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OPERATIONALLY EFFICIENT PROPULSION SYSTEM STUDY(OEPSS) DATA BOOK

Volume IX Preliminary Development Plan for an Integrated Booster Propulsion Module (BPM)

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FOREWORD

This document is part of the final report for the Operationally Efficient Propulsion System Study (OEPSS) conducted by the Rocketdyne Division of Rockwell International. The study was conducted under NASA contract NAS10-11568, and the NASA Study Manager was Mr. R. E. Rhodes. The Rocketdyne Program Manager was R. P. Pauckert, the Deputy Program Manager was G. Waldrop, and the Project Engineer was T. J. Harmon. The period of study was from April 1989 to October 1992.

ABSTRACT

A preliminary development plan for an integrated propulsion module (IPM) is described. The IPM, similar to the STME engine, is applicable to the ALS baseline vehicle. The same STME development program ground rules and time schedule were assumed for the IPM. However, the unique advantages of testing an integrated engine element, in terms of reduced number of hardware and number of system and reliability tests, compared to single standalone engine and MPTA, are highlighted. The potential ability of the IPM to meet the ALS program goals for robustness, operability and reliability is emphasized.

TABLE OF CONTENTS

TABLES

FIGURES

INTEGRATED PROPULSION MODULE (IPM) DEVELOPMENT PROGRAM

1.0 Introduction

The Advanced Launch System (ALS) Phase B engine program has defined a baseline engine configuration designated the Space Transportation Main Engine (STME). This standalone engine has a fixed thrust of 580,000 lb. vacuum and a chamber pressure of 2250 psia. The engine uses a gas generator (GG) to drive the liquid hydrogen (LH_2) and liquid oxygen (LOX) turbopumps that are mounted in series. The combustion chamber is cooled with LH_2 and the separable nozzle is cooled with turbine exhaust gas. This engine is shown in Figure 1 and the baseline ALS booster propulsion module with 7 STME's is shown in Figure 2. Although the ALS program has stated goals of reducing overall costs and improving operability without degrading reliability, the selection of a standalone engine concept similar to previous main engine configurations indicates that the goals may be difficult to achieve.

As part of the ALS Advanced Development Program (ADP) a parallel study was initiated to determine an alternate approach to the rocket engine configuration that could be shown with higher certainty to be able to meet the ALS goals of lower cost and improved operability without degrading reliability. This study titled the Operationally Efficient Propulsion System Study (OEPSS) has determined that an Integrated Propulsion Module (IPM) is the best approach to achieve the aforestated goals. This concept packages the major engine components and subsystems into an engine element consisting of a single gas generator driving the fuel and oxidizer turbopumps closely mounted in series. The discharge flow from the pumps is routed through high pressure ducts to their respective inlet ports in 2 thrust chamber assemblies (TCA's). Multiple engine elements are packaged with the vehicle propulsion module subsystems including the electrical power, pneumatic, control monitor and propellant feed systems to form the IPM. The ALS baseline vehicle has 7 STME's in the booster stage and 3 STME's in the core stage. An equivalent IPM capability consists of a 4 engine element booster and 2 engine element core. The engine element is shown in Figure 3 and the booster configuration with 4 engine elements is shown in Figure 4. A description of the IPM major propulsion module and engine element subsystems is shown in Figure 5.

This report describes the development programs for the standalone STME (ALS) and the IPM in sufficient detail to allow comparison. This comparison clearly shows the benefits of the IPM concept.

SPACE TRANSPORTATION MAIN ENGINE

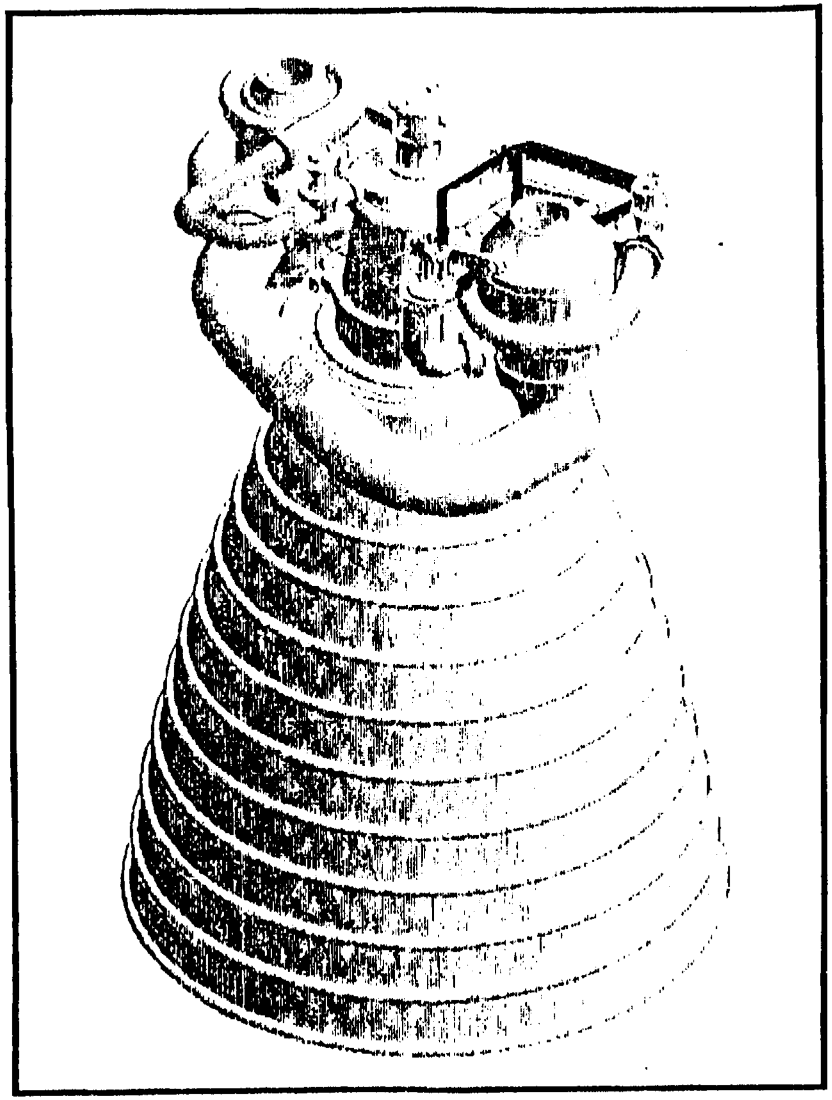

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FIGURE 1

CONVENTIONAL BOOSTER PROPULSION SYSTEM
7 – ENGINE

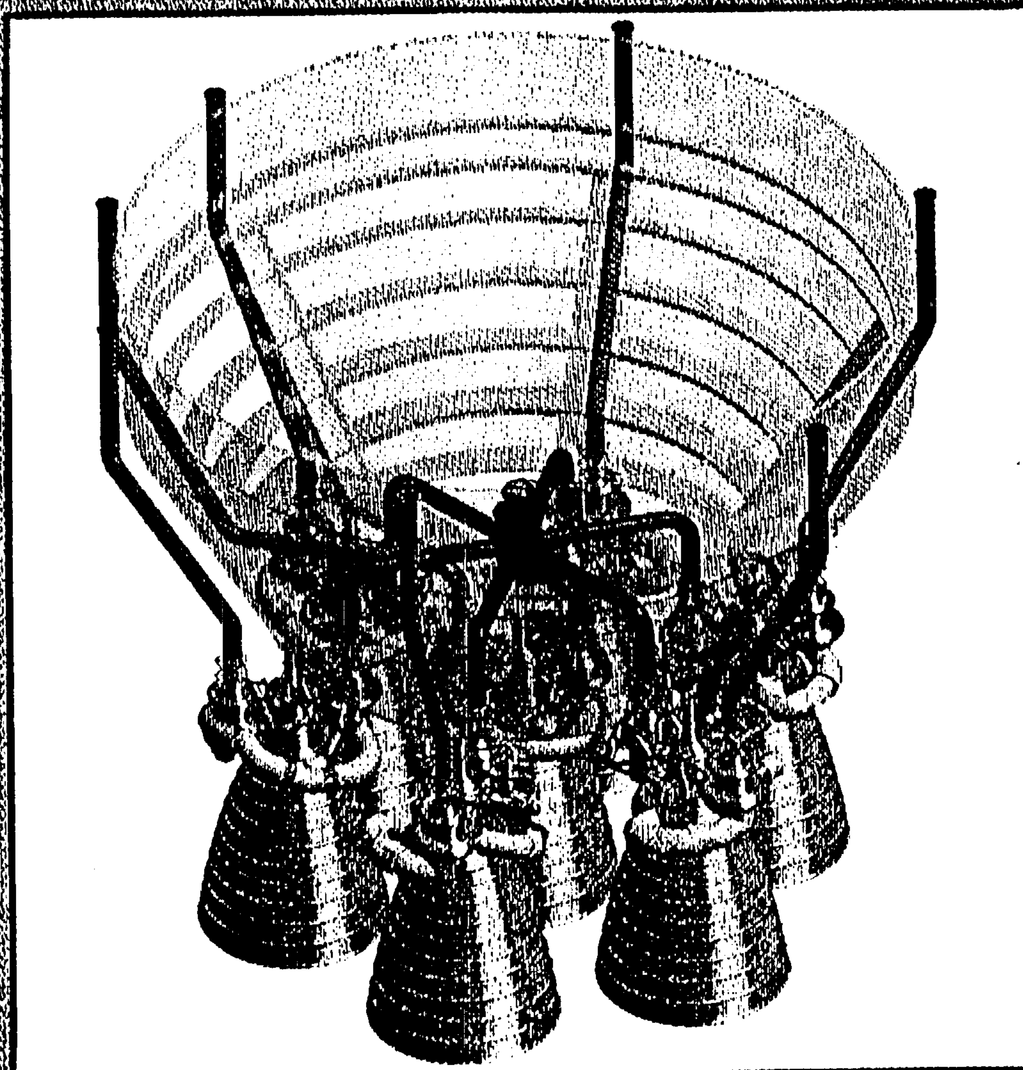

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FIGURE 2

INTEGRATED PROPULSION MODULE – ENGINE ELEMENT

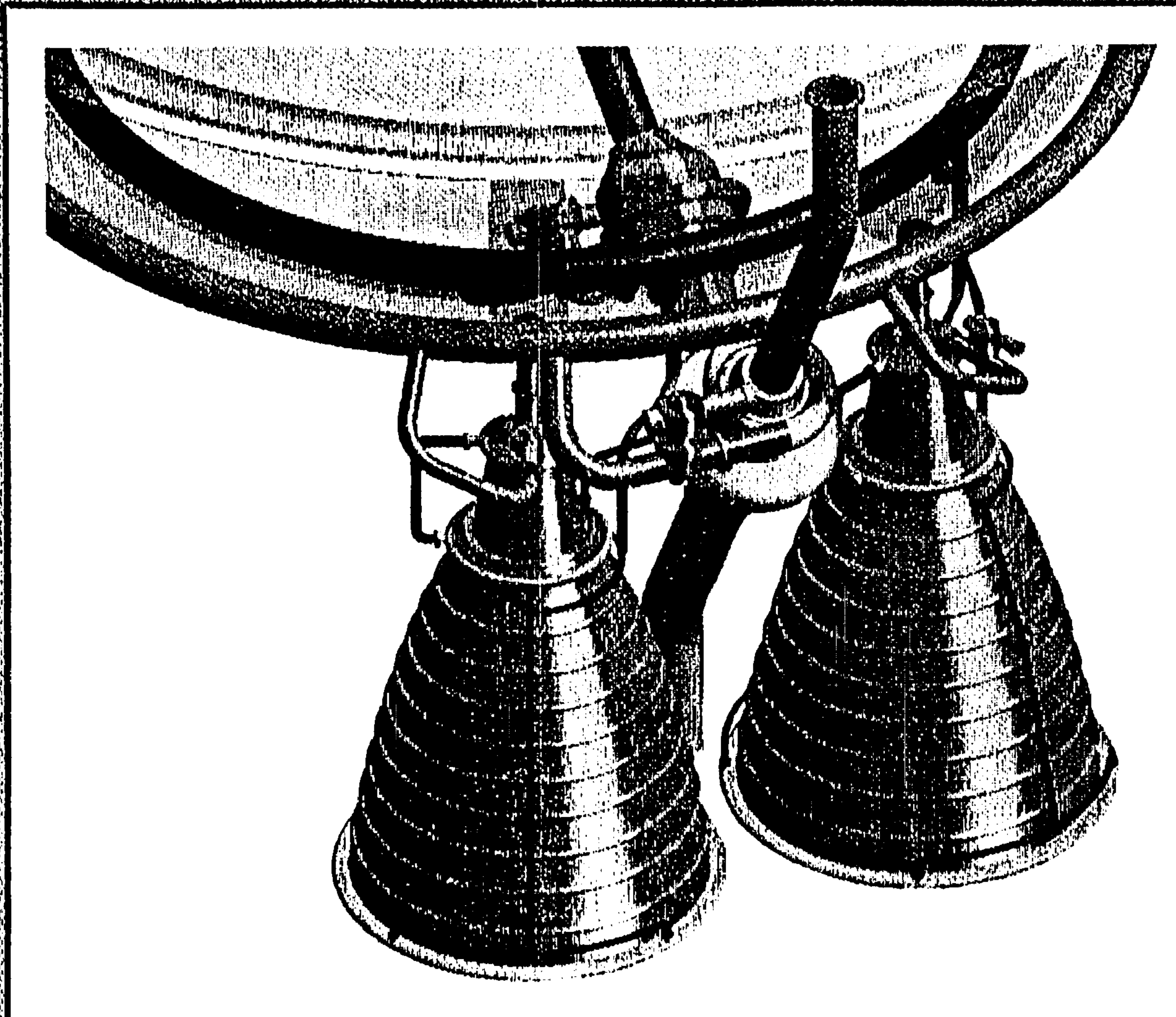

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FIGURE 3

INTEGRATED BOOSTER PROPULSION MODULE – ENGINE
8 – THRUST CHAMBERS

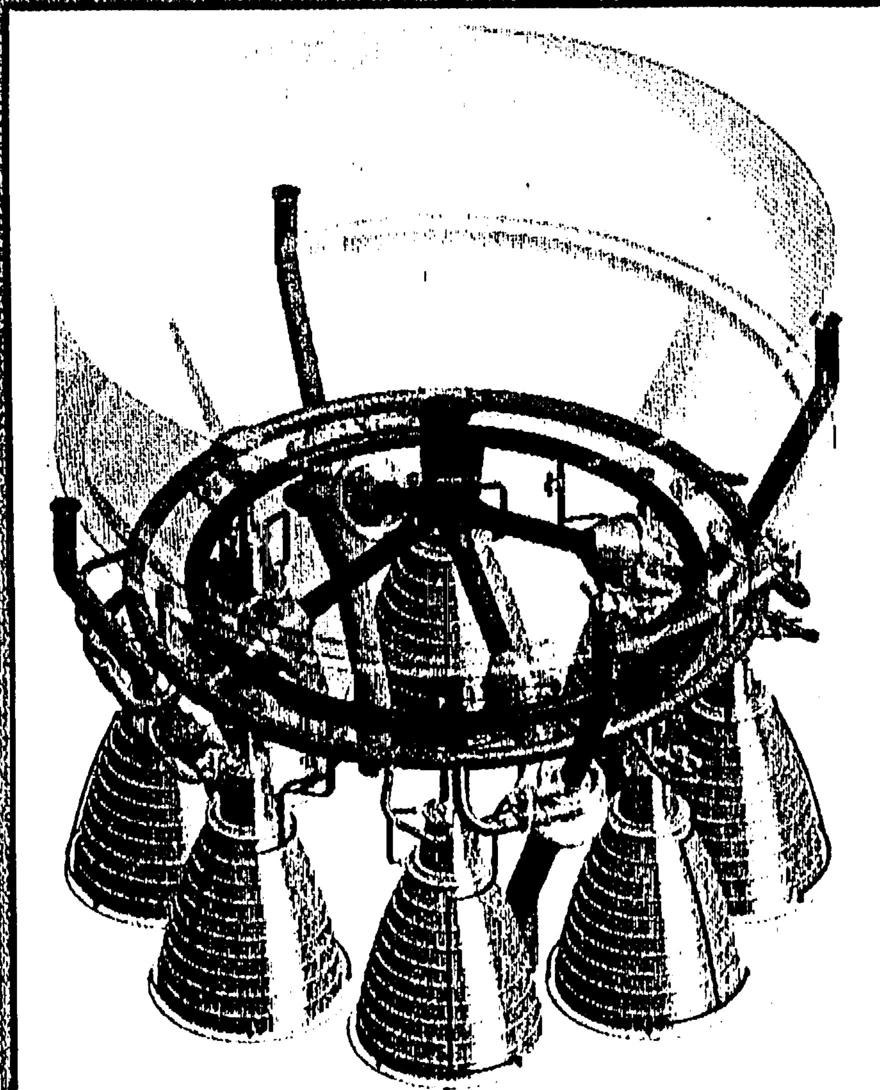

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FIGURE 4

INTEGRATED PROPULSION MODULE SUB-SYSTEMS

Propulsion Module

- Propellant feed systems
  - Pre valves
  - Fill and drain disconnects
  - Staging disconnects
  - Ducting and manifolds
- Helium system
  - Tank(s)
  - Valves
  - Lines
- Tank Pressurization
  - Lines
  - Orifices
  - Valves
- Electrical power supply
  - Batteries
  - Harnesses
  - Buses
- Control system
  - Controller(s)
  - Sensors
  - Harnesses
- Heat exchanger

Engine Element

- Gas Generator
  - Valves
  - Injector / combustor
- Fuel turbopump
- Oxidizer turbopump
- Thrust chamber assemblies (2)
- Control valves
- Ducting

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FIGURE 5

91ALS-012- 70

1.1 Advantages of the IPM Concept

The IPM Concept shown in Figure 4 has eight thrust chamber assemblies (TCA's) fed by two high pressure manifolds. One for LOX and the other for LH_2 propellants. Four turbopump packages each consisting of a gas generator, LH_2 turbopump and LOX turbopump in a series arrangement are shown to supply the respective high pressure manifolds. The fuel propellant supply ducting system from the main vehicle tank to the pump inlet is shown as a single line from the main vehicle tank splitting into four outlets, one to each of the four turbopumps. Although not shown in Figure 4, the pneumatic (Helium) system, main tank pressurization system (consisting of a single heat exchanger with plumbing and control valves for each main tank) the electrical power and associated distribution system and the engine control monitor module are similarly manifolded or their functions are combined into respective single packages to serve the turbopumps or TCA's. A comparison of the ALS propulsion module with 7 STME's shown in Figure 2 and the IPM configuration shown in Figure 4 for an equivalent 7-engine booster, shows a reduction in the number of turbopump sets from 7 to 4. Also the number of heat exchangers and controller monitor systems are reduced from 7 to 1. The reduction in major subsystems allows a significant reduction in the number of lines, valves and flow restrictors required for the pneumatic systems used for control and purging. Also the number of harnesses and buses for the electrical power supply system would be significantly reduced. This reduction in major engine subsystems and support systems allows significantly greater access within the propulsion module compartment as compared to the ALS 7-engine booster configuration. The reduced number of components and subsystems results in increased design reliability.

Integration of the major engine subsystems with the propulsion module subsystems requires that they be designed and tested simultaneously. The integrated design will be strongly driven by operability features such as access, servicing and maintenance. The early integrated testing of the module subsystems with the engine element subsystems will allow any integration problems to be surfaced early.

The traditional approach for a new vehicle system such as the ALS is to design and test the stand alone engine components and complete system independent from the propulsion module subsystems and them integrate them late in the program into a limited Main Propulsion Test Article (MPTA) hotfire test program. Any major problems surfaced at this late date will most likely delay the first flight.

As stated previously the IPM approach to design and testing requires that they be accomplished simultaneously. The simultaneous design will significantly benefit operability and the reduced number of components and subsystems will increase design reliability (see reliability section). The other major benefit of the IPM comes from the simultaneous testing of the propulsion module subsystems with the single element subsystems early in the program. This integrated testing starts with the component hot fire testing when the module propellant ducting, pneumatic, and control systems are tested with the gas generator / turbopumps and thrust chamber assembly subsystems. Component testing is followed by single-engine element testing which again allows the module subsystems to be integrated into the system test program early and in a more complete manner. The next level of testing is the complete IPM which allows testing of the multi-engine elements with the module subsystems much earlier in the program.

The development approach described for the IPM offers the added advantage of eliminating the traditional interface between the standalone engine and the module subsystems thus significantly reducing the coordination and documentation required. The IPM approach has the potential to significantly reduce the Life Cycle Cost (LCC) of the propulsion system by reducing the number of components required, improving operability and reducing the number of hotfire tests. The reduced number of components and the earlier testing of the integrated systems will result in a safer and more reliable system. The advantages of the IPM approach are summarized in Figure 6.

2.0 Ground Rules and Assumptions

The groundrules and assumptions used to prepare the DDT&E program for the IPM are essentially the same as those used for the standalone STME DDT&E program. These are:

- DDT&E consists of 2 sub-phases: Prototype subphase and Full Scale Development (FSD) subphase
- IPM Developed for both the booster and core vehicles
- Reliability goal demonstrated for engine element as follows...
  - 99% with 50% confidence prior to first flight
  - 99% with 90% confidence prior to third flight
- Booster and core IPM's for first 2 flights included in planned program
- Contractor facilities used for component laboratory testing of certain items and subsystems such as control / monitor system, valves, pneumatic system components, etc. prior to use in hotfire testing
- Government supplied hotfire and IPM's assembly facilities

ADVANTAGES OF AN INTEGRATED PROPULSION MODULE (P/M)

- **Propulsion module sub-systems designed and tested with engine-element (problems surfaced early)**
- **Traditional engine/vehicle interface eliminated (coordination/ documentation significantly reduced)**
- **Operability features will drive integrated design**
  - Access, servicing, maintenance must be considered during initial design
  - Reduced number of major components
- **More hot-fire testing of the complete propulsion module**
  - More thorough characterization of the total system
  - Reliability demonstration tests reduced (-83%)
  - Required hot-fired tests reduced (-66%)
  - Formal demonstration (MPTA, PFC, FFC) integrated into development program with minimal additional effort
- **Increased operating robustness**
  - 3 major subsystems can fail and still make mission
- **Higher overall reliability because of reduced number of major components and subsystems**

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FIGURE 6

91ALS-012-62

- Contractor services provided to support hotfire and assembly operations include: test article assembly, test article installation into the hotfire test facilities, testing and removal, data analysis and contractor supplied GSE / STE maintenance.
- Prototype sub-phase IPM design close to production design; design update only planned in FSD program
- Majority of component testing accomplished in prototype program; component testing in FSD program to evaluate design changes
- 4 single-engine elements tested in prototype program (comparable to 4 standalone engines in STME program)
- FSD testing will achieve the following objectives
  - Complete characterization testing of single-engine element
  - Complete reliability demonstration on booster module (allows testing of 4 engine elements for each hotfire test)
  - Complete certification program PFC and FFC on multi engine elements (simulating booster and core configurations)

The programmatic groundrules and assumptions listed are the same as those planned for the STME program. The hotfire test program differs in that a majority of the testing in the FSD program is accomplished with multi - engine elements simulating the booster (4 engine elements) or core (2 engine elements) configurations. This difference is one of the major benefits of the IPM approach.

3.0 Development Program

The development programs for the STME and the IPM are presented in the section. The development program for the STME is based on the NASA program plan and schedule in effect in mid 1990. NASA has changed the plan and schedule several times since and it is still changing today. The development program plan and schedule for the IPM has the same start to completion period, but some of the activities are scheduled differently from the NASA mid 1990 STME plan and schedule. These two schedules are shown in Figures 7 and 8 respectively.

3.1 STME Development Program

The STME development plan and schedule is shown in Figure 7 has 2 subphases: prototype engine subphase lasting 71 months and an FSD subphase lasting 108 months with the 2 subphases overlapping by 54 months. The planned prototype subphase design effort will produce an engine configuration close to the production design. Full Total Quality Management (TQM) techniques will be applied to the design to achieve the objective. The overlapping FSD design effort will basically update the prototype design based on data acquired from the prototype component and engine hotfire testing.

The prototype hotfire testing consists of 60 to 70 major engine subsystem tests, including the gas generator, fuel and oxidizer turbopumps and thrust chamber assembly, and 120 complete engine system tests. All component and engine system hotfire tests are conducted in static test positions with facility provided propellant feed, electrical, and pneumatic systems.The FSD component hotfire test plan provides for 40 to 60 major engine subsystem tests to verify changes to the gas generator, fuel and oxidizer turbopumps and thrust chamber assembly. The engine system hotfire test program includes 622 tests to characterize engine operation, demonstrate the reliability goals and complete the PFC and FFC certification tests.

The combined prototype and FSD engine system test program plan and schedule is shown in Figure 9. As shown a Main Propulsion Test Article (MPTA) hotfire test program is planned to start approximately 6 1/2 years after program start and 1 year prior to the first vehicle launch. The MPTA test program planned as 12 hotfire tests of a 7-engine cluster is the only testing of the STME with the vehicle propulsion support systems such as the propellant supply, electrical and pneumatic systems. A significant problem surfaced at this late date could delay the first flight. The DDT&E program for the STME is planned for a total of 960 equivalent single engine tests. A breakdown of these tests is shown in Table 1. This testing will be accomplished with 65 new and 4 rebuilt engines. A breakdown of the engine hardware requirements is shown in Table 2.

STME DEVELOPMENT PROGRAM PLAN AND SCHEDULE

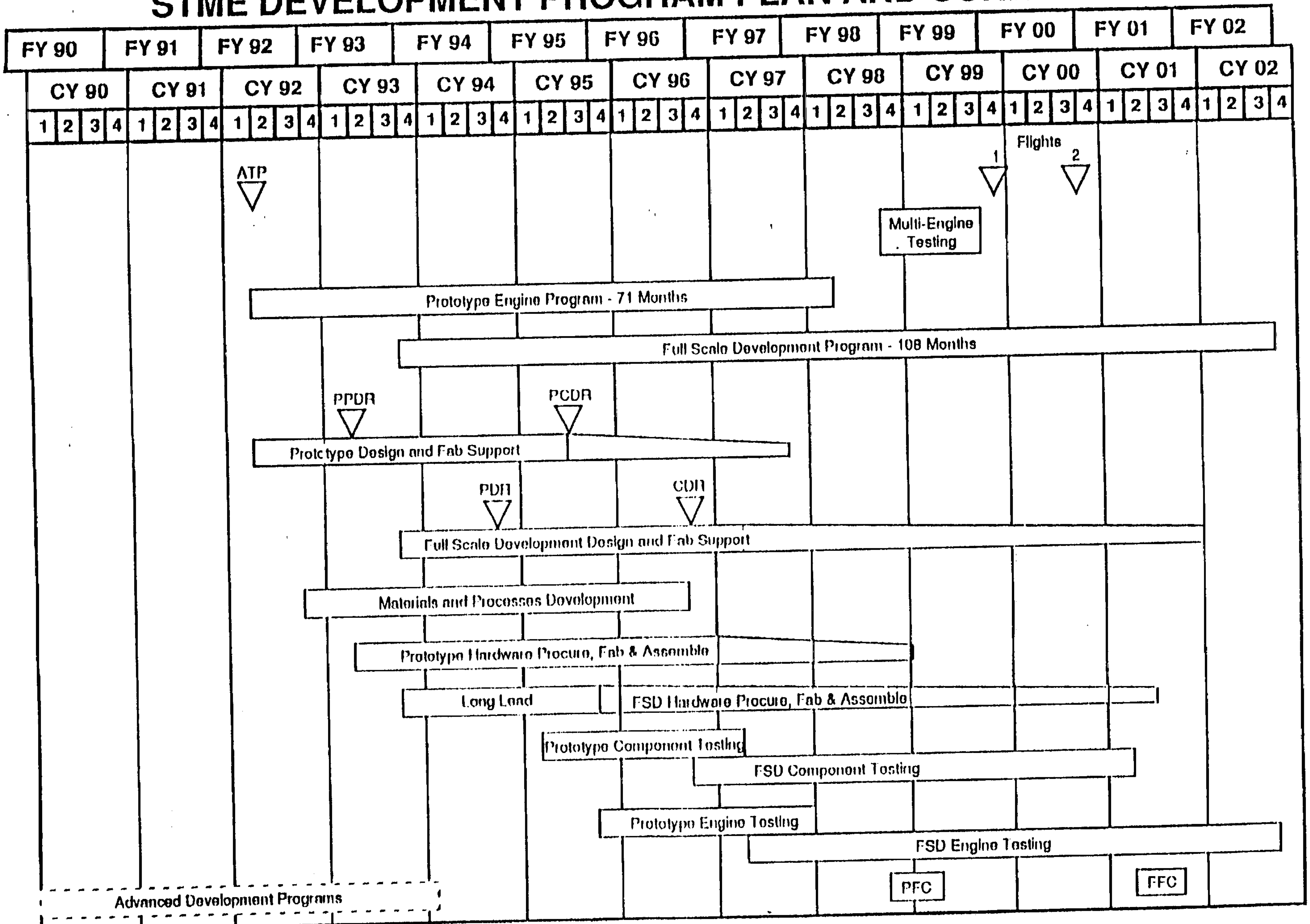

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FIGURE 7

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INTEGRATED P/M DEVELOPMENT PROGRAM PLAN & SCHEDULE

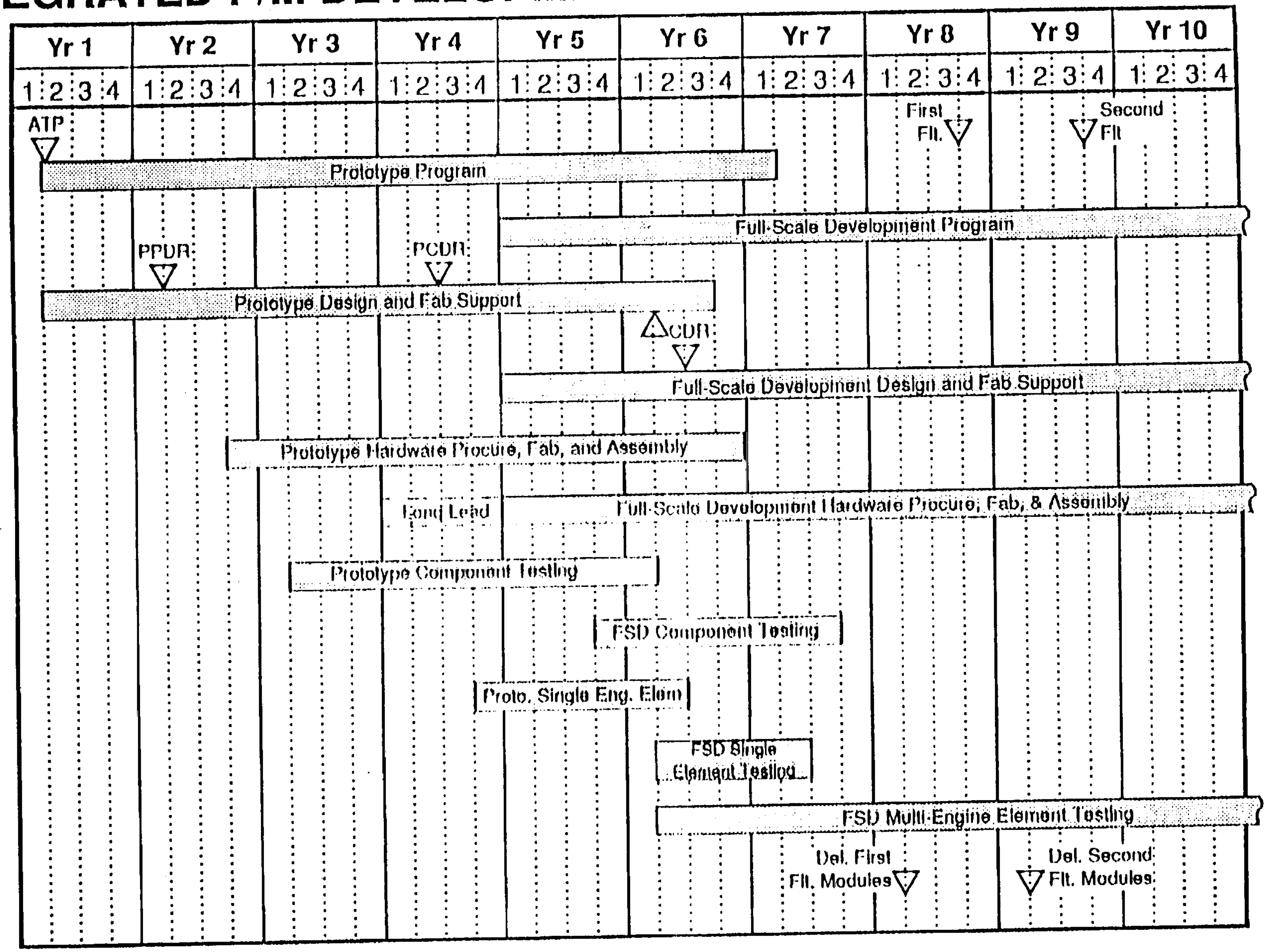

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FIGURE 8

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91ALS 012 67

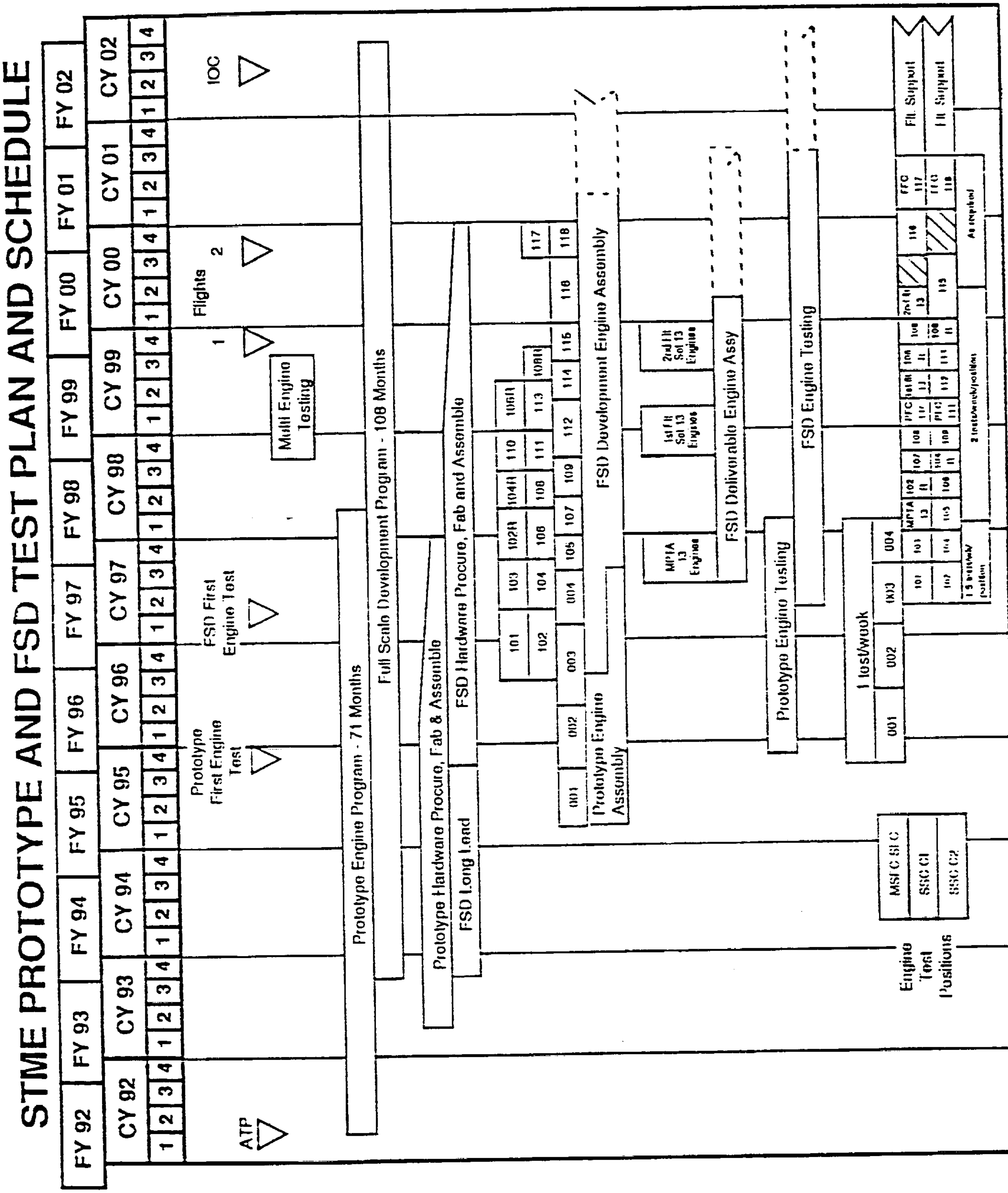

FIGURE 9

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STME SYSTEM DEVELOPMENT TESTS

Purpose	Number Planned
Prototype program	120
FSD development (includes PFC & FFC)	622
MPTA acceptance (2 tests x 13 engines)	26
MPTA program (12 tests x 10 engines)	120
Flight engine acceptance (2 tests x 26 engines)	52
Flights (2 x 10 engines)	20
	960

TABLE 1

STME DEVELOPMENT ENGINE REQUIREMENTS

Application	Number Required
Development Program	
Prototype sub-phase	4
FSD sub-phase	18 (14 new; 4 rebuilds)
PFC	2
FFC	2
Spares	4 (3 FSD, 1 prototype)
MPTA Program	
Booster	7
Core	3
Spares	3
Flight Program	
Vehicle sets (2)	20
Spares	6
Total	69 (65 new, 4 rebuilds)

TABLE 2

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91ALS-012- 69

3.2 IPM Development Program

The IPM development plan and schedule shown in Figure 8 also has 2 subphases; a prototype engine subphase listing 72 months and an FSD subphase lasting 60 months with the 2 subphases overlapping by 27 months. This schedule has approximately the same number of months for the prototype subphase (71 months for STME vs. 72 months for IPM) but the overlap is reduced from 54 months to 27 months and the FSD phase is reduced from 108 months to 60 months. By delaying the start of FSD until the prototype single-engine element testing is in progress the design update will have a larger hard database available which will reduce risk in the FSD design. The approach to designing the IPM in the prototype phase is the same as in the STME approach, that is, produce a design close to the production design. Full TQM techniques will be applied to achieve the objective.

The prototype hotfire testing of the IPM components consists of 60 to 70 major subsystem tests including the gas generator, fuel and oxidizer turbopumps and thrust chamber assembly. The major difference between the planned STME component tests and the IPM component tests is that the IPM engine element components are tested with the propulsion module subsystems including the low pressure inlet ducting to the turbopumps, the high pressure ducting to the TCA's and gas generator and the control / monitor systems to the extent possible. The propulsion module and engine element subsystems are described in Figure 5.

The prototype subphase engine element testing includes testing of 4 single-engine elements integrated with the module subsystems including propeliant ducting, control monitor system, and pneumatic system for 120 tests.

The FSD component hotfire testing consists of 40 to 60 major subsystem tests including the gas generator, fuel and oxidizer turbopumps and TCA's and their respective propulsion module subsystems to verify any design changes resulting from testing in the prototype program. The integrated engine propulsion module component / subsystem test plan is shown in Figure 10. The prototype single engine test schedule is shown in Figure 11 and the test objectives are shown in Table 3.

The FSD integrated engine propulsion module system hotfire test plan is also shown in Figure 11. As indicated, 2 single-engine elements are planned for hotfire testing. The single elements will be tested with their propulsion module subsystems as described in Figure 5 to the extent possible. The objective of testing these single engine elements is to verify any design changes resulting from the prototype program and characterize the operation of the single-elements in preparation for the multi element testing to follow. As shown in Figure 11, both 2-engine element and 4-engine

INTEGRATED P/M COMPONENT/SUBSYSTEM TEST PLAN

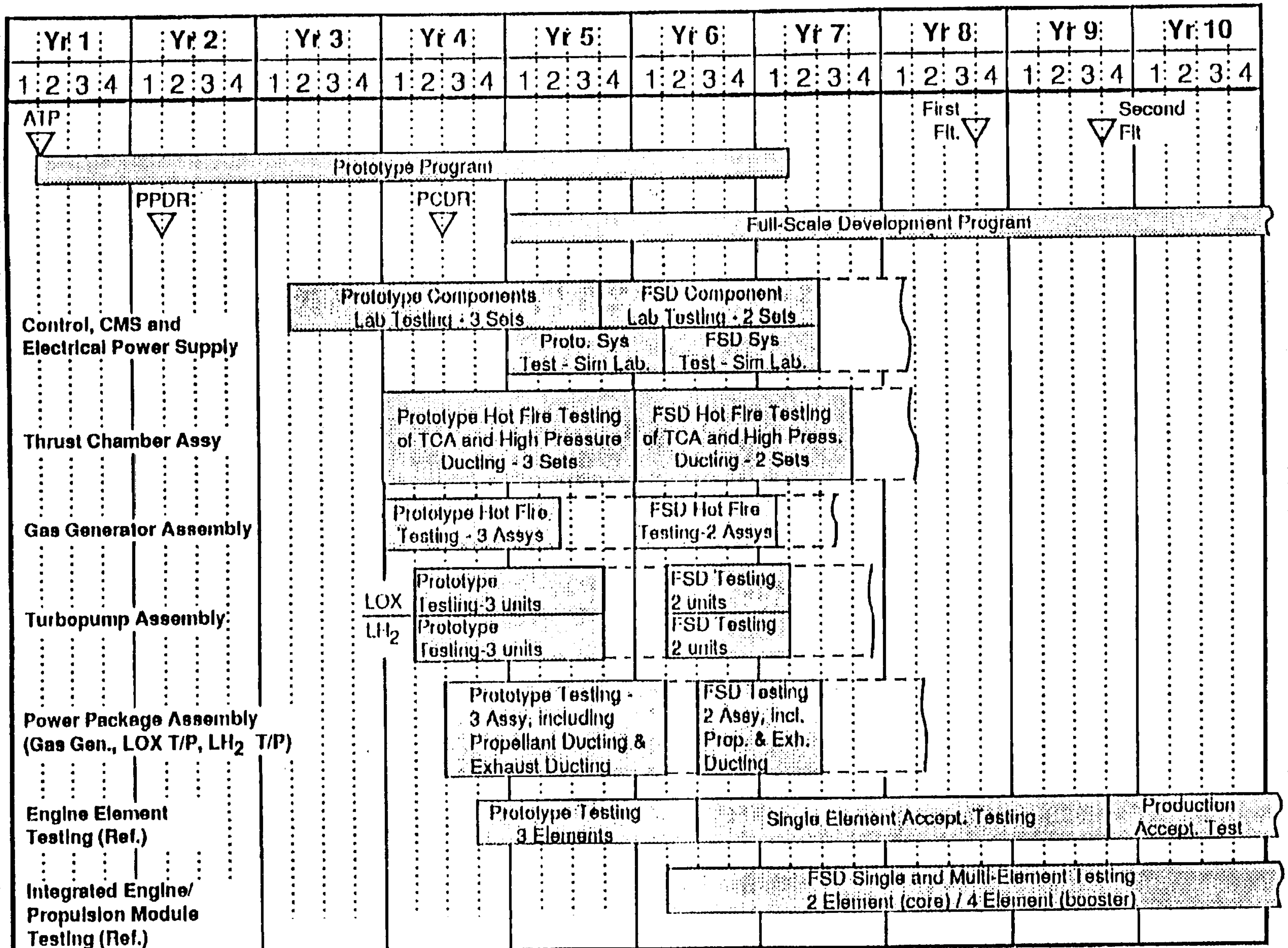

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FIGURE 10

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INTEGRATED P/M SYSTEM TEST PLAN

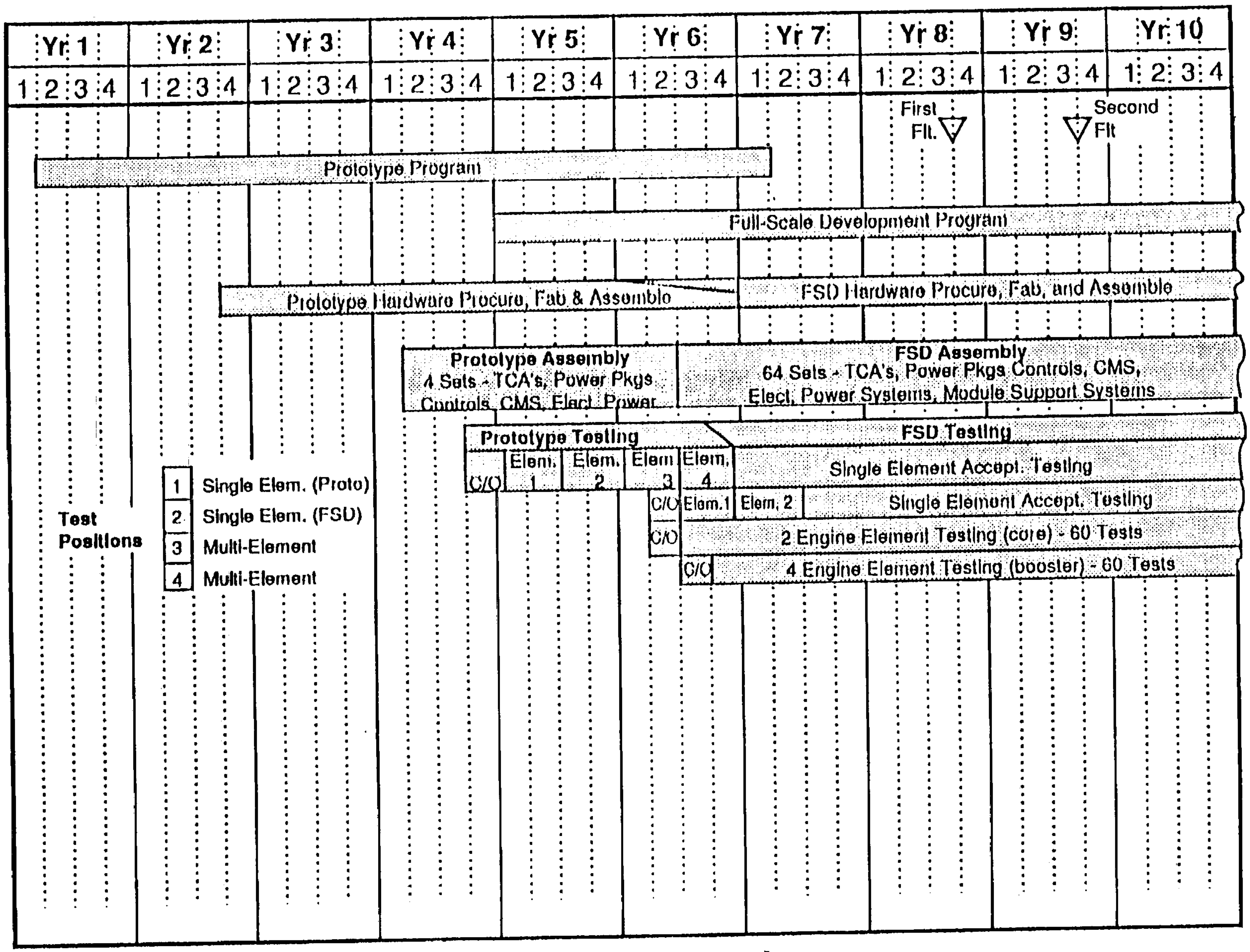

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FIGURE 11

91ALS-012- 73

INTEGRATED P/M TEST MATRIX

	Prototype				FSD Program								
	Single Element Testing				Single Element Testing		Core (2 Element)			Booster (4 Element)			
Test Objectives	1	2	3	4	1	2	1	2	3	1	2	3	
Ignition	20	10	5	5	10	5	10			10	10		
Start / shutdown	20	10	5	5	10	5	10			10	10		
Performance	10	10	10	10	10	10	10	10	10	10	10	10	
Operating environ.	10	10	10		2	2	15	10		15	10		
Stability		2	8	8	2	2							
Duration		2	5	10	10	10	10	20	20	10	20	20	
Gimbaling							10	10	10				
Limits		10	10	10	10	10	10	10	10	10	10	10	
Over stress				2	2	2	2			2			
Fail safe							3	3	3	3	3	3	
Heat exchanger							5	10	10	5	10	10	
Life				20				20	20		20	20	
Throttling								10	10	10	10	10	
Reliability											20	20	
Comp. Interchange							5			5			
PFC								10					
FFC									10				
	30	30	30	30	25	25	20	20	20	20	20	20	290 Tests

TABLE 3

element testing is planned. The 2-engine element is representative of a core stage which lifts the payload into orbit and the 4-engine element is representative of a booster stage. The system hotfire test matrix planned for each of these configurations in the FSD program in shown in Table 3. As indicated, 50 single engine element, 60 2-engine element and 60 4-engine element tests are planned for a total of 170 tests. Table 3 also shows the planned test objectives and number of times each objective will be tested. It should be noted that in order to achieve the objective the number of times shown will require that multiple objectives be accomplished on each test.

Table 3 shows that a total of 290 system hotfire tests are planned for the combined prototype and FSD subphases for the IPM development program compared to 780 system hotfire tests planned for the STME Development Program (Table 1). The reason that the number of hotfire tests is significantly reduced for the IPM program is that multiple engine elements are hotfire tested during most of the program, thus exposing more hardware to the hotfire environment for each test. Since a test setup for a IPM multi engine element configuration is only slightly more complex than the setup for a standalone STME hotfire test a significant reduction in test setup costs will be realized. Also, since the IPM development program tests the multi-element configuration to the extent shown, there is no need for a separate Main Propulsion Test Article (MPTA) program as required for the standalone STME program. This results in a reduction in the amount of hardware required for the IPM development program. A comparison of the engine system hardware required for the STME and IPM development programs is shown in Table 4. The total number of system tests planned for the IPM program including the first 2 flights is shown in Table 5. The preceding discussion show that the IPM hotfire test program is a more efficient approach to propulsion system development because:

- The propulsion module and engine element components and subsystems are tested together thus uncovering any design problems earlier.
- Each multi-engine element hotfire test exposes more hardware to the hotfire environment thus requiring less test setups to complete the program.
- Since multi-engine element testing is the major part of the system test program a separate MPTA program is not necessary thus reducing the amount of hardware required.
- The test objectives are accomplished with significantly fewer hotfire tests (see Table 6 for comparison).

COMPARISON OF ENGINE SYSTEM REQUIRED FOR THE STME AND INTEGRATED P/M DEVELOPMENT PROGRAMS

Application	Number Required for STME	Number Required for Integrated P/M
Development Program		
● **Prototype phase**	4	4
● **FSD phase** - Development	10	8
- Reliability	8	8
- PFC	2	2
- FFC	2	2
● **Spares**	4	4 (3FSD, 1 prototype)
Total development	30	28
MPTA Program		
● **Booster**	7	0
● **Core**	3	0
● **Spares**	3	0
Flight Program		
● **Vehicle sets (2)**	20	12 (4 core, 8 booster)
● **Spares**	6	4
Total Program	69	44

TABLE 4

INTEGRATED P/M SYSTEM DEVELOPMENT TESTS

Purpose	Prototype	FSD			
	Single Element	Single Element	Core (2 Element)	Booster (4 Element)	
• **Prototype program**	120				
• **FSD program**					
• Characterization		50	40	20	
• Reliability		--	--	40	
• PFC		--	10	--	
• FFC		--	10	--	
Total development	120	50	60	60	290
• **Flight Program**					
• Element acceptance tests (16)		32			
• Flights (2)			2	2	
Total flight		32	2	2	36
• **Total Program**	120	82	62	62	326

TABLE 5

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SUMMARY
Development Tests And Hardware Required

	STME	Integrated P/M
• **System tests**		
• Prototype	120	120
• FSD (incl. PFC, FFC)	768	170
• Flight (acceptance & flight	72	36
Total	960	326 (-66%)
• **Reliability demonstration tests***	230	40 P/M (-83%)
• **Number of engine or engine - elements required**	69	44 (-36%)
• No. of major components**	483	352 (-27%)

* Equivalent mission tests
** T/C, T/P, HX, GG, Controls, He supply system

TABLE 6

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91ALS-012- 77

3.2.1 IPM Reliability

The ALS program has established a single STME design reliability goal of $R_{eng} = 0.999$ and a demonstrated reliability goal of R_{eng} demo = 0.99. The IPM program will have the same design and demonstration reliability goals, but the IPM approach should result in significantly higher design and demonstrated reliability values.

3.2.1.1 Design Reliability

Table 7 shows that the IPM has a significantly higher overall reliability based on the fact that the number of major components and sub-systems are significantly reduced as shown in Table 8. The component reliability values shown are based on failure data from the J-2 and SSME engine programs. The reduced number of major components and subsystems plus the fact that the IPM design will employ the same Total Quality Management (TQM) techniques planned for the STME design effort should result in quantified IPM design reliability greater than 0.999. Another potential reliability advantage of the IPM (booster configuration) over the 7-engine ALS is in the consequences of a catastrophic failure. As stated previously a significant advantage of the IPM is greater access and therefore improved operability as a result of the integration of the propulsion module and engine components and subsystems. The resulting reduced number of components packaged in essentially the same envelope as the ALS propulsion module not only improves operability but allows for installation of blast containment features which could not be reasonably provided in the ALS propulsion module. The ability to provide a physical safeguard against catastrophic failure will reduce the catastrophic factor in reliability and will increase system reliability. As shown in Figure 12 for a catastrophic factor of $C_F = 0.05$ (used for ALS), a 7-engine cluster would have a system reliability of $R_{sys} = 0.9947$. With a capability of blast containment the catastrophic factor could be reduced to $C_F = 0.02$ and the system reliability of the engine cluster would increase to $R_{sys} = 0.9967$.

3.2.1.2 Demonstrated Reliability

The ALS STME reliability demonstration requirement is $R_{eng} = 0.99$ with 90% confidence. To fulfill this requirement, a binomially based, reliability demonstration program is planned that required 230 equivalent mission hotfire tests without a failure. An equivalent demonstration is require for the IPM.

BOOSTER PROPULSION MODULE HARDWARE COMPARISON

Separate Engines vs. Integrated System

Engine Elements	Separate Engines No. of Components	Integrated System (Static) No. of Components
Thrust chamber:		
MCC	7	8
Injector	7	8
Nozzle	7	8
Igniter	7	8
Oxidizer turbopump	7	4
Fuel turbopump	7	4
Gas generator	7	4
Heat Exchanger	7	2
Start System	7	1
PCA	7	1
Controller (avionics)	7	1
Gimbal bearing	7	0
Gimbal actuator	14	0
Propellant lines	14	4
Flexible inlet lines	14	0
Fixed inlet lines	0	8
Main valve/actuator	14	24
Prevalves	14	0
Crossover duct/lines	7	0
HP T/P discharge lines	0	8
Ring manifold	0	2
HP T/C inlet lines	0	8
Miscellaneous	7	8
Center engine mount	1	0
Total	169	111

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TABLE 7

BOOSTER PROPULSION MODULE RELIABILITY

Separate Engines vs. Integrated System

Engine Elements*	Component Reliability	Separate Engines		Integrated system	
		No. of Components	Subystem Reliability	No. of Components	Subsystem Reliability
Thrust chamber assy	0.99978	7	0.99846	8	0.99824
T/C ISO valve, ox	0.99996	0	-	8	0.99968
T/C ISO valve, fuel	0.99996	0	-	8	0.99968
Oxidizer turbopump	0.99986	7	0.99902	4	0.99944
Fuel turbopump	0.99972	7	0.99804	4	0.99888
MOV	0.99996	7	0.99972	4	0.99984
MFV	0.99996	7	0.99972	4	0.99984
Gas generator	0.99983	7	0.99881	4	0.99932
PCA	0.99999	7	0.99993	1	0.99999
Controller	0.99996	7	0.99972	1	0.99996
Gimbal system	0.99999	7	0.99993	0	-
Heat exchanger	0.99989	7	0.99923	2	0.99978
Propellant lines	0.99999	14	0.99986	4	0.99996
Inlet line, flex	0.99980	7	0.99860	0	-
Inlet line, fixed	0.99980	7	0.99860	4	0.99920
Prevalve, oxid	0.99996	7	0.99972	0	-
Prevalve, fuel	0.99996	7	0.99972	0	-
Crossover duct	0.99980	7	0.99860	0	-
HP T/P discharge lines	0.99999	0	--	8	0.99992
Ring manifold	0.99991	0	-	2	0.99982
HP T/C inlet lines	0.99999	0	-	8	0.99992
Overall reliability		0.98775		0.99351	

*STME Components

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TABLE 8

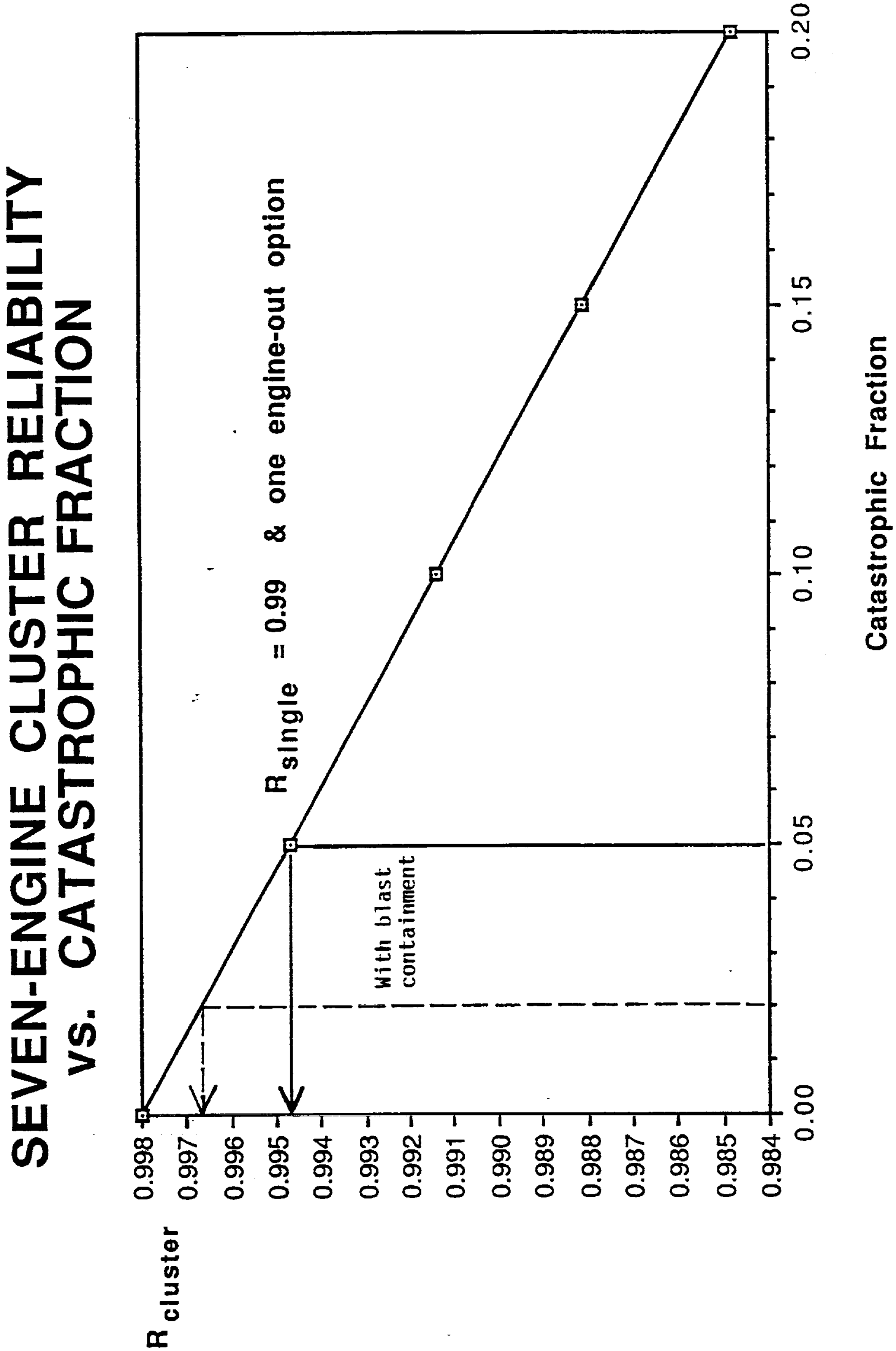
SEVEN-ENGINE CLUSTER RELIABILITY
vs. CATASTROPHIC FRACTION
R_{single} = 0.99 & one engine-out option
With blast
containment
$R_{cluster}$
0.998
0.997
0.996
0.995
0.994
0.993
0.992
0.991
0.990
0.989
0.988
0.987
0.986
0.985
0.984
0.00
0.05
0.10
0.15
0.20
Catastrophic Fraction

FIGURE 12

A baseline ALS booster vehicle configuration is a cluster of seven, independent engines with "one engine out" capability. Since the demonstrated reliability of each of the engines is $R_{eng} = 0.99$, the booster propulsion system reliability, with one engine out capability, is $R_{sys} = 0.9947$. It is an objective of the IPM development program to demonstrate the same system reliability, i.e. $R_{sys} = 0.9947$.

The IPM configuration consists of four turbopump sets and eight thrust chambers, with common propellant manifolds between pumps and between thrust chambers (see Figure 4). This configuration enhances reliability through a reduction in the number of generally higher failure rate subsystems (turbopumps), and configuring them in a redundant pumping arrangement. The eight, as opposed to seven, thrust chambers arrangement utilizes equivalent sized thrust chambers to give an approximately equivalent thrust condition (i.e., equivalent single engine out). To ensure full pumping capability and no propellant loss through a failed pump, the integrated system does add approximately 21 isolation valves which adds complexity.

In order to determine the required IPM reliability demonstration program some assumptions were made. First, the major engine subsystems were assumed to be similar, generally bell-nozzle, gas generator cycle type hardware, to the STME. The assigned reliabilities of the components used were the same as that established for the ALS STME components based on the ALS single engine reliability goal of $R_{eng} = 0.999$ and the analysis of failure data from the J2 and SSME engine programs. Second, the assignment of reliability allocations assumed no hardware scale factor effects. The allocations are based on rocket engine component types, and the same reliability allocation is assigned for the smaller, single engine components as they are for the same type of hardware on the integrated modular engine system. The capacity of the latter system's turbopumps, for example, would be approximately 2.3 times greater when considering the reduction in numbers (4 vs. 7==> 1.75 factor), plus the additional reserve capacity to accommodate one out of four pumps out (3 vs. 4==> 1.33 factor) capability. However, in actual size the IPM turbopumps are only approximately 20 percent larger than the STME turbopumps.

Finally a catastrophic fraction (i.e., the fraction of failures whose effects may be uncontained and catastrophic in magnitude) of 0.05 was applied, which is consistent with the ALS requirement and data from 1,391 engine tests and launches during the Apollo era. The catastrophic fraction causes the propulsion system reliability to decrease as the number of individual engines or components increases.

The analysis showed that the same clustered engines, booster propulsion system reliability of 0.9947 can be achieved with IPM engine elements having 0.9855 reliability. This level of reliability could be demonstrated to a 90% confidence level with a series of 158 equivalent mission tests without failure. This analysis is illustrated in Figure 13. The ground testing of this integrated system configuration could be accomplished with a single-engine element, consisting of two thrust chambers and one set of pumps, which is a representation of all the major subsystems of the system or with a 4-engine element IPM in which case only 40 equivalent mission tests were required. Completing the reliability demonstration with 40 test setups is a significant cost reduction compare to the 230 test setups for the STME.

Another reliability advantage of the integrated system approach is the significant gain in operating robustness. The integrated system can withstand failures in each of it's three major subsystem, namely oxidizer turbopump, fuel turbopump and thrust chamber subsystems, and still maintain an equivalent engine out thrust level. The clustered engine system can tolerate only one major subsystem failure.

3.2.2 IPM Flight Certification

The flight certification program for the IPM is the same as that planned for the STME. The program consists of Pre Flight Certification (PFC) and Final Flight Certification (FFC) test series. The PFC is scheduled to be completed approximately 6 months prior to the first flight and FFC is scheduled to be completed 6 months after first flight. Each test series consists of 10 tests each on 2-engine elements. The objective of the PFC program is to certify that the engine element design has matured sufficiently for the first flight. The objective of the FFC program is to certify that the engine element design is ready for production and operational status. Since the test series requires that 2-engine elements be tested, the respective program can be conducted with 2 separate single elements or with a 2-engine element IPM or 4-engine element IPM where only 2engine elements are designated as the certification test articles. As indicated on Table 3. The 2-engine element IPM has been selected for the certification programs. This selection results in the lowest cost test program because only 10 test setups and 2-engine elements are required to complete each certification program. If 2 single-engine elements are used, 20 tests would be required. If testing is accomplished on the 4-engine element configuration the program would still require 10 test setups but 4-engine elements would be required. Another advantage of completing the certification test series with multi-element IPM, not only do the engine element components and subsystems get certified but also the propulsion module subsystems including the propellant feed, pneumatic, tank pressurization, electrical power supply, and control monitor systems will be certified. A significant benefit compared to the STME certification programs which are accomplished with standalone STME's with facility support systems.

CLUSTERED VS. INTEGRATED PROPULSION MODULE SYSTEM RELIABILITY

- **Clustered engines reliability* (single engine R=0.99)**
  - No engine-out (7 engines) $R_{clus} = 0.9321$
  - One engine-out (7 engines) $R_{clus} = 0.9947$
- **Integrated engine reliability* (4 pump sets, 8 thrust chambers)**
  - $R_{clus} = 0.9947 \longrightarrow R_{IPM} = 0.9855$
  - No. tests to demonstrate $R_{IPM} = 0.9855$ @ 90%
    - Single-engine element = 158
    - 4-engine element = 40

*Catastroplic factor $C_F = 0.05$

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FIGURE 13

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