hardware** • remote high resolution visual **Alternate Design Recommendations** • n/a	

Part B - Issues and Benefits of Preflight Methods - Servicing Tasks

CHECKOUT	APPROACH	ISSUES AND BENEFITS	APPLICABLE ISSUES AND BENEFITS REFERENCES	COMMENTS
1 Combustion zone drying	a. Prelim power-up	**Issues:** • no advantage over operational redline **Benefits:** • see references	**General Approaches** • Preliminary power up **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • Assumes purge system is available **Benefits:** • Simple task performed during normal shutdown purge sequence. • requires no change in routine system operation to perform servicing. • Vacuum environment simplifies task due to rapid dissapation.	**General Approaches** • Automated component precycling **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	With a purge system, this task is simple and routine. Without a purge system, self drying of sensors is a possible approach.
	c. Automated static	Not applicable		
2. HPOTP LOx turbine drive gas seal pre-start purge.	a. Prelim power-up	**Issues:** • no advantage over operational redline **Benefits:** • see references	**General Approaches** • Preliminary power up **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	
	b. Automated pre-cycling	**Issues:** • assumes purge system is available **Benefits:** • Part of normal pre-start procedure • requires no change in routine system operation to perform servicing.	**General Approaches** • Automated component precycling **Sensors/Hardware** • n/a **Alternate Design Recommendations** • n/a	With a purge system, this task is simple and routine. Without a purge system, non-purge seals would be required. These would effectively eliminate this task.
	c. Automated static	Not applicable		

Part C - Issues and Benefits of Preflight Methods - ICHM Sensors and Hardware

Sensor Measurement /Advanced Hardware	Issues and Benefits			Comments
	Space Basing	Vehicle/Infrastructure	Engine system	
Static Pressure	**Issues:** • Solar radiation effects unknown **Benefits:** • Calibration can be verified at any point without engine operation • Vacuum can verify absolute pressure.	**Issues:** • Required features dictate size (weight) ie, number of channels, structural requirements, installation needs, etc. **Benefits:** • Sensor is self contained - no additional support hardware required. •No external power supply required.	**Issues:** • Sensor is intrusive - Access must be made through fluid media. **Benefits:** • Calibration can be verifed without engine operation. • Vacuum can verify absolute pressure.	
Static Temperature	**Issues:** • Solar radiation effects unknown • May be subject to long term drift (certain technologies). **Benefits:** • Continuity can be confirmed without engine operation	**Issues:** • Required features dictate size (weight) ie, number of channels, structural requirements, installation needs, etc. **Benefits:** • Sensor is self contained - no additional support hardware required. •No external power supply required.	**Issues:** • Sensor is intrusive **Benefits:** • Continuity can be confirmed without engine operation.	
Flow	**Issues:** • Solar radiation effects on lubricant unknown. **Benefits:** • To Be Determined	**Issues:** • Turbine flowmeters tend to be heavy (16 - 20 oz.) **Benefits:** • Flowmeter is integral with duct - no servicing required. • Pickups are passive - no external power required.	**Issues:** • Flowmeter requires major component teardown is repair is necessary. **Benefits:** • Integral to engine component.	
Speed	**Issues:** • To Be Determined **Benefits:** • No moving parts	**Issues:** • To Be Determined. **Benefits:** • Pick-ups are passive - No external power supply required.	**Issues:** • Intrusive design is mature - non-intrusive design is not. **Benefits:** • Can be non-intrusive.	
Displacement	**Issues:** • To Be Determined **Benefits:** • To Be Determined.	**Issues:** • Sensors require their own unique signal processor. **Benefits:** • Sensor are non-contacting.	**Issues:** • mature design for engine non-existent. **Benefits.** • To Be Determined	
Position (on/off)	**Issues:** • To Be Determined **Benefits:** • No moving parts. • Static displacement can always be measured.	**Issues:** • Limited experience on liquid rocket programs. **Benefits:** • Sensors are lightweight and occupy a small volume.	**Issues:** • To Be Determined **Benefits:** • Sensor can be used in any fluid including lox.	
Acceleration	**Issues:** • To Be Determined. **Benefits:** • Piezoelectric crystals maintain stability over time. • No external power required.	**Issues:** • Piezoelectric transducer output subject to "spiking" at cryogenic temperatures. • Proper operation cannot be verified statically - requires mechanical input. **Benefits:** • Sensors are lightweight.	**Issues:** • To Be Determined. **Benefits:** • Simple non-intrusive installation.	

art C - Issues and Benefits of Preflight Methods - ICHM Sensors and Hardware contd.)

ensor Measurement dvanced Hardware	Issues and Benefits Space Basing	 Vehicle/Infrastructure	 Engine system	Comments
eflectometer	**Issues:** • Limited thermally to 250 F (709 R) **Benefits:** • Fliberoptics unaffected by long term storage. • Immune to EMI/RFI.	**Issues:** • To Be Determined. **Benefits:** • Fiberoptic assembly is lightweight.	**Issues:** • Engine version not mature. • Probe is intrusive. **Benefits:** • To Be Determined.	
xo-electron fatigue detector	**Issues:** • May require routine optical re-allignment. • Light source has limited life. **Benefits:** • Best results have been achieved in vacuum environment. • Can be automated.	**Issues:** • System is currently at prototype stage. • Sensor probe needs to be ruggedized. **Benefits:** • Can be made lightweight. • High sensitivity with low power consumption.	**Issues:** • Repeatability has not been demonstrated on engine materials. **Benefits:** • Non-destructive measurement. • Limited engine disassembly.	
sotope wear detector	**Issues:** • Historical data base required. • Need long-lived reference activity for anchoring data. • Time dependent crystal/detector degradation. • Compensation required for backround radiation via backround subtraction. **Benefits:** • Monitors mass loss from exterior.	**Issues:** • Requires power for multi-channel analyzer and detector. • Detector requires LN_2 cooling. **Benefits:** • Simple data analysis. • Possible real-time implemetation.	**Issues:** • Electronics are suceptable to shock, vibration, and thermal effects. • Type and amount of activation is material dependant. • Shielding of activation by intervening materials. **Benefits:** • Non-intrusive.	
Torquemeter	**Issues:** • Long term stability not demonstrated. **Benefits:** • Eliminate human intervention for torque and runout measurement. • Not affected by vacuum environment.	**Issues:** • May require specialized signal processor. **Benefits:** • Torque and speed measurements aquired from a single sensor. • Torque and speed can be corellated with vehicle parameters.	**Issues:** • Pickup sensor is intrusive. • Pump shaft requires magnetoresistive deposits **Benefits:** • Increase efficiency and reliability of engine system. • Measureing speed, torque, and shaft displacement eliminates redundant sensors resulting in reduced system weight and complexity.	
Automated Visual Inspection	**Issues:** • Computer/video system required to be radiation hardened. • Requires knowledge based system for independent decisions. **Benefits:** • Eliminate human intervention for inspection procedures.	**Issues:** • Computer and optics susceptability to vibration, shock and thermal effects. • Power required for computer, camera, and camera robotics. **Benefits:** • Can be used for vehicle inspections also.	**Issues:** • Criteria needs to be established for determining component condition. • View of component required - either direct access or inspection port. • Resolution of video system. **Benefits:** • Decreases cost and increases speed, reliability, and repeatability of between flight inspections.	
Optical Leak Detection	**Issues:** • Has not been tested in vacuum environment. • May require routine optical reallignment. • Light source has limited life. **Benefits:** • Can be automated. • Eliminate human intervention for leak detection procedures.	**Issues:** • Optics need to be ruggedized. • System requires gas purge. • Currently requires cryogenic (LN_2) cooling for detector. **Benefits:** • Can be made lightweight. • Low power consumption.	**Issues:** • Tracer gas compatability not demonstrated on engine materials. **Benefits:** • Highly sensitive to pinpoint leaks. • Remotely automated operation. • Limited or no engine disassembly required.	

Part C - Issues and Benefits of Preflight Methods - ICHM Sensors and Hardware (contd.)

Sensor Measurement /Advanced Hardware	Issues and Benefits			Comments
	Space Basing	Vehicle/Infrastructure	Engine system	
Plume Spectroscopy	**Issues:** • Calibration required prior to engine start. • Potential interference from backround solar radiation. **Benefits:** • Demonstrated long term component stability .	**Issues:** • Optics need to be ruggedized. **Benefits:** • Low power consumption.	**Issues:** • Spectrometer must be isolated from engine. Uses fiberoptic probe to transmit data to spectrometer. **Benefits:** • Modular components for repair simplicity. • Verification of nominal combustion. • Thrust level determination. • Realtime evaluation of hardware erosion and anomalous combustion. • Identification and quantification of eroding materials. • Engine readline/cutoff capability.	

Part D - Issues and Benefits of Preflight Methods - Alternate Design Recommendations

Design Recommendation	Effected Preflight Requirement(s)	Issues and Benefits: Space Basing	Issues and Benefits: Vehicle/ Infrastructure	Issues and Benefits: Engine System
Component: <u>Heat Exchanger</u> **Motivation for selecting an alternate:** To delete the requirements for the heat exchanger leak test and proof test. Based on the current design, small leaks would be very difficult to detect. A robust design will greatly reduce the probability of this leakage over the life of the engine. **Current Design Description:** Cylindrically contoured section, flat thin multi-brazed panels. This design reflects minimum weight and convenient packaging. **Suggested Alternate Design Description:** Highly robust flexible line in shell. This design reflects a minimal number of welds and effectively eliminates coil leakage. **Other alternate Design Concepts:** 1. Similar to current design with minimal changes to the basic geometry. Materials would be selected for high fatigue life. Design would reflect use of intermediate channels containing inert fluid would be located between the Lox and the hydrogen for minimum risk.	**Leak checks:** The following requirements may be deleted using the proposed robust design rationale. 1. Heat exchanger coil leak test. 2. Heat exchanger coil proof test. **Inspections:** The following inspection may be required less frequently , however the requirement cannot be deleted. 1. Heat exchanger inspection for cracks, evidence of wear, and damage.	**Issues:** • Heat exchanger may be subject to debris damage because of large surface area. The actual surface area exposed will depend on the location of the heat exchanger in the powerhead. • Damage caused by debris may propogate with repeated engine firings. • Thermal cycling caused by solar radiation may increase probability of failure - the alternate design should allow for this. • Radiation effects on brazed joints - Long duration space exposure may degrade material and reduce strength. A solution might be diffusion bonding or some protective coating. **Benefits:** • A robust design will eliminate the leak check requirements and make the heat exchanger less vulnerable to damage from debris. • Robust design should not be adversely affected by the space environment. • Small volume leakage of gasses into space will dissipate rapidly thus reducing the overall risk of space combustable mixtures.	**Issues:** • Payload may possibly be impacted because of the increased heat exchanger weight. • A mature operational data base is required to reduce the need for an external inspection of the heat exchanger. **Benefits:** • Overall simpler diagnostics since the leak check requirements can be deleted	**Issues:** • Robust design may result in different engine performance characteristics due to different system delta-P and heat transfer characteristics. • Higher weight and volume may impact the component arrangement on the engine powerhead. **Benefits:** • Robust design improves overall engine reliability, maintainability, and safety. • No special checkout valves required.
Component: <u>Combustion and propellant system joints.</u> **Motivation for selecting an alternate:** To delete the requirement for leak checking the combustion and propellant system joints. **Current Design Description:** Flanged and bolted joints located throughout the engine system **Suggested Alternate Design Description:** Welded combustion and propellant system with the exception of the vehicle interface flanges and possibly the extendible / retractable nozzle attach point. The welds would reflect a very high factor of safety. **Other alternate Design Concepts:** 1. Welded nozzle extension which would allow the nozzle to extend from a retracted position using a bellows-convolute nozzle design. This eliminates leakage from the extendible nozzle attach point.	**Leak checks:** The following leak check requirement would not be deleted, however it would be simplified using the proposed design rationale . This is because only the extendible nozzle attach point seal would need to be checked for seal integrity. 1. Combustion and propellant system joints for leakage.	**Issues:** • Radiation effects on welds may cause degradation. No other problems are anticipated. • Special tools for space maintainability would need to be developed if space maintainability was a consideration. **Benefits:** • Small volume leakage of gasses into space will dissapate rapidly. • Overall simpler diagnostics since the leak checking requirement has been simplified. • Space maintainance is potentially simpler with welds than bolted flanges because of fewer parts. This assumes the development of special tools.	**Benefits:** • Heavier payload permitted since welds are lighter in weight than flanges. • Cost and reliability benefits since welded joints are simple, rugged, and have fewer parts.	**Issues:** • Engine removal for maintenance is currently assumed. • A very high factor of safety is required to assure quality welds which can withstand many cycles under extreme conditions. • Drop-through of weld into system may cause downstream contamination. There are design solutions to mitigate this, possibly at the cost of weight. **Benefits:** • Reduction in the number of leakage paths . • Eliminates concern for damage to flanges, seals, and a large number of bolts. • Tighter and lighter packaging is possible because of elimination of bulky flanges and bolts.

Part D - Issues and Benefits of Preflight Methods - Alternate Design Recommendations (contd.)

Design Recommendation	Effected Preflight Requirement(s)	Issues and Benefits		
		Space Basing	Vehicle/ Infrastructure	Engine System
Component: Turbopump Bearings **Motivation for selecting an alternate:** To delete the requirement for the axial shaft travel check, and the bearing damage inspection for the fuel and lox turbopumps. **Current Design Description:** Ball bearings on both the pump and turbine ends of both the fuel and oxidizer pumps. One alternative design included a series hybrid bearing which consists of a ball bearing and a hydrostatic bearing on the outside diameter of the ball bearing. **Suggested Alternate Design Description:** Exclusive use of hydrostatic bearings on the high presure turbopumps. **Other alternate Design Concepts:** 1. Hybrid bearing concept where the hydrostatic bearings are augmented with a ball bearing.	**Functional Checks** :The following checkouts are not eliminated but would need to be modified. For example, a torque check with an unpressurized hydrostatic bearing will always reveal rubbing at the bearing. For the torque check to be meaningful, the bearing should either be pre-pressurized or be augmented with some kind of axial centering support or ball bearing : 1. HPFTP torque check. 2. HPOTP torque check. 3. LPFTP torque check. 4. LPOTP torque check. The following checkout can be deleted since it would not be meaningful with the use of hydrostatic bearings: 1. Axial shaft travel check. **Inspections**:The following requirements cannot be eliminated but would need to be modified to accommodate hydrostatic bearings. The main hydrostatic bearing issue is wear. 1. HPOTP bearings for damage (wear). 2. HPFTP bearings for damage (wear).	**Issues:** • Materials and coatings selected for hydrostatic bearing components may be affected by solar radiation, however these effects are likely to be minimal. • The lengthy downtime in space could effect the hydrostatic bearings depending on the configuration. **Benefits:** • Shaft could be held in the centered position with relative ease due to lack of gravity. A centered shaft would virtually eliminate wear of the bearing during start-up, shutdown, and transport. Adequate hydrostatic support forces to overcome hydraulic side forces during start/shutdown must be assured.	**Issues:** • External hardware including lines, fluid tank, several valves, and some electronics hardware for feedback and control are required for hydrostatic bearing pressurization. Pressurization is required as a means of eliminating bearing wear during transients. • Payload will be impacted by the additional weight of a filtration system required for the hydrostatic bearing fluid. • Line interfaces to the vehicle will be required if the hydrostatic bearings are fed from from an external source. **Benefits:** • Vehicle vibration and noise levels may be reduced as a result of the increase in bearing damping.	**Issues:** • Contamination could result from hydrostatic bearing wear therefore some form of filtration may be required. Added filters could increase the system pressure drop. • Hydrostatic bearing flows are typically parasitic and do lead to a slight reduction in pump efficiency. **Benefits:** • Significant gain in bearing life can be achieved by using hydrostatic bearings. The actual life will depend on the duty cycle. Many starts and stops will limit the life, however, no wear occurs during sustained operation.