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OEPSS
Operationally Efficient Propulsion System Study

Final Briefing/Report with Additional Backup Material

NAS10-11568
NASA/John F. Kennedy Space Center

Rocketdyne Division/Rockwell International

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OEPSS Study Tree
GW/Bv 8/23/93-1a

OEPSS Study

The Operationally Efficient Propulsion System Study (OEPSS) surfaced as a NASA/KSC generated request for proposal (RFP) in April, 1988. Both NASA and the Air Force Space Systems Command (El Segundo, California) invested funds to support the study. During the first year, the Air Force identified the study as ADP 5103 as an advanced development project under the Advanced Launch System (ALS) program. The Rocketdyne Division of Rockwell International was awarded the competitively bid program in December, 1988. Authority to proceed was received in April, 1989. The program was structured as a basic 12-month study with the potential for two 12-month options to follow. The study was managed by Mr. William Dickinson and Mr. Russell Rhodes, both NASA Special Project Managers at the John F. Kennedy Space Center. Early in calendar year 1990, the ALS program experienced a downsizing as a result of reduced funding. The OEPSS was one of the casualties of these cuts. NASA/KSC and Headquarters, both recognizing the importance, and potential positive impact of this study, continued the funding to complete the basic plus the two options periods. The study concluded in December 1992.

OEPSS
Operationally Efficient Propulsion System Study

A Focused Review of Propulsion System Operations at the Launch Site

The initial OEPSS effort was to focus on a more complete review of propulsion system operations at the launch site. A comprehensive database was generated for ground processing of the propulsion system to provide the designer an understanding of the magnitude of the requirements, at the maintenance and operations levels, to process their design. This data has been documented in OEPSS Databook Volume I: Generic Ground Operations Data. Another database was generated reviewing major operations problems, or concerns, encountered by propulsion systems that will have serious impact on the successful flight rate of the launch vehicle. This data has been documented in OEPSS Databook Volume II: Ground Operations Problems.

A Focused Review of Propulsion System Operations at the Launch Site

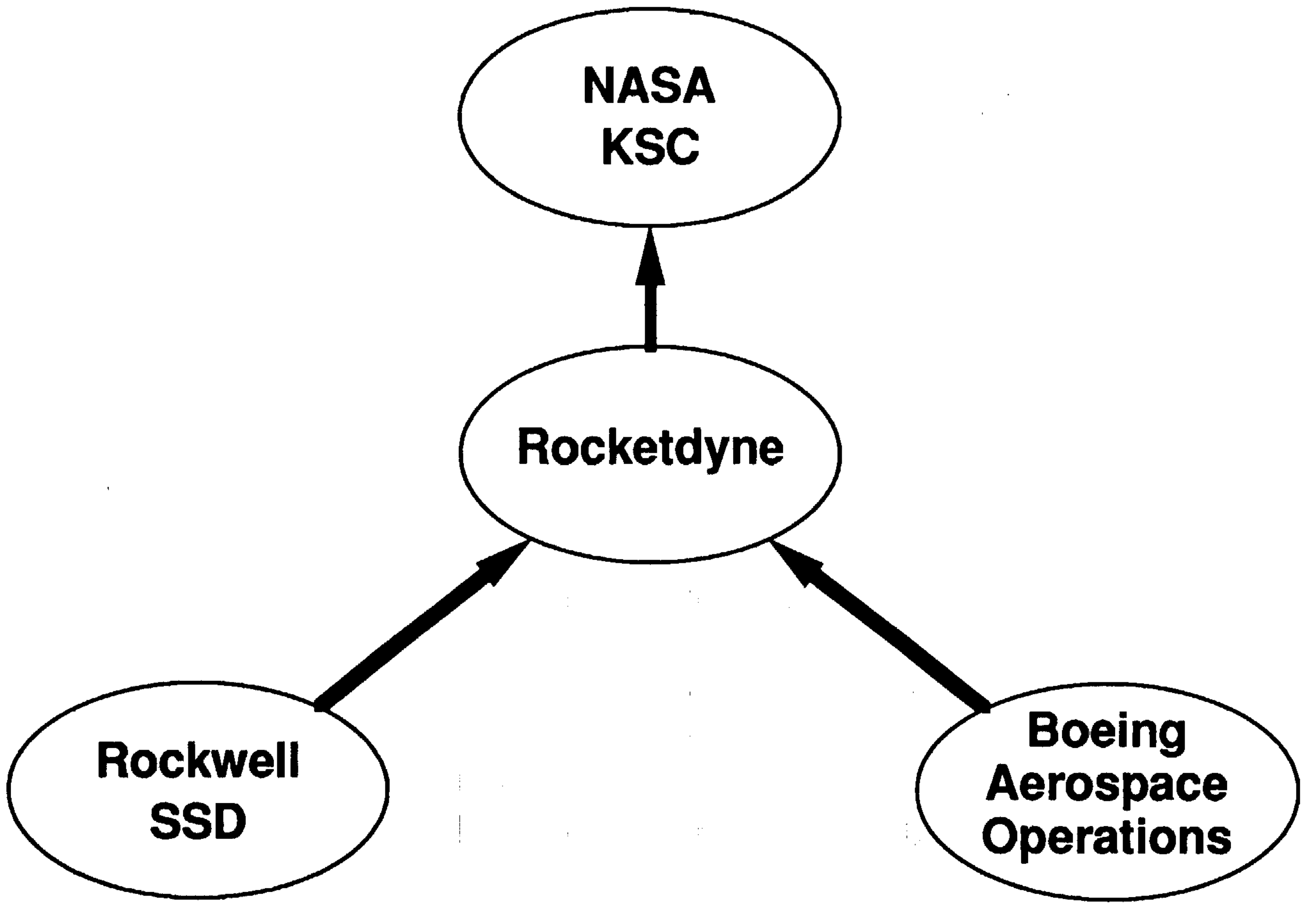
- Operationally Efficient Propulsion System Study (OEPSS):
  - Key objectives
    - Evaluate propulsion system operations at the launch site
    - Generate launch site data to assist the design community in more efficient propulsion system designs

Communicate launch site propulsion system operations experience data to the aerospace community

The OEPSS Team was Formed

The OEPSS team formed to conduct the propulsion system study is depicted. The Boeing Aerospace Operations, who conducted the SGOE/T study, provided the background and continuity for the study. The Space Systems Division of Rockwell International, as a team member, provided an important propulsion system experience base stemming from the design community. Rocketdyne, as the key contractor team member, provided the design, technology and operational experiences of a prime rocket engine manufacturer. The most vital and integral part of the OEPSS Team were the NASA/KSC Study Managers, Mr. Russel E. Rhodes, and William J. Dickinson from Kennedy Space Center.

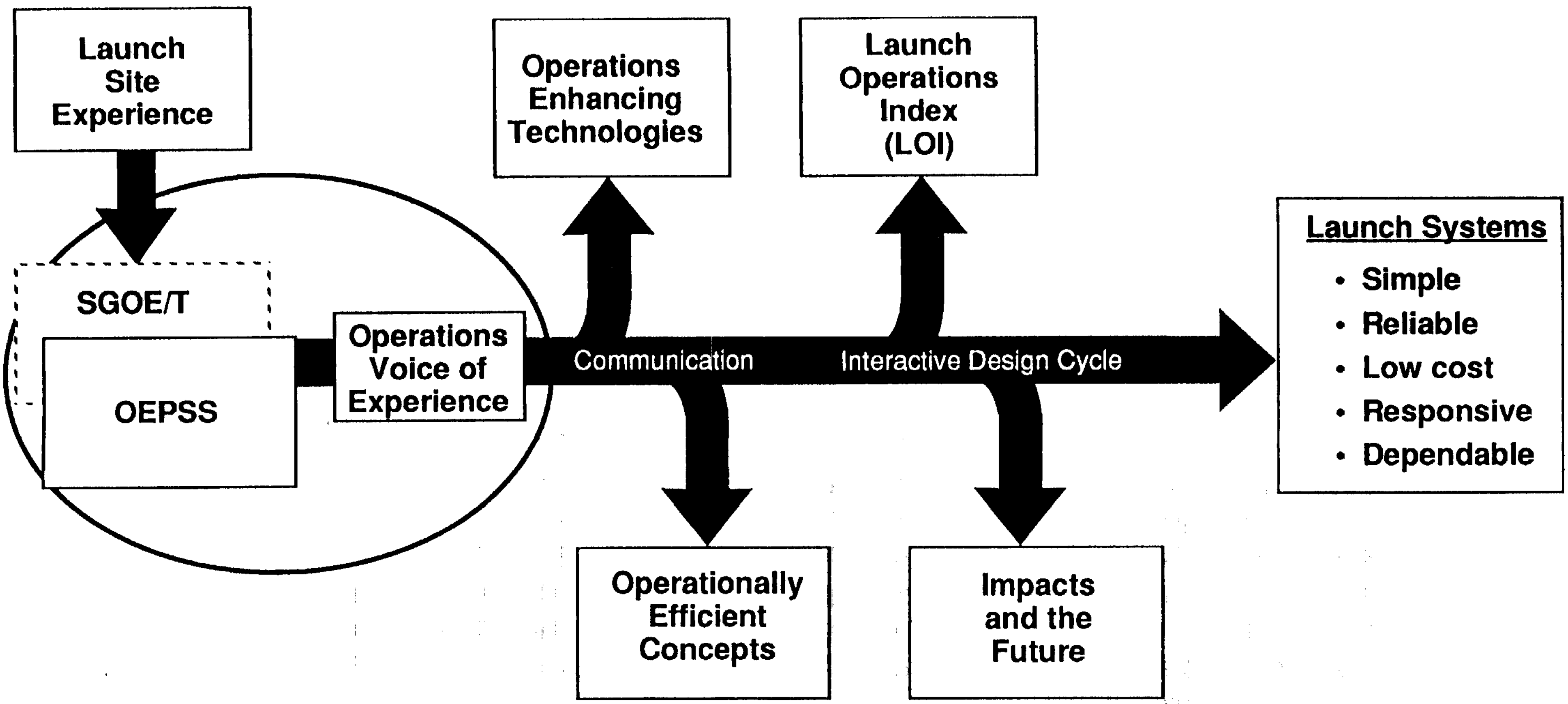
The OEPSS Team Was Formed



Kennedy Space Center Performs a Self-Examination

The primary focus of this final briefing will be Option I and II of the OEPSS study as the effort continues to reap the benefits of a thorough review made of launch activities and problems at Kennedy Space Center and the Cape Canaveral launch sites and to communicate launch site experience and voice of operations experience to the design community. The study also continues to define operations technologies and propulsion system architectures that will increase system operability and eliminate operational requirements and increase operations efficiency at the launch site and Space Transportation Program. The flowchart below describes elements of the OEPSS program and serves as and index to the material in this final briefing/report.

Kennedy Space Center Performs a Self Examination



A Global Review of Launch Site Operations

The shuttle ground operations efficiencies/technologies study (SGOE/T) was the initial Kennedy Space Center managed activity made that essentially conducted a self-examination of launch site operations. It was broad in scope in that it evaluated all activities at the launch site in an attempt to identify major cost drivers. One of these cost drivers was propulsion systems.

SGOE/T was a three-year study conducted by Boeing Aerospace Operations out of their Cocoa Beach, Florida, office.

A Global Review of Launch Site Operations

- Shuttle Ground Operations Efficiencies/Technologies Study (SGOE/T):
  - Key objectives
    - Self examination of launch site operations
    - Identify launch operations cost drivers

Propulsion systems surfaced as one of the major cost drivers

OEPSS Objectives

The original focus of the OEPSS study was to generate a generic liquid propellant vehicle and associated launch site operations data, and use this as a barometer to evaluate operations efficiency of various propulsion system concepts. However, very early in the study, the effort was refocused more along the lines of identifying and documenting launch site operations impacts and communicating this information to the design centers.

Along with identifying the concerns and impacts, additional data was to be gathered on various achievable technologies that would answer the concerns and ultimately drive down launch site operations costs. To illustrate the positive impact to launch site operations by considering the concerns and applying these technologies, "operations-driven" innovative propulsion system architectures were to be generated. To further anchor the importance of considering operations in the design process, it was felt that an operations criteria, or Figure of Merit, was needed to measure how operationally efficient any propulsion concept would be.

Then, the most important objective of all would be to communicate this operations experience data effectively to the aerospace community.

OEPSS Objectives

- Document launch site operations experience
- Provide operations experience to conceptual designers
- Identify current operations concerns and impacts
- Identify operations enhancing technology
- Develop propulsion system operations criteria
- Identify "operations-driven," propulsion system architecture
- Participate in interactive design cycle

Transportation System Customer and Operator Needs

All too often we lose sight as to who is the customer and who is the operator and what each desires. The customer, or the owner of an expensive payload, wants to get his product in space safely, quickly, and cheaply. He really is not interested in the delivery system until he finds his product spending an abnormal amount of time at the launch site or waiting in a long manifest line where it generates no revenue.

On the other hand, the operator, in this case the launch site, in order to stay in business, must have a dependable, reliable, and affordable delivery system that can satisfy the customer's desires. Making the delivery system robust, forgiving, simple, and with minimum operational needs is the only way we will keep our customers.

Transportation System
Customer and Operator Needs

OEPSS Focus

Customer:

- Needs a transportation system with:
  - Capability
  - Availability
- Desires a transportation system that is:
  - Affordable
  - Dependable
  - Responsive
  - Safe
  - Etc.

Operators:

- Need a transportation infrastructure that supports customer requirements
- Desire a transportation system that is:
  - Affordable
  - Operable
  - Dependable/Reliable
  - Safe
  - Environmentally Compatible
  - Etc.

Source:
Space Propulsion Synergy Group

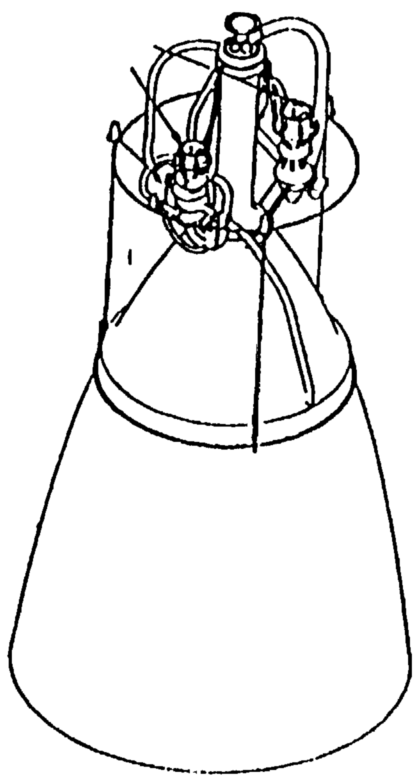
What is a Propulsion System?

The words "propulsion system" mean different things to different people. Probably the majority would associate them with a standalone engine, or the component that produces thrust. However, in reality, it is not just a single component, but an assembly of all the components, and the support infrastructure that puts the fire-in-the-hole.

OEPSS interprets "propulsion system" to include such broad items as tankage, fluid management and control, and the "engine." We also believe that to properly and completely evaluate the impact a propulsion system has on operations costs, the support infrastructure must be included. This not only refers to the pad(s), service towers, pneumatic panels, propellant handling and distribution systems, etc., but the "army" that it takes to operate and maintain these systems.

What is a Propulsion System?

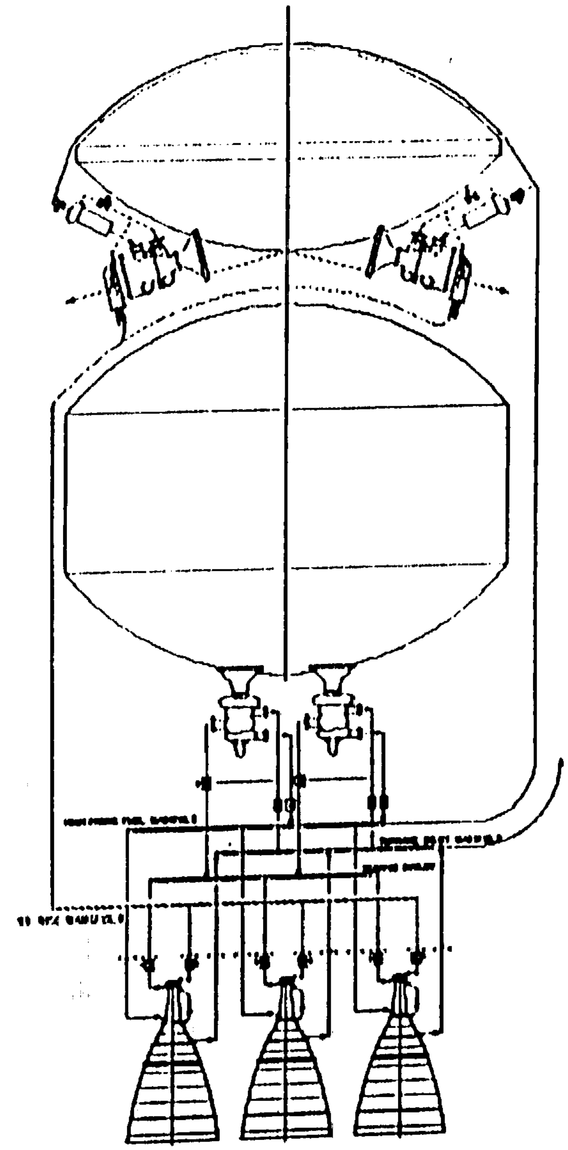
Usual Perception By Most



Standalone engine

Total system including support infrastructure

OEPSS Interpretation



Operationally Efficient System

An operationally efficient system is one that is simple, robust, forgiving and has minimum operational needs. The figure illuminates those areas which are improved in an operationally efficient system.

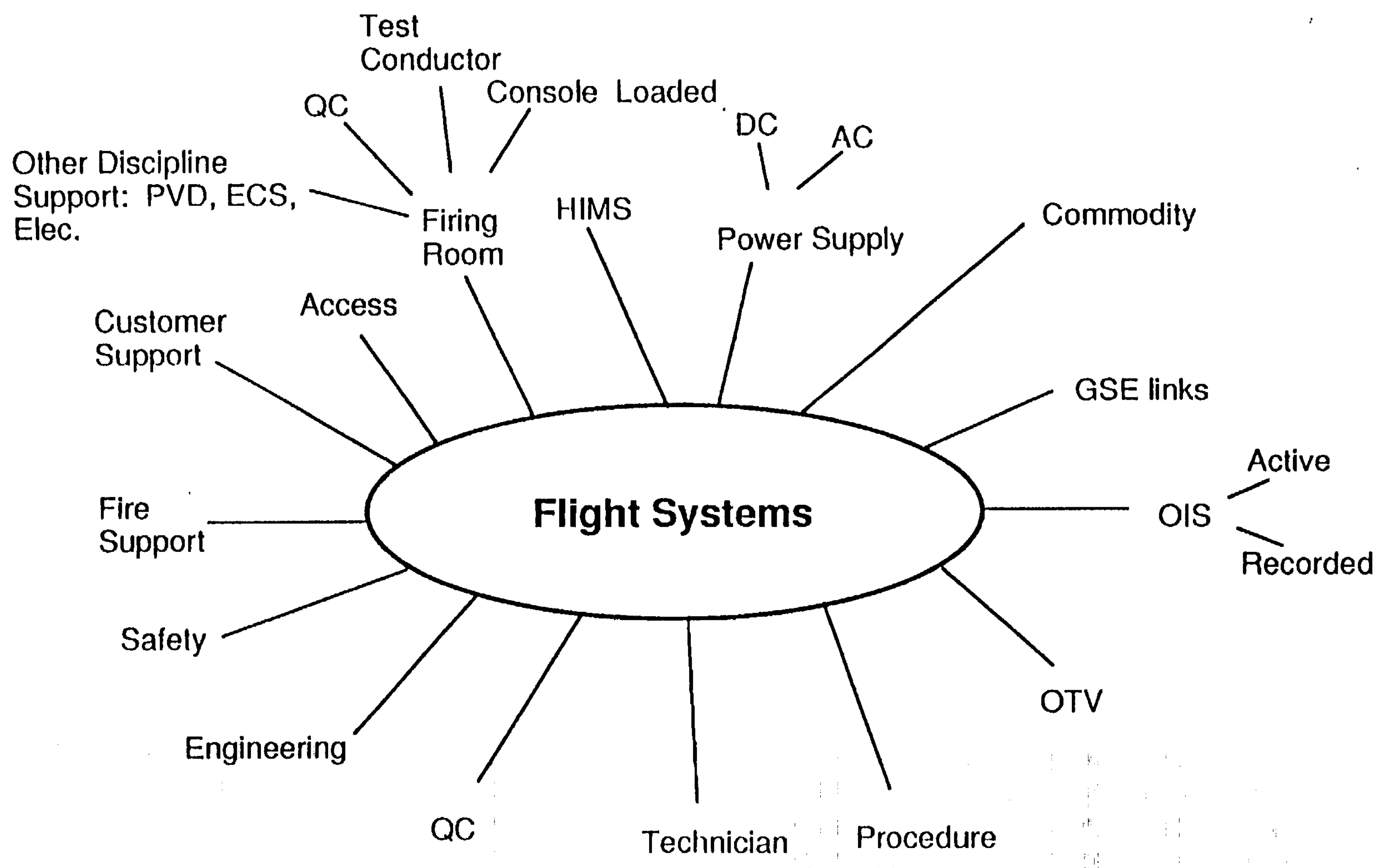
OPERATIONALLY EFFICIENT SYSTEM

- **Any vehicle or system that simplifies, reduces or eliminates operations requirements**
    - Less manpower
    - Lower cost
    - Shorter timelines
    - Less equipment, facilities
    - High operability
        - Technician level operation

Launch Site Systems Create a "Nightmare" in Process Scheduling

A typical illustration of the technical disciplines and operations support required for flight system checkout is shown in the figure. It is not surprising that operations support is complex, manpower-intensive, time-consuming and costly. A launch system that consists of many separate, independent systems exacerbates the launch operations support problem.

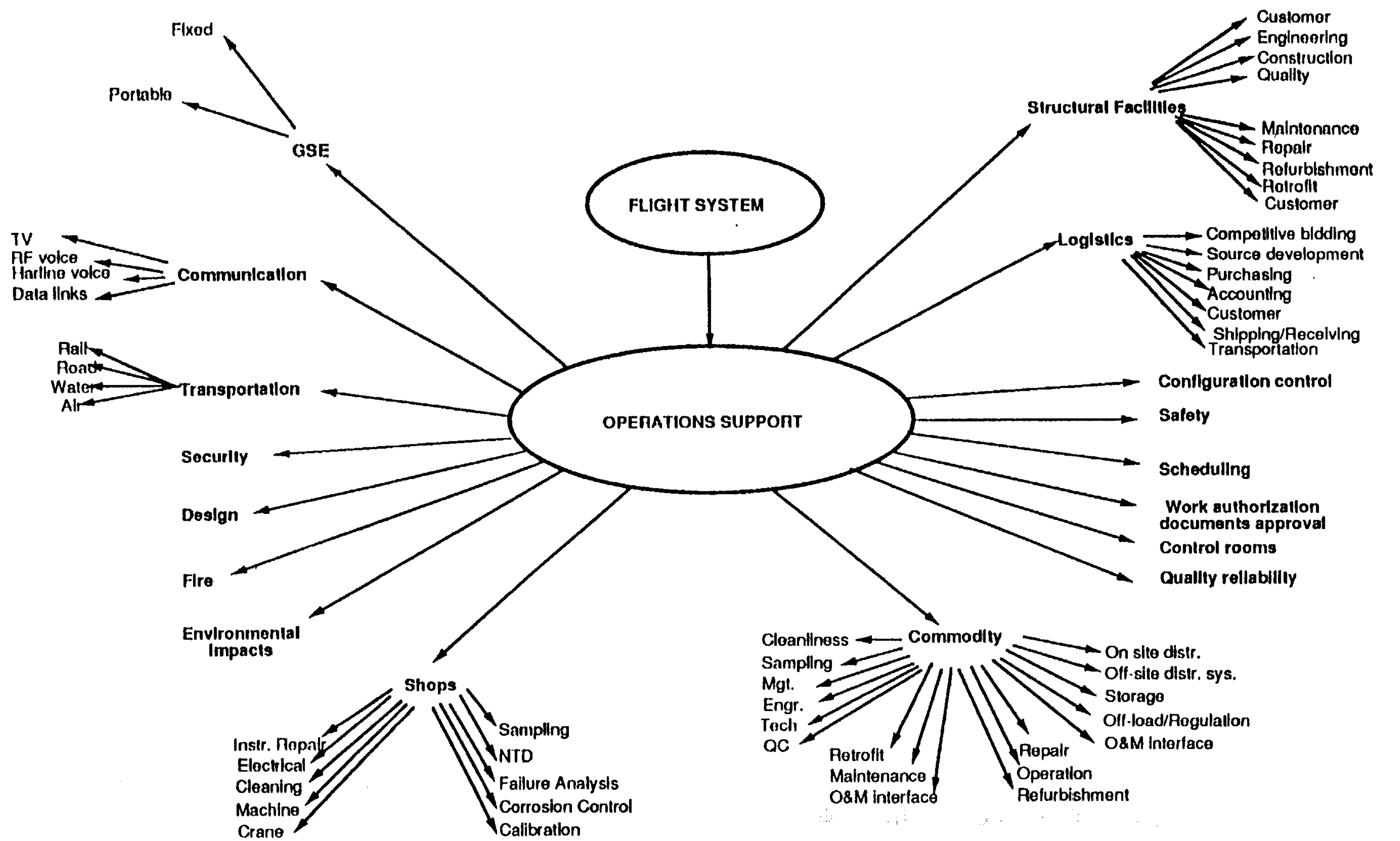
LAUNCH SITE SYSTEMS CREATE A "NIGHTMARE" IN PROCESS SCHEDULING



Operations Support Structure is Complex

An illustration of the large infrastructure of logistics, supplies, equipment, and facilities to support system checkout is shown in the figure. Every different commodity required on the vehicle adds another tentacle to the operations support structure. For example, the requirement for Helium gas, no matter how small the amount, dictates the need for additional facilities, GSE, logistics, and transportation to ensure the gas is at the processing site when needed.

OPERATIONS SUPPORT STRUCTURE IS COMPLEX



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Backup C to
OEPSS Study Tree

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OEPSS Concerns List

Since the rocket engine/propulsion system represents one of the more complex and expensive systems in the launch vehicle, the OEPSS study focused on identifying operations problems in this area. The concerns list describes major operations concerns encountered in today's launch vehicles and how these problems have adversely affected the ability to achieve serviceability, reliability and operability.

OEPSS CONCERNS LIST

- **Follows on the heels of SGOE/T findings**
- **Focused on propulsion system only**
- **Represents "launch site experience base"**
  - Expendable launch vehicles (Atlas, Delta, Titan)
  - Apollo/Saturn
  - NSTS
- **Major launch site operations cost drivers**

OEPSS Concerns List
"Launch Site Experience Base

An example of a concern from the concerns list is presented in the figure. The operational impact and related issues are also shown. A description of the concerns and their operational impact, that evolved from this study is presented in the OEPSS databook Volume II, Ground Operations Problems.

OEPSS CONCERNS LIST
"Launch Site Experience Base"

- **Concern: OEPSS - 1**
  - Closed aft compartments
- **Operational impacts:**
  - Confinement of potential propellant leaks - criticality 1 failure
  - Requires inert purging during loading operations
  - Requires conditioned environment for personnel
  - Requires sophisticated hazardous gas detection system
  - Drives the requirement for sophisticated heat shielding
  - Inhibits proper access to components
  - Drives the requirement for specialized/dedicated GSE
  - Imposes manloading restrictions for confined space
  - Unnatural personnel passageways elevates potential for H/W damage
  - Additional interfaces required between vehicle and ground
  - Requires sophisticated ground support equipment
    - Environmental control system for personnel
    - Gaseous nitrogen regulation and distribution system
    - Must have redundant systems
    - Capable of local and remote operation
    - Requires an "army" for operation, maintenance, certification
    - Adds another function to the firing room operation
  - Tremendous risk to the safety of personnel and hardware
  - Drives many operations to be serial in flow
  - Drives need for LCC that could delay or scrub a launch
- **Potential options for consideration:**
  - Aft area should be completely open - Ref SII and SIVB vehicle config.

The Foundation of OEPSS

The effectiveness of the OEPSS team can be measured by its foundation, i.e., providing extensive launch site operations experience base and effectively sharing this experience base with the aerospace community. This invaluable hands-on experience base spans the era's of all major programs at the launch site -- starting with the Jupiter and Redstone systems and progressing through 35+ years to the systems of today.

Documenting, for the first time, this propulsion system experience in terms of launch site operations concerns and impacts was a very important task, but getting the message out to the design centers was equally paramount.

This has been an intense activity of the OEPSS team and will be made evident in the presentation to follow.

The Foundation of OEPSS

"The launch site operations experience....

...and communicating this experience effectively to the aerospace community"

The Voice of Experience

For the first time in the history of launch site operations, the launch site was identifying and documenting major categories of cost drivers based on 35+ years of experience at the launch site. The list was originally assembled by the members of the OEPSS team that represented the 35+ years in part or in total association with the launch site. To further anchor this data, workshops with each of the Atlas, Delta, and Titan launch teams at the Cape Canaveral Air Force Station (CCAFS) were held.

Not to our surprise, the OEPSS Team found that the same operations impacts existed with these systems.

The original operations concerns List (found in OEPSS Databook Vol. II) listed twenty-six items, some of which were directed specifically at a point design. However, following the workshops, these 26 items were re-evaluated and reformatted to reflect a generic impact.

TH/Bv 9/2/93-25

The Voice of Operations Experience

OEPSS Identifies Major Operations Concerns and Impacts

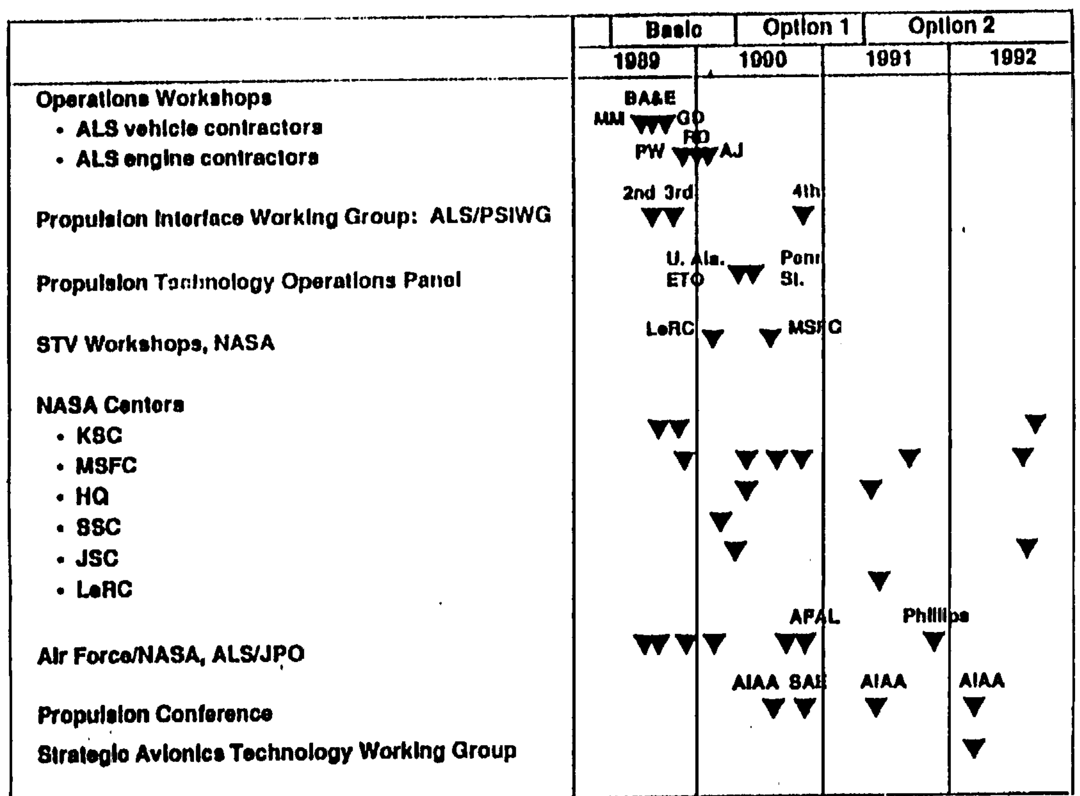
Operations Experience Base

No.		No.	
1	Closed aft compartments	13	Gimbal system
2	Fluid system leakage • External • Internal	14	High maintenance hardware
		15	Ordnance Operations
		16	Retractable T-O umbilical carrier plates
3	Hydraulic system	17	Propellant tank pressurization system
4	Ocean recovery/refurbishment	18	Excessive interfaces
5	Multiple propellants	19	Conditioning/geysering (LOX tank forward)
6	Hypergolic propellants (safety)	20	Preconditioning system
7	Accessibility	21	Expensive commodity usage -- helium
8	Sophisticated heat shielding	22	Lack hardware commonality
9	Excessive components/subsystems	23	System contamination
10	Lack of hardware integration		
11	Separate OMS/RCS		
12	Pneumatic systems		

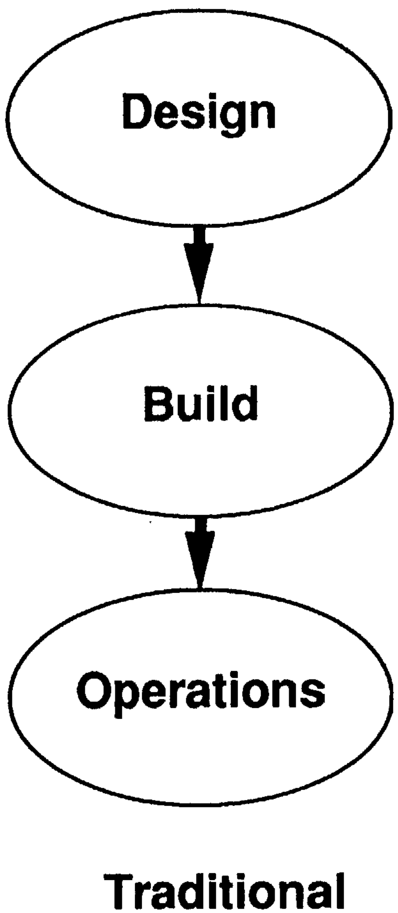
OEPSS Is Interactive

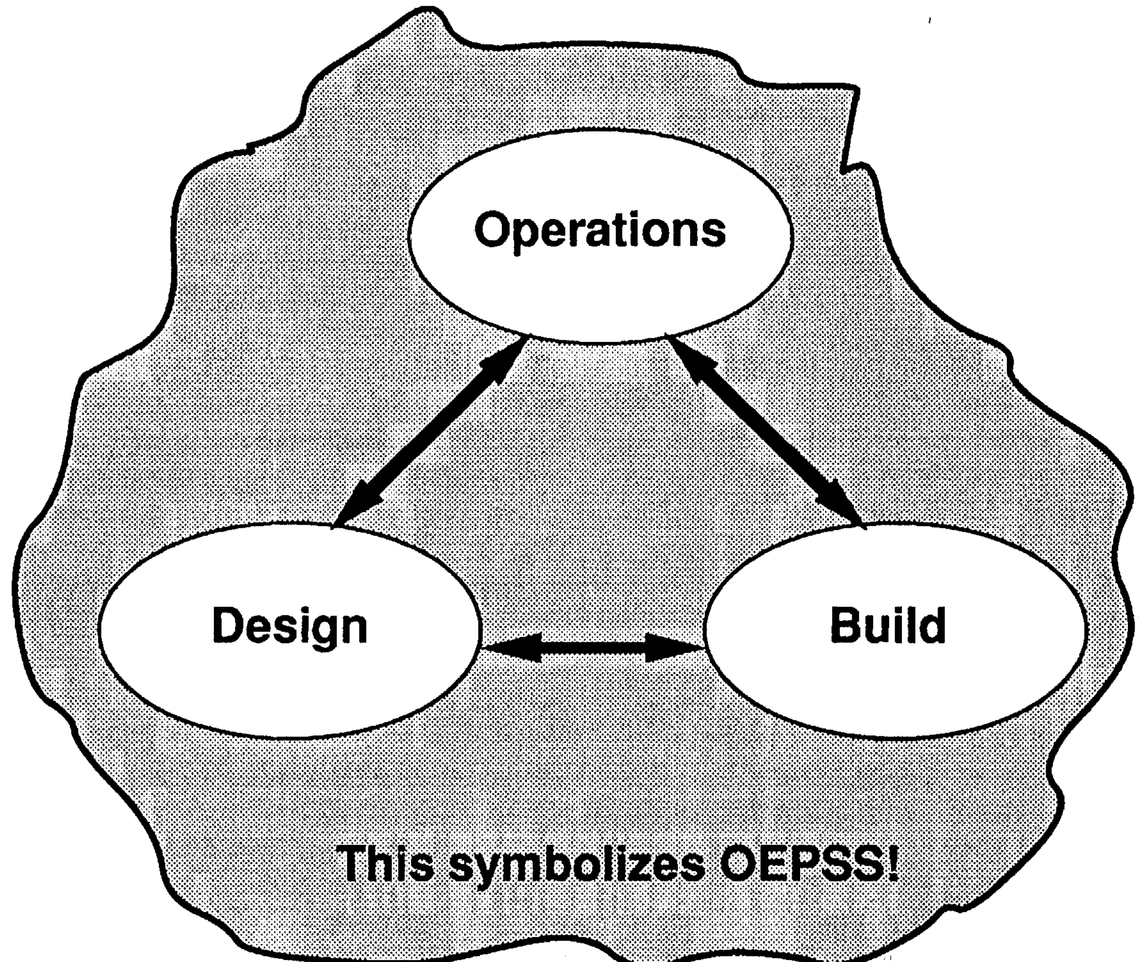
The traditional program "hardware" flow has been serial in nature. The hardware was designed, then fabricated and assembled, and finally shipped to the launch site for use. The most important part of any educational process, i.e., feedback, and in this case, the "operations experience," never made it back completely to the design centers for incorporation into the next program. The OEPSS team was tasked to become proactive in sharing launch site operations experience with the "design centers." As a result, the team took advantage of every available opportunity to become interactive with the Design, Build and Operations community. Implementing the basic principles of Total Quality Management (TQM) will further ensure that "operations" becomes interactive and an integral part of the total program cycle.

OEPSS Is Interactive



Operations and Design Must Be Interactive





Scope of OEPSS

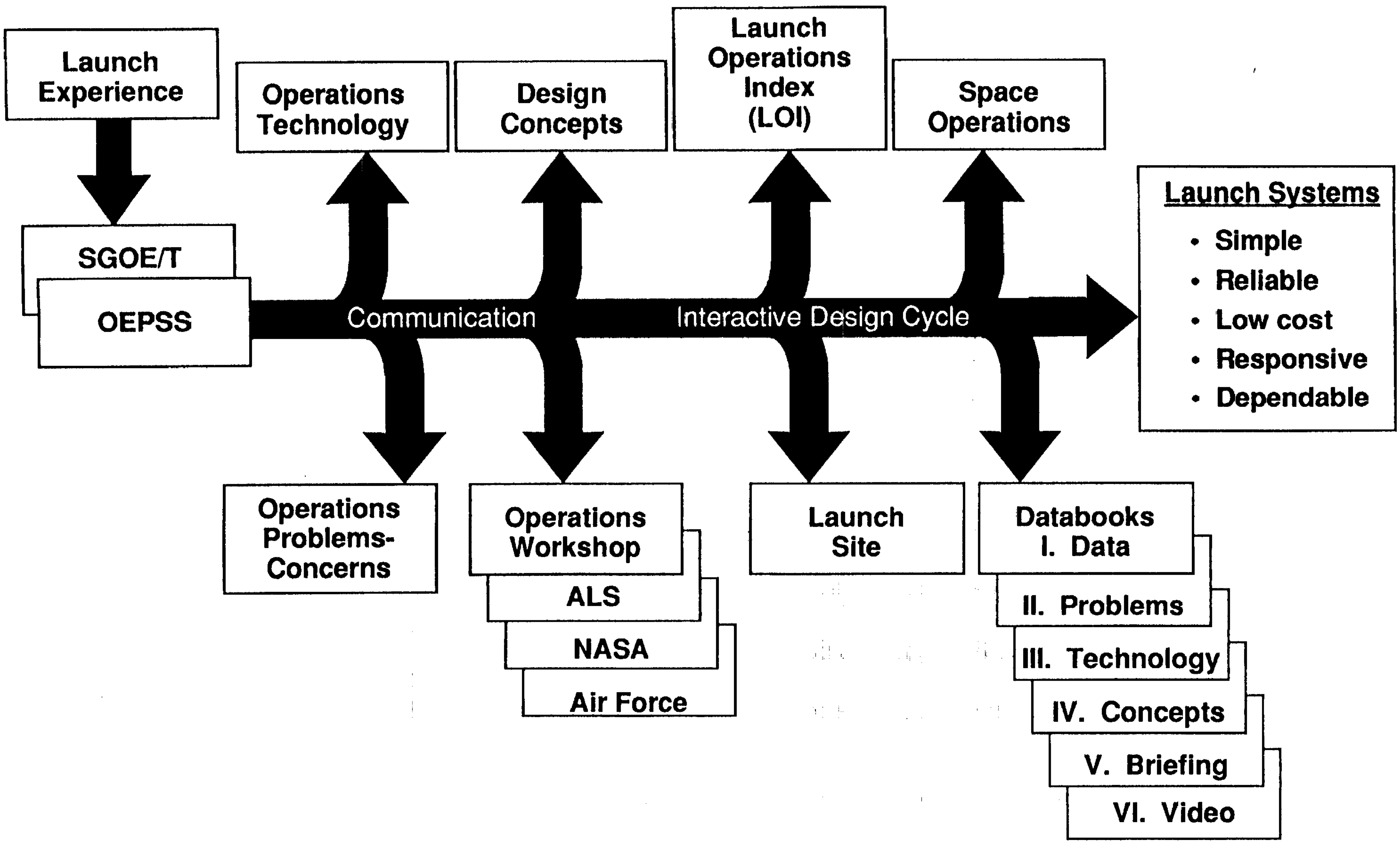
OEPSS, looking back, had a scope that was most active and intense. Some of the subjects and tasks addressed were:

- Generated a generic liquid propulsion system and associated operations data
- Identified major operations concerns at the launch site
- Identified and promoted operations enhancing technologies, including preparing and submitting them in RTOP format
- Produced illustration(s) of operations-driven architectures to show how operations concerns are addressed and howoperations-enhancing technologies are applied
- Embarked on establishing a conceptual tool (Figure-of-Merit) to evaluate how well a propulsion architecture meets launch operations efficiency
- Looked at "space Operations" relative to:
    1) What some of the goals should be,
    2) What some operations-driven Lunar Lander concepts might be, and
    3) What the scope of an in-space operations index should be
- Graphically illustrated what is meant by an operationally efficient launch facility
- Scoped out the feasibility and advantage(s) of a launch operations test bed (LOTB)
- Produced a video that depicts vividly the main theme and three-year activity of the OEPSS study
- Communicated the above activities through workshops, symposiums, conferences and presentations at various other forums

All of the subjects and tasks addressed had one single goal:

"Promote the need for simple, reliable, low cost, responsive, and dependable launch systems"

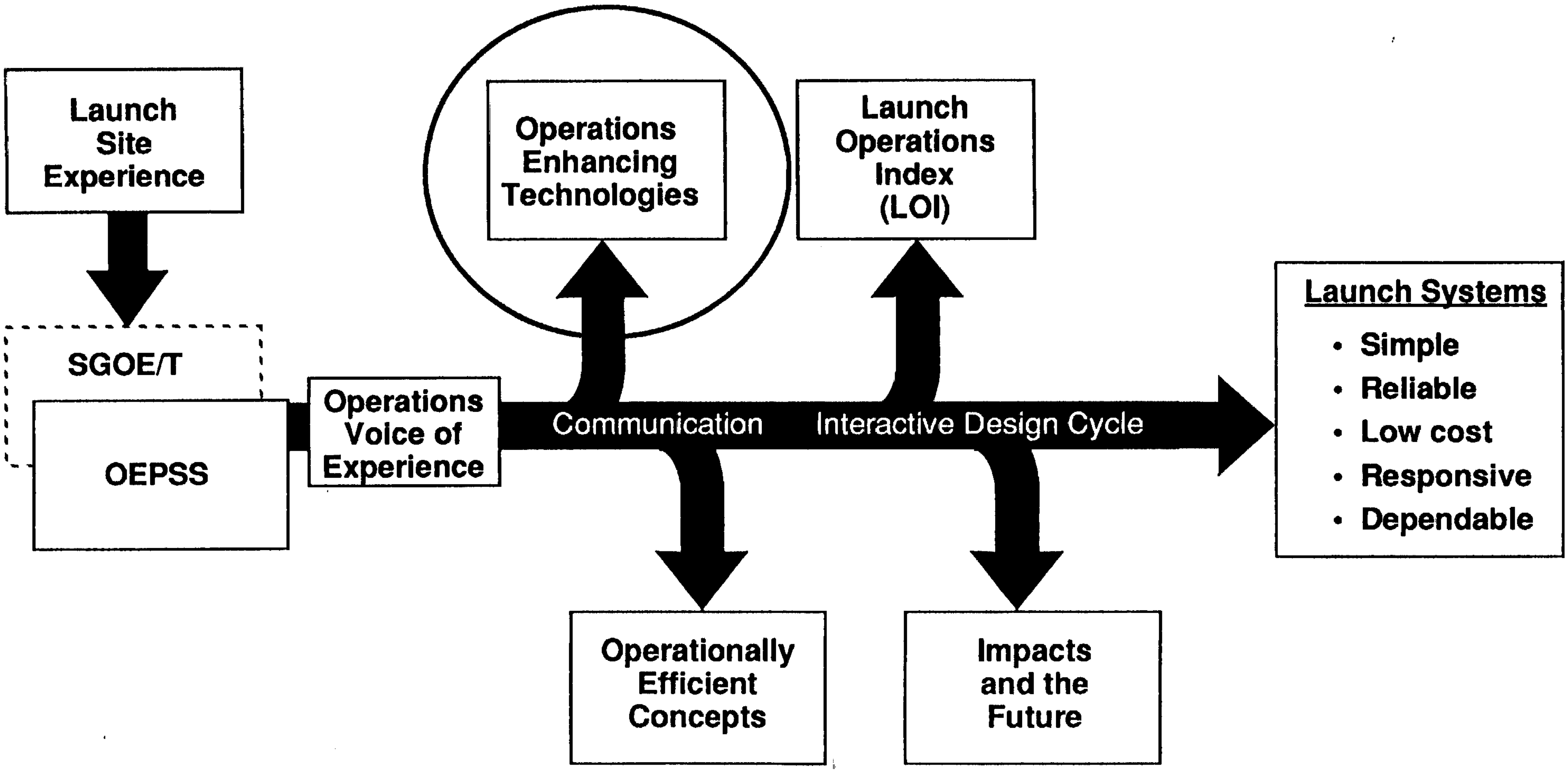
Scope of OEPSS



"Advanced Technology, a Key Ingredient In Driving Down Operations Cost"

The next section will describe how key operations technologies will simplify and reduce operational requirements and will lead to significantly lower operations cost.

"Advanced technology, a key ingredient in driving down operations costs"



Operations Enhancing Technology

During the early portions of the OEPSS study, it became evident that one of the keys to achieving quantum gains in operational efficiency was to identify technology areas that would benefit the operability of a launch system. The result was the identification of a series of ongoing and new technologies that possessed significant operational gains as well as improvements to other system attributes.

Operations Enhancing Technologies

Operations Focus on Technology Required

Propulsion technology has traditionally been focused in areas other than operations. Improvements in performance such as higher specific impulse or greater thrust to weight have been well studied. Methods to reduce the acquisition cost have also been well explored, even forming the foundation for programs such as ALS and NLS. Significant efforts to improve reliability have been ongoing through existing propulsion programs such as SSME and the expendable launch vehicles. These areas have consumed the vast majority of propulsion technology resources in the past.

In the OEPSS study, the concerns list was used as a method of identifying and evaluating promising, high value technologies for their applicability in increasing total system operability. This list was used since it includes insights into critical operational areas, provides understanding on both propulsion and vehicle system level operational issues, and provides a clear rationale for the need of operations related technologies.

An initial list of operations focused technologies was generated and the relationship of each technology was related to the applicable operational concerns. Also as part of the study, the development effort required for a representative sampling of the technologies was produced. The conclusion was that operations is a new, economically justifiable and rewarding class of technology

Operations Focus on Technology Required

- Traditional propulsion technologies have not focused on operability
  - Increased performance
  - Reduced acquisition cost
  - Improved reliability
- OEPSS concerns list is useful in identifying and focusing on new technologies
  - Points out key high value operations areas that must be addressed
  - Provides insight in propulsion, vehicle level issues, and "complexities"
    - Provides more global vision of propulsion (traditional engine, vehicle, MPS, tank and ground)
    - Provides vast opportunities for integration and simplification
  - Establishes the need for developing highly operable systems and technologies
- Initial list of operations-focused technologies identified
  - Relationships to concerns documented
  - Scope of required technology development defined

Operations- a new class of technology

Goal of OEPSS Technologies

The intent of producing an OEPSS technology list, from the standpoint of assessing operations and identifying requirements, was to document technology tasks that will provide major improvements to operations. Once the operations technologies were identified, the relationship with emphasis to performance, cost, and reliability were assessed. Operations gains will be defined by LOI or applicable tool when available.

The intent of this approach was to define a traceable path of technology development to ultimately eliminate the operations concerns. It was recognized that a broad range of technologies was required to address the diverse list of operational issues. It was also recognized that the definition of the propulsion system had to be enlarged from just the engine to also include the propellant feed system, tankage, and supporting vehicle and ground systems. The scope of "fair game" technologies included the complete launch system, emphasizing a major reduction in ground support items (large reductions in infrastructure).

It was clear that there will be a need to provide focus on maturing technologies to a level appropriate for acceptance by program managers, relative to low cost and risk, to complete the development. It was also clear that top level planning, including cost estimates and schedule projections, must be accomplished and scoped.

Goal of OEPSS Technologies

- Identify major technologies with primary emphasis and focus on operability
  - Address top priority concerns initially
  - Establish relationships and emphasize benefits to performance, cost, & reliability
- Establish logic path to allow mitigation of concerns
  - Define broad (global) technology rather than single focus
  - Utilize enlarged propulsion system definition
  - Account for total launch system - vehicle and ground based
- Define scope and lay out top level planning for development to acceptable maturity
  - Characterize areas of uncertainty
  - Estimate effort required to demonstrate feasibility and dispell areas of uncertainty

Technologies must be matured to allow use by propulsion system and component designers in existing or new programs

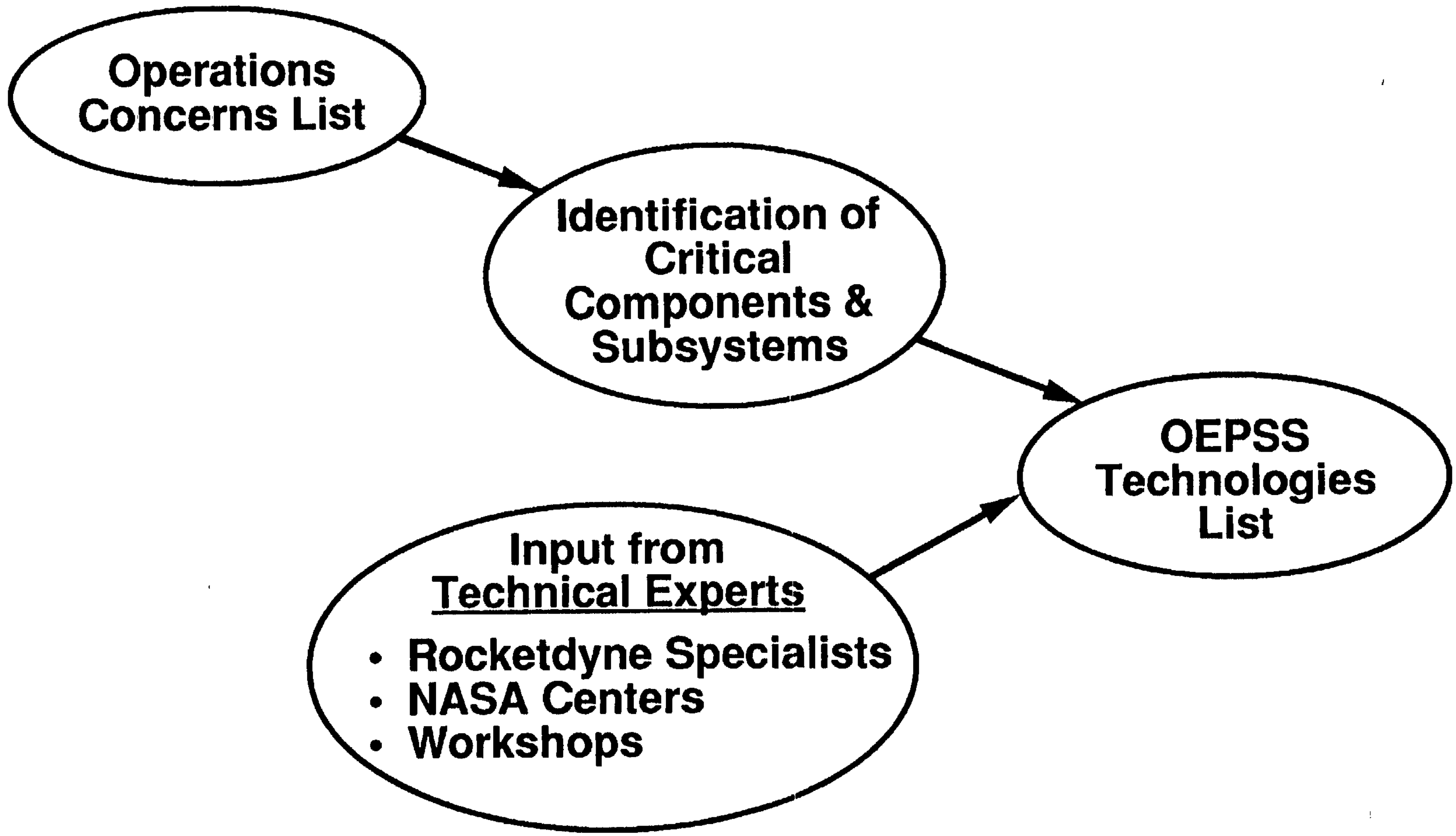
Origin of OEPSS Technologies List

The basis for the OEPSS technologies list is in addressing the operations concerns. This allowed the identification of critical components and subsystems. In this case, critical components were those that could, with modification, eliminate or greatly mitigate the concerns being addressed. An example would be to address the copious helium consumption of the high pressure oxidizer turbopump intermediate seal purge by either modifying the seal to eliminate the need for the helium purge, or to drive the turbine with a fluid that was compatible with the fluid being pumped.

Once a number of critical components were identified, input was solicited from a number of technical experts throughout the Country to identify the state-of-the-art and to pin-point what specific technologies were in need of development. This input produced the OEPSS technology list.

The technologies identified were required to have two characteristics. First, they had to provide high operational pay-off. The goal was to completely eliminate a given concern. Second, the technologies had to be deemed feasible by the panel of technical experts. With sufficient development, any of the listed technologies is feasible.

Origin of OEPSS Technologies List



Identified operations technologies that have high payback and are achievable

Guidelines Used in Defining OEPSS Technologies

In order to provide focus on the identification of technologies, a series of guidelines were established. The general rule-of-thumb provided by the study manager was to "...evaluate minimum commodity and maximum integration approach to derive a simple solution."

The scope of these technologies was limited to O_2/H_2 systems because this system yields maximum integration; i.e., propulsion, power, life support and thermal management. These concepts needed to be applicable to the next generation of launch systems, not "wouldn't it be nice if..." scenarios. This meant the avoidance of technologies that dictated overall system architecture and furthermore these technologies needed to be applicable to any type of launch vehicle. The focus was applied to identify multiple uses for each of the newly tagged technologies.

Identification of technologies alone was insufficient since it did not allow vehicle designers insight as to their actual readiness level. For this reason the study also identified the technologies with an estimate of their potential implementation time. Technology readiness level is acceptable for immediate implementation while the remainder of the technologies were classified according to how soon they could be developed for a program as candidates for acceptance.

Additions or changes in these guidelines would alter the list of OEPSS technologies

Guidelines Used in Defining OEPSS Technologies

"...evaluate minimum commodity and maximum integration approach to derive a simple solution"

- Focus on O2/H2 systems
- Driven by function and not "conceptual cartoons"
  - Avoid specialized technologies that drive or limit vehicle architecture
  - Identify technologies applicable to generic vehicles
- Focus on multiple use
- Identify TRL 5 & 6 technologies already existing for system development if supporting operation and operability focus
- Segregate technologies that are fast track, Mid-term, far term

Focus on functions with supportability and operability

Operations-Focused Technology

A comprehensive list of technologies identified by the OEPSS study that will focus on operability and reduce operational requirements is shown. The approximate maturity or technology readiness level (TRL) of each technology item is indicated.

Operations Focused Technology

- No leakage mechanical joints (2)*
- Electromechanical Actuator (EMA) (5)
- Automated leak detection/location discriminator (5)
- Automated internal leak detection (2)
- No purge pump seals (3)
- No flight purge combustion chamber (flight-shutdown) (2)
- Flash boiling tank pressurization (3)
- Non-intrusive instrumentation (3)
- Differential throttling (2)
- Low NPSH pumps (3)
- Large flow range pumps (3)
- Oxidizer-rich turbine, LOX turbopump (3)
- Hermetically sealed inert engine (prelaunch) (2)

*(2) TRL (Technology Readiness Level)

Operations-Focused Technology
(Contd.)

This list shows additional OEPSS technologies along with their approximate NASA technology readiness levels.

Operations-Focused Technology
(Contd.)

- Combined hydrogen/oxygen systems (MPS, OMS, RCS, ECLSS, fuel cell) (3)*
- Automated, self-diagnostic, condition monitoring system (2)
- Automated visual inspection (3)
- SLIC™ turbomachinery (5)
- Smart components (valves, etc.) (2)
- Hydrostatic bearings (5)
- Integrated propulsion module concept (2)
- Antigeyser LOX tank aft propulsion concept (9)
- Rocket engine air augmented afterburning concept (1)
- LOI software tool family (2)
- Closed compartment** (2)

*(3) TRL (Technology Readiness Level)

**Control the environment and base drag

Concerns Addressed by OEPSS Technology

This chart shows the OEPSS technologies along with a listing of which specific concerns are addressed. A concern was considered addressed whch it was either completely eliminated or significantly mitigated. An example of a technology that complete eliminates an entire concern is the development of combined O2/H2 systems to eliminate the need for hypergolic propellants (Operations Concern 6).

Most technologies provide significant mitigation of multiple concerns, such as the oxidizer-rich turbine in the LOX turbopump. This addresses the internal fluid leakage system (Operations Concern 2) by removing the criticality of the turbopump intermediate seal (thus eliminating the mandatory post-flight checkouts). It also greatly reduces the helium consumption of the engine, thus simplifying the pneumatic system (Operations Concern 12). It also reduces hardware maintenance (Operations Concern 14) by eliminating turbomachinery seal checkouts and turbine hot section checkouts since the required turbine temperature would be significantly reduced. It also mitigates Operations Concerns 18 and 21 for similar reasons.

This system level evaluation was applied to each of the technologies to determine the actual benefit to the identified operations concerns.

Concerns Addressed by OEPSS Technology

Technology	Concerns Addressed
Antigeyser LOX Tank Aft Propulsion Concept	10 17 18 19 20
Hydrostatic Bearings	7 9 14
SLIC™ Turbomachinery	7 9 14 18
Electromechanical Actuators (EMA)	2 3 7 9 12 14 18 21 23
Non-Intrusive Instrumentation	2 18 23
Automated Leak Detection	1 2 7 8
Automated Self-Diagnostic, Condition Monitoring System	1 7 8 10 14 18 23
Integrated Propulsion Module Concept	1 4 7 8 9 10 13 18 19 20 22
Combined Hydrogen/Oxygen Systems (MPS, OMS, RCS, ECLSS, etc.)	5 6 11
Flash Boiling Tank Pressurization	2 9 14 17 18 23
No Leakage Mechanical Joints	2 18
Automated Internal Leak Detection	2 7 8 14
No Purge Pump Seals	2 12 14 21
No Flight Purge Combustion Chamber (flight-shutdown)	12 21 23
Differential Throttling	3 7 8 9 10 13 14
Low NPSH Pumps	17 20
Large Flow Range Pumps	11 20
Oxidizer-Rich Turbine, LOX Turbopump	2 12 14 18 21
Hermetically Sealed Inert Engine (Prelaunch)	12 18 20 21
Automated Visual Inspection	1 7
Smart Components (Valves, etc.)	2 18 23
Rocket Engine, Air Augmented Afterburning	Eliminates complete stage/operations
Aft Closed Compartment	1 6 7 8 18
LOI Software Tool Family	

Technology Applicable to a Wide Range of Vehicles

The OEPSS technologies have been evaluated for applicability with existing and proposed launch systems. Evaluated were: the Space Shuttle (STS), a liquid rocket booster (LRB); and single stage to orbit (SSTO) and two stage to orbit (TSTO) vehicles; a new high energy upper stage and a space based application. Most technologies were applicable to future propulsion systems, meaning that the technologies were kept at a sufficiently generic level.

The technologies applicable to the Space Shuttle represent those technologies available in the near term that are adaptable to, and beneficial for, the existing STS architecture.

Technology Applicable to a Wide Range of Vehicles

Technology	STS	LRB	SSTO/ TSTO	Upper Stage	Space Based
Antigeyser LOX Tank Aft Propulsion Concept		X	X	X	X
Hydrostatic Bearings	X	X	X	X	X
SLIC™ Turbomachinery	X	X	X	X	X
Electromechanical Actuators (EMA)	X	X	X	X	X
Non-Intrusive Instrumentation	X	X	X	X	X
Automated Leak Detection	X	X	X	X	X
Automated Self-Diagnostic, Condition Monitoring System	X X	X	X	X	X X
Integrated Propulsion Module Concept		X	X	X	X
Combined Hydrogen/Oxygen Systems (MPS, OMS, RCS, ECLSS, etc.)		X	X	X	X X
Flash Boiling Tank Pressurization		X	X	X	X
No Leakage Mechanical Joints		X	X	X	X
Automated Internal Leak Detection		X	X	X	X
No Purge Pump Seals		X	X	X	X
No Flight Purge Combustion Chamber (flight-shutdown)		X	X	X	X
Differential Throttling			X	X	X
Low NPSH Pumps		X	X	X	X
Large Flow Range Pumps		X	X	X	X
Oxidizer-Rich Turbine, LoX Turbopump		X	X	X	X
Hermetically Sealed Inert Engine (Prelaunch)		X	X	X	X
Automated Visual Inspection		X	X	X	X
Smart Components (Valves, etc.)		X	X	X	X
Rocket Engine, Air Augmented Afterburning			X		
LOI Software	X	X	X	X	X
Aft Closed Compartment Elimination		X	X	X	X

ch 3

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Technology Readiness/Level

In order to avoid debate on the actual NASA technology readiness level (TRL), a more general grouping of TRL's was performed for OEPSS technologies. This grouping is sufficient to evaluate the maturity of an item without requiring an exhaustive literature search to determine an exact TRL. Since the intent of this task was to help in the classification of technologies into near term, mid term, and far term, this definition of level was more than sufficient.

Basic technology research was assigned Level I, roughly corresponding to NASA TRL 1 and 2. Research to prove feasibility was assigned Level II, corresponding to NASA TRL 2 through 4. Technology development was given Level III, similar to NASA TRL 3 through 6. Technology demonstration was assigned Level IV, similar to TRL 5 through 7. System or subsystem development was given Level V, approximately equal to NASA TRL 6 through 8. System test, launch and operations was given Level VI, comparable to NASA TRL 8 and 9.

This general ranking of technology level will be used for the remainder of the technology discussions.

Technology Readiness/Level

Level		TRL
I.	Basic Technology Research	1-2
II	Research to Prove Feasibility	2-4
III	Technology Development	3-6
IV	Technology Demonstration	5-7
V	System/Subsystem Development	6-8
VI	System Test, Launch and Operations	8-9

Operations Technology Levels

When the technologies are grouped in the OEPSS generalized technology levels, it becomes more apparent what are the relative maturities of the various items. The air augmented afterburning concept requires basic technology research to validate the expected performance gains using higher resolution performance models. It also requires a conceptual design and layout that would allow reasonable weight estimates to be made.

A large number of technologies still require research to prove feasibility. These technologies have been shown analytically to be viable, however the analyses must still be anchored through subscale testing. The Level II technologies offer the promise of significant operational benefits while only requiring low funding efforts to verify the expected gains.

Operations Technology Levels

I Basic Technology Research

- Rocket engine, air augmented, afterburning (1)

II Research to Prove Feasibility

- Integrated propulsion module concept (3)
- Combined hydrogen/oxygen systems (MPS, OMS, RCS, ECLSS, fuel cell) (3)
- Flash boiling tank pressurization (3)
- Smart components (valves, etc) (2)
- No leakage mechanical joints (2)
- Automated internal leak detection (2)
- No purge pump seals (3)
- No flight purge combustion chamber (flight-shutdown) (2)
- Differential throttling (2)
- Low NPSH pumps (3)
- Large flow range pumps (3)
- Hermetically sealed inert engine (prelaunch) (2)
- Automated visual inspection (3)
- LOI software (2)
- Aft (closed) compartment (2)
- Automated, self-diagnostic condition monitoring system

Operations Technology Levels
(Contd.)

Technology development is underway on a series of technologies, classified as level III. Actual subscale hardware has been tested or is currently in test. These items require little additional technology development prior to being implemented in new propulsion system designs.

Technology demonstration has been completed on the hydrostatic bearing. This bearing was tested in the MSFC Technology Test Bed SSME high pressure oxidizer turbopump (HPOTP) for several tests. This concept requires no additional investment prior to incorporation in future turbopump designs.

The only operationally proven OEPSS technology item is the aft LOX tank. This type of system has been used in vehicles such as Redstone, Jupiter, Juno I and II, Saturn S-1B, S-II, S-IV and the Centaur stage prior to S-IC and the incorrect perception of thrust vector control is a non-issue. These stages did not suffer from criticality 1 geysering, (Operations Concern 19) such as those experienced in the S-IC or Space Shuttle.

Operations Technology Levels
(Contd.)

- LOI software (2)
- Aft (closed) compartment (2)

III Technology Development

- SLIC™ turbomachinery (5)
- Electromechanical Actuator (EMA) (5)
- Non-intrusive instrumentation (3)
- Oxidizer-rich turbine, LOX turbopump (3)
- Automated leak detection/location discriminator (5)

IV Technology Demonstration

- Hydrostatic bearing (5)

V System/Subsystem Development

- None

VI System Test, Launch and Operations

- Antigeyser LOX tank aft propulsion concept (9)

Example Operations Technology

Several operations technologies with substantial payback in reducing operational requirements and increasing operations efficiency are selected to illustrate near and far term technology levels.

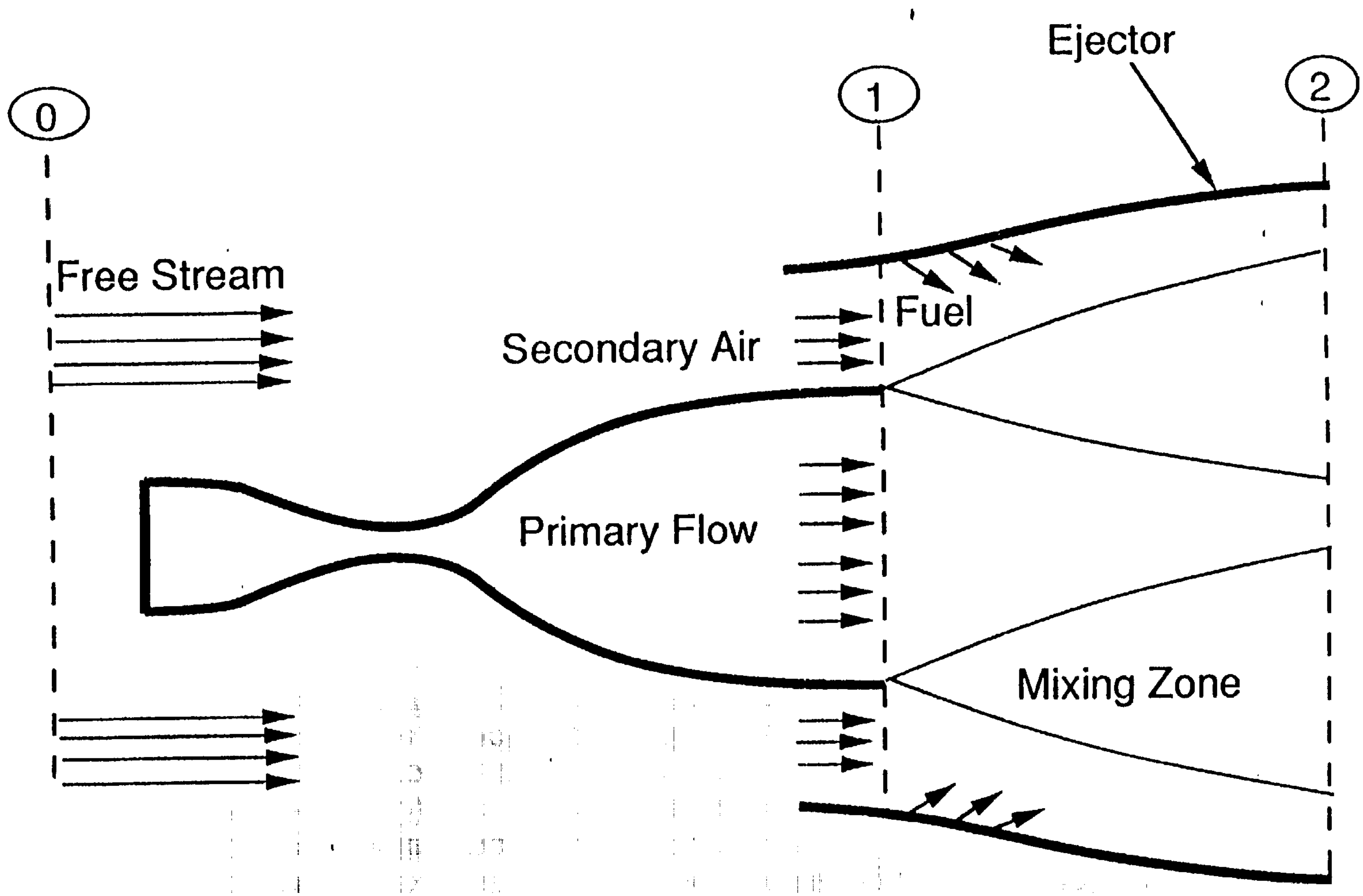
Example Operations Enhancing Technology

Level I	Air augmented afterburning rocket
Level II	Flash boiling tank pressurization
Level III	SLIC turbopump

Air-Augmented Ejector/Rocket

The air-augmented ejector/rocket is an example of a Level I technology. The distinct operational advantages of this potentially operationally efficient system warranted a review of the concept, a search of the most current experimental data, and identifying any recent related state-of-art. Successful thrust augmentation potentially could reduce a multistage vehicle to a single stage-to-orbit vehicle (SSTO) and, thereby, eliminate the associated ground support facility infrastructure and ground processing required by the eliminated stage. This would constitute a quantum simplification at the launch site. Preliminary analyses of performance, configuration and size indicated that a simple, fixed geometry ejector/rocket operating within the atmosphere was feasible and viable. A discussion of this concept is found in the OEPSS Databook volume IV.

AIR AUGMENTED EJECTOR/ROCKET



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Air Augmented Ejector/Rocket Preliminary Results

The ejector/rocket geometry was determined for the STME engine-propulsion module using the vehicle and flight trajectory of the Advanced Launch System (ALS). Since the ejector produces maximum thrust augmentation only at its point-design flight speed during the air breathing portion of the trajectory (in terms of altitude, thrust and flight Mach number), a series of ejector point designs were analyzed for a range of flight Mach numbers (0, 0.45, 0.80, 1.0 and 2.0), and were iterated over the ALS flight trajectory trading-off overall effective thrust increase with ejector drag and weight. The best ejector geometry and design-point flight speed is one which results in maximum payload increase or gross liftoff weight decrease.

Preliminary results indicate that the fixed geometry ejector concept, by afterburning the H_2-rich rocket exhaust, can achieve an average net thrust augmentation of $\Delta T = 15\%$ over the range of Mach number $M_o = 0$ to 2.0 ($\Delta T = 31.5\%$ at $M_o = 1.0$). The corresponding potential net payload increase for the ALS vehicle is 27.7%. Based on the ALS vehicle sensitivity factor ($\Delta PL/\Delta I_s = 828$ lbs/sec @ $I_s = 434$ secs), this payload increase is equivalent to a performance increase of $\Delta I_s = 40$ secs. As described earlier, the ejector/rocket has distinct advantages for possible application to an operationally simple, single stage to orbit vehicle.

Air Augmented Ejector/Rocket Preliminary Results

- Air augmented thrust, with fixed geometry ideally achievable by after-burning H2-rich exhaust (avg. over M0 = 0 to 2.0)

  ΔT = 15% w/o fuel addition*

- Potential payload increase using ALS trajectory

  ΔPL = 27.7% w/o fuel addition*

- Using ALS 1-1/2 stage vehicle sensitivity factor

  $$\frac{\Delta PL}{\Delta Is} = 828 \text{ lb/sec @ Is} = 434 \text{ secs}$$

  27.7% ΔPL = 40 secs. Is

- Ideal application for SSTO

*With fuel addition ΔT = 20% and ΔPL = 33.7%

Flash Boiling Tank Pressurization Technology

Flash boiling tank pressurization is an example of Level II technology. The intent of this technology is to eliminate the need for complex propellant tank pressurization system. This reduces the number of components, interfaces and multiple high maintenance areas of the propulsion system. This technology addresses the numerous operations concerns while providing enormous benefits in simplifying the ground support systems, in reducing system cost and in increasing reliability.

Flash Boiling Tank Pressurization Technology

- Driver/application:
  - Eliminate engine supplied or vehicle dedicated He gas propellant tank pressurization flow
  - Action reduces components, interfaces, and high maintenance associated with engine supplied tank pressurizing systems
- Operations concerns addressed*:
  - Fluid system leakage (2)
  - Excessive components/subsystem (9)
  - Lack hardware integration (10)
  - Pressurization system (17)
  - Excessive interfaces (18)
  - System contamination (23)

*OEPSS Databook: Volume II - Operations problems

Flash Boiling Tank Pressurization Technology (Cont.)

The primary objective of flash boiling tank pressurization is to simplify the tank pressurization system. There are several ways to implement this system. Analyses must be completed to select the most promising method. Once the baseline concept is selected considerable development testing is still required.

This system, which replaces today's complex autogenous pressurization systems, is currently being analyzed using low level IR&D funding within Rockwell. If funding were to increase, this type of system could be available for the next generation launch vehicles.

Flash Boiling Tank Pressurization Technology (Contd.)

- Objective/technical requirements:
  - Simplify pressurization scheme for vehicle
  - Investigate various means for propellant heating including propellant latent heat
  - Demonstrate proof of concept

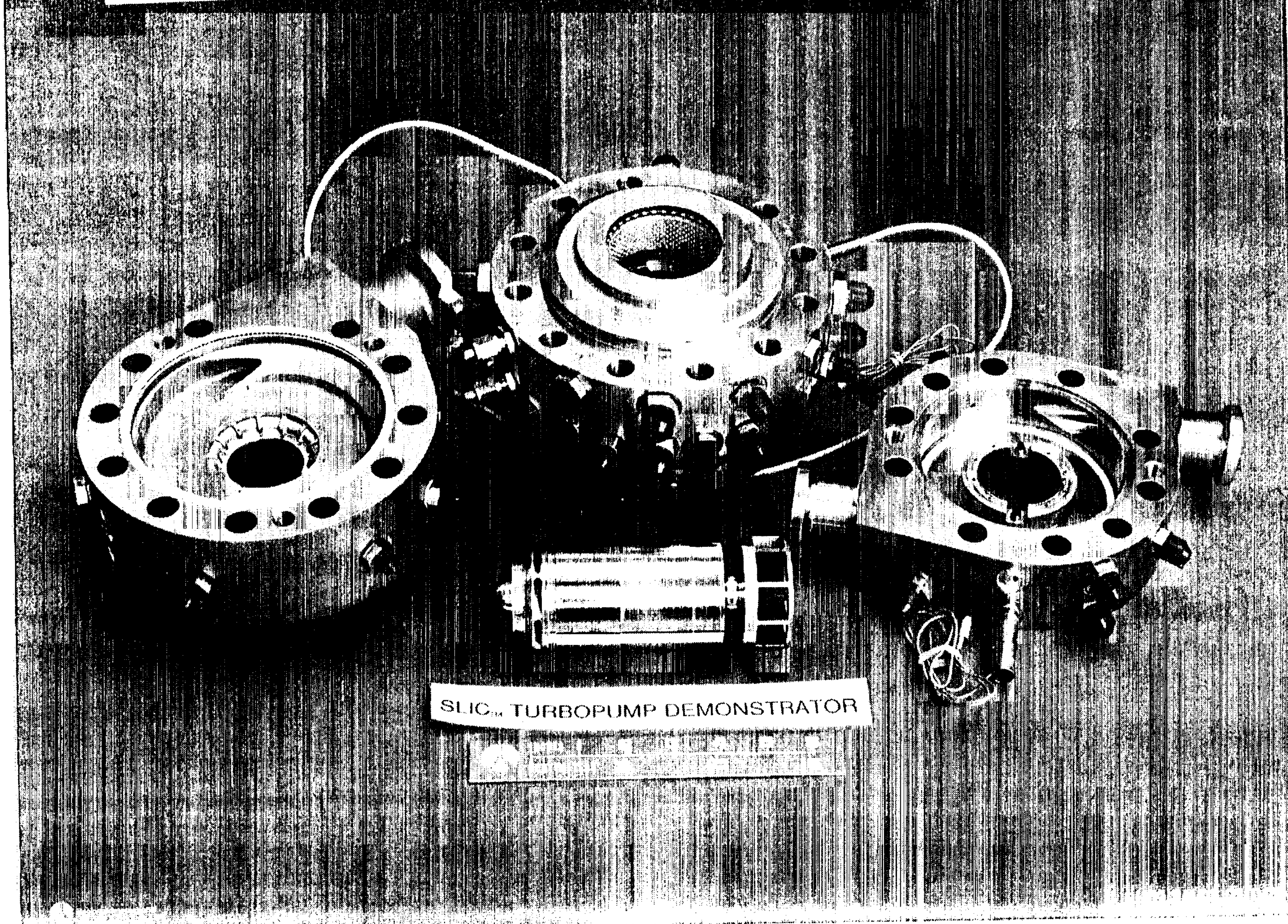
- Current state-of-art:
  - Current systems use engine supplied pressurization or stored pressurant

- Maturity level:
  - Technical Readiness Level 3
- Reference:
  - OEPSS Databook: Volume III - Operations Technology

Simple Low Cost Innovative Concept Turbopump

The Rocketdyne advanced technology liquid hydrogen turbopump is an example of Level III technology. This photo is a disassembled view of the SLIC™ turbopump successfully tested at Rocketdyne. It was tested with nitrogen to a speed of over 75,000 rpm. This photo was taken at the conclusion of three test series. Note that the hardware condition would allow continued testing with no need for refurbishment or inspection between tests.

Simple Low Cost Innovative Concept Turbopump



Simple, Low Cost Innovative Concept (SLIC™) Turbopump Simplicity Now Reality

The SLIC™ demonstrator turbopump has very unique design requirements allowing its unusually high performance and operability. It incorporated hydrostatic bearings to completely support the rotor, minimized the number of required parts; used scaling of existing turbopumps to minimized design effort; and demonstrated the high reliability required in future generation launch systems.

The operational benefits of the SLIC™ turbopump lie in its simplicity relative to recurring operationally intensive requirements for service, maintenance and checkout. Another operational benefit lies in its robust design which will eliminate any need for intrusive instrumentation and make it more reliable, dependable and cost effective.

Along with the performance and operational benefits seen with this unique turbopump, comes additional program benefits. This demonstrator was produced in one-fifth the normal time and as much as one-fifth the normal cost required for a typical turbopump.

The SLIC turbopump represents a technology that has already been demonstrated and can be considered sufficiently mature to enter full scale development for an actual engine system.

Simple, Low Cost Innovative Concept (SLIC™) Turbopump Simplicity Now Reality

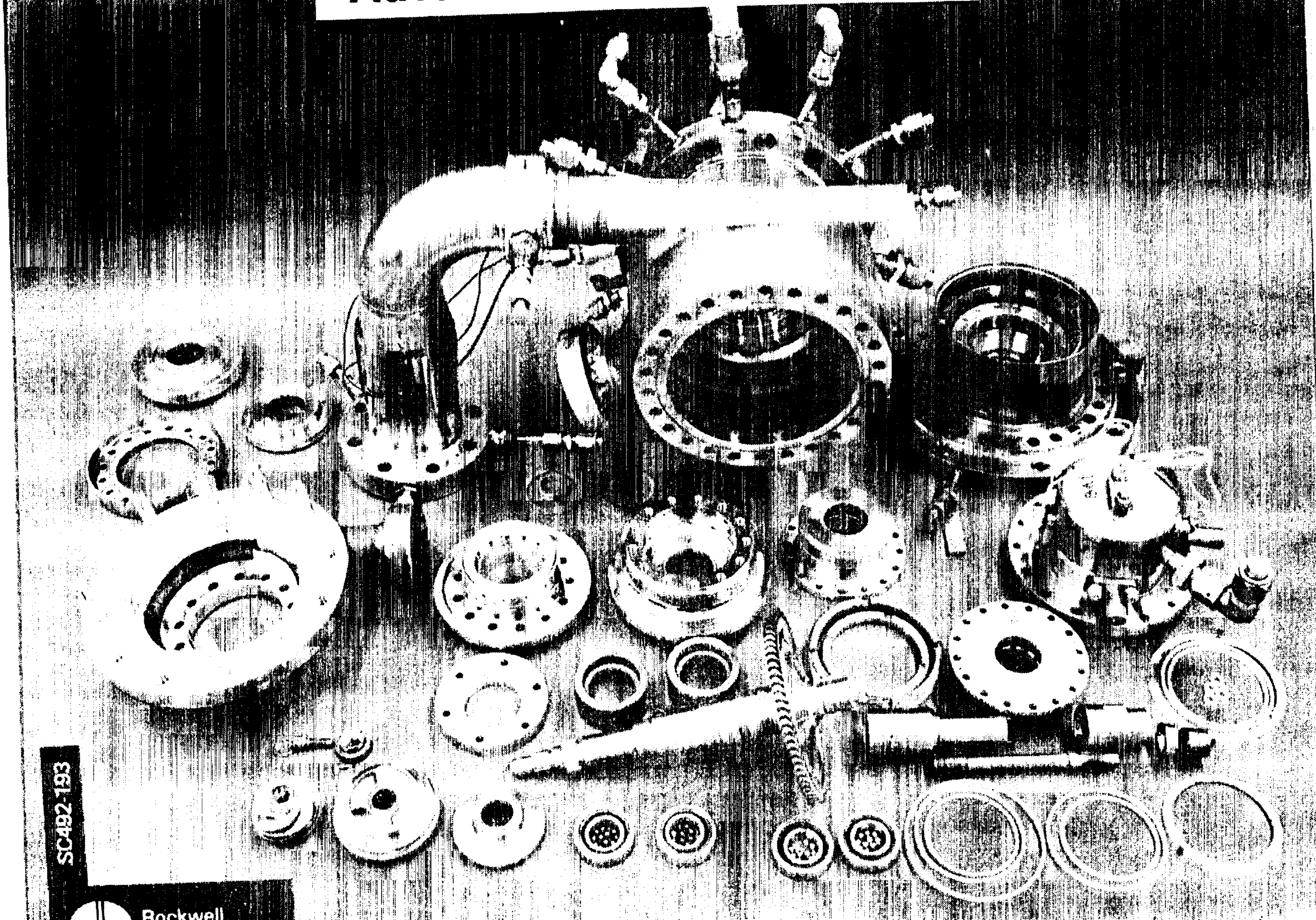
- Unique design objectives
  - Hydrostatic bearing technology incorporated
  - Minimize numbers of parts
  - Sizing is scalable
  - Significant increase in reliability
- Operations benefits
  - Significant reduction in inspection requirements
  - No "barrier" purges required
  - Design applicable to "family" of transportation systems
- Programmatic benefits
  - 1/5 traditional cost
  - 1/5 traditional schedule

Feasibility of concept has already been demonstrated

Advanced LH_2 Turbopump

A high speed liquid hydrogen turbopump is depicted. This unit designed by Rocketdyne (MK-49F) for upper stage applications represents a concept in the Technology Level III, or a Technology Readiness Level 5, category. It is presented here to illustrate the dramatic operational advantages the SLIC turbopump would have in simplicity and reliability.

Advanced LH_2 Turbopump



OEPSS Technology Infusion

The most significant reason for identifying the OEPSS technologies was to begin infusion of these technologies into the propulsion design communities. This has already begun through introduction of these technologies into activities of the SPSG, NASA's access to space activity, as well as several Air Force study contracts.

It has become clear that all vehicles require and stand to benefit from the development of the listed technologies through either preplanned product improvement to existing systems or complete bottoms-up integration into the next generation launch systems. It has also been identified that without starting technology work in the more far term technologies today, these concepts will not be available for any future launch system.

The greatest barrier to OEPSS technology infusion is lack of technical maturity for the technologies. Program management for new vehicles are and must be sensitive to high risk and cost, therefore they adopt a "show me" position on technology maturation. To overcome this traditional shortcoming, focused technology development is required and ultimately a system operations test bed must be produced to facilitate the implementation of the new technologies.

Operations technology development is a needed, viable area for further propulsion technology effort.

OEPSS Technology Infusion

- Technologies must be focused primarily on the visionary mission
- All vehicles require and greatly benefit from operations-driven technologies
  - Planned product improvement for existing systems
  - Complete integration into next generation launch system
  - Initiate development required for far term technologies
- Technologies are being identified for future launch systems
  - Space Propulsion Synergy Group
  - NASA Access to Space Option 3 Team
  - Air Force
- Further development maturation required for acceptance by program management
  - Focused technology development
  - Systems operability test bed

Operations is an essential class of vehicle/propulsion system technology

Space Propulsion Synergy Group and OEPSS are in Agreement

The SPSG has recently identified high value/payback technologies in its example findings. The most desirable technologies identified had the traits of high benefit with low cost and/or risk. These technologies are shown. Note the similarity with the OEPSS list. Also note that there are additional technologies on this list demonstrating the the OEPSS technology list is not closed ended, but should remain a living roadmap for future technology.

Space Propulsion Synergy Group and OEPSS are in Agreement

- Identification of high value/payback technologies
- Good benefit, low cost and/or risk
  - Automatic leak detection/location/discrimination system
  - Automated self-diagnostic condition monitoring supporting ground checkout and maintenance
  - Modularization for operability and vehicle integration
  - Propulsion system architecture
  - Long-life dynamic seals (like shaft)
  - Electromechanical actuators
  - Turbomachinery architecture
  - Leak-free tubing and ducts
  - Non-intrusive highly reliable sensors (smart components)
  - Automated handling and installation equipment
  - Designing for operationally Efficient interfaces
  - No Leakage static seals
  - Exhaust spectrometry

Source: Space Propulsion Synergy Group
ETO Technology Assessments
James Bray
Martin Marietta Manned Space Systems

OEPSS-Identified Technologies Meet "Leap-Frog" Technology Criteria

Several of the OEPSS technologies are applicable to the "Leap-Frog" approach to providing a world class competitive launch system. Some of the key near term technologies that would allow this to occur are shown on this chart. These systems offer a quantum leap in operations efficiency and could be ready for full scale development within three years.

OEPSS-Identified Technologies Meet "Leap-Frog" Technology Criteria

- Simple, low-cost innovative concept (SLIC™) turbopump
- Integrated Modular Engine (IME)
- Non-intrusive instrumentation
- Hydrostatic bearings for rotating machinery
- Advanced fiber-optic leak detection systems
- EMA's

Offers quantum leap in operational benefits--
Operational readiness level within three years

OEPSS-Identified Technologies Meet "Leap-Frog" Technology Criteria

Another approach to this "Leap-Frog" approach is to implement the integrated modular engine concept. This unique architectural change provides significant operational benefits using existing technologies. This approach would be further enhanced as operational technologies become available.

OEPSS-Identified Technologies Meet "Leap-Frog" Technology Criteria

- Integrated Modular Engine (IME)
    - Fast-track development program (3-Yr.)
    - Reduced number of major components
    - Two-fluid system
    - All-welded system, i.e., no leakage
    - Conservatively estimated at 1/5 traditional development cost

Technology Assessment at the Transportation System Level

When examining technologies it is always critical to reevaluate the impact of the item at the systems level. Those technologies that merely shift the location of the concern are of no real benefit. It is imperative that the impacts be summed over the entire propulsion system, including ground systems.

Proper integration of the technologies will also maximize the benefit seen by the system. An overall systems integration effort will yield the solutions to the operational concerns.

Another reason for viewing technologies in the transportation system level is because the individual technology benefits may be understated otherwise. For example visual inspection of the SSME powerhead is perceived to be not a large effort, however achieving access to the area and verifying leak tight integrity are substantial. This system level examination will continue to point out additional benefits yielded by operational technology.

Technology needs and benefits are only truly quantifiable at the overall system level.

Technology Assessment at the Transportation System Level

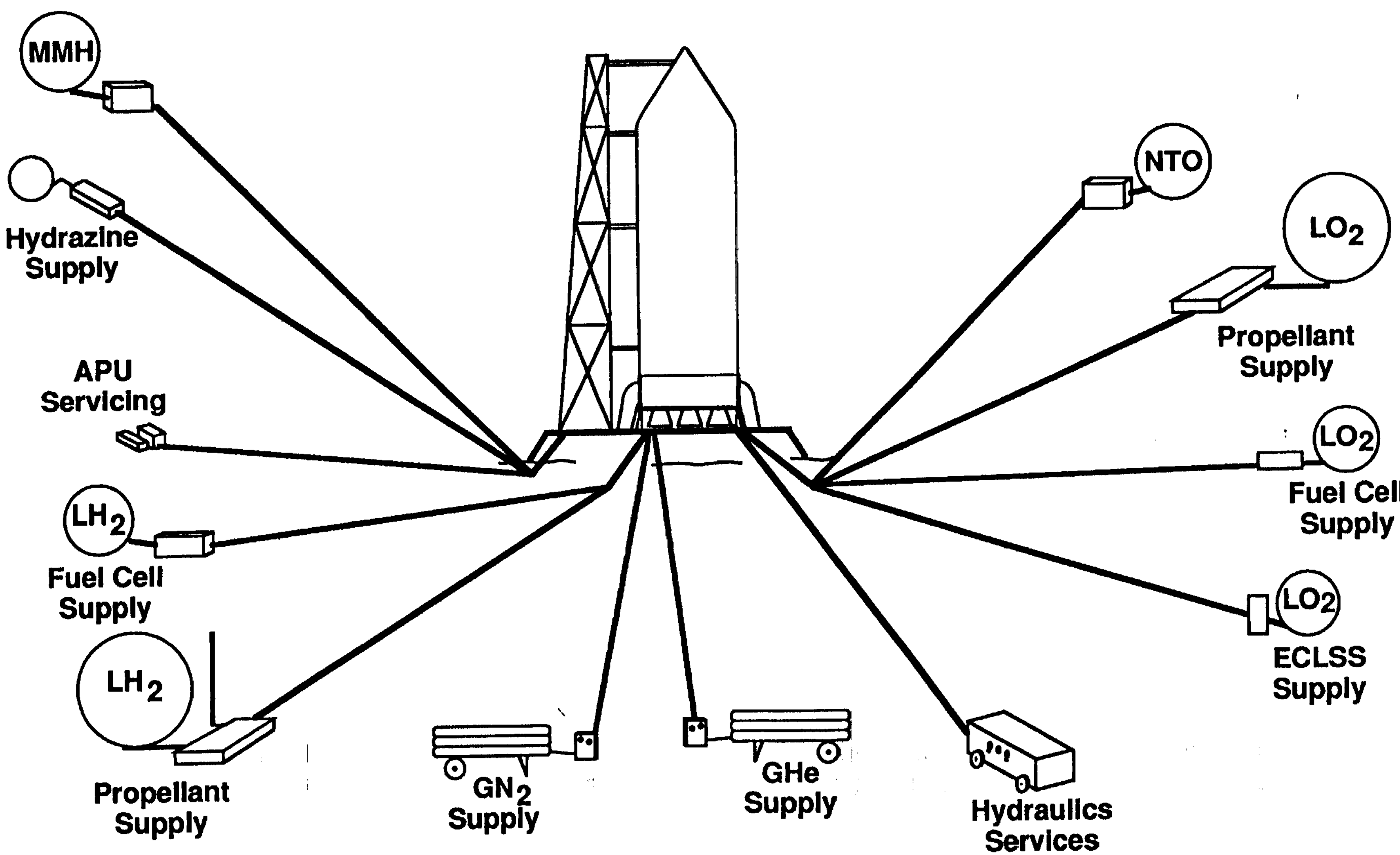
- Enlarged propulsion system definition must be adopted
  - Technologies that merely shift concerns are no real program benefit
  - Must sum impacts to entire transportation system (ground, ascent and flight operations)
- Integration required to determine true merit of technologies
  - Technologies can be applied to maximize operability and operations benefits
  - Focusing on operations concerns by developing a measureable quality characteristic is the key
- Transportation system context required to understand actual operations benefits or impacts
  - Individual technology benefits tend to be understated and misunderstood
  - Proper transportation system design integration approach can bring additional benefits to system and give complete view of overall infracture.

Maximized technology benefits can only be quantified, achieved and understood at the transportation system level

Traditional Launch Facility

This stick figure of a traditional launch facility demonstrates the complexity required by conventional launch system. Each of the subsystems shown involves a significant quality assurance infrastructure that must exist to assure high launch success.

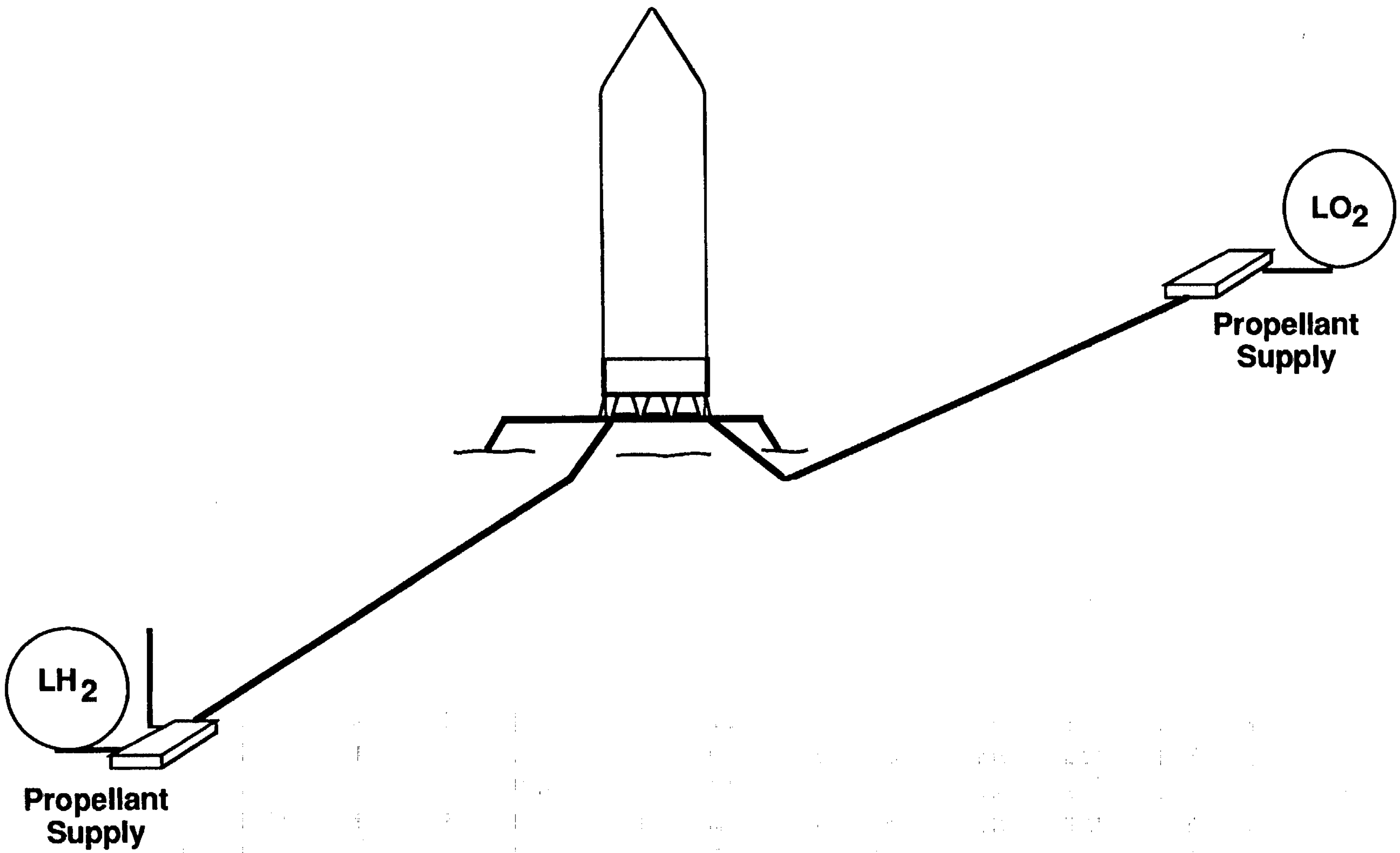
Traditional Launch Facility



Operationally Efficient Launch Facility

If the operations technologies identified by the OEPSS study (such as EMA's, no purge system, flash boiling pressurization systems, single propellant combination system, etc.) are successfully developed and implemented, this would result in eliminating massive ground support infrastructures and produce an operationally efficient and simple launch facility as shown. And, indeed, a barren pad with a simple two propellant facility should be made the ultimate goal for all future launch systems.

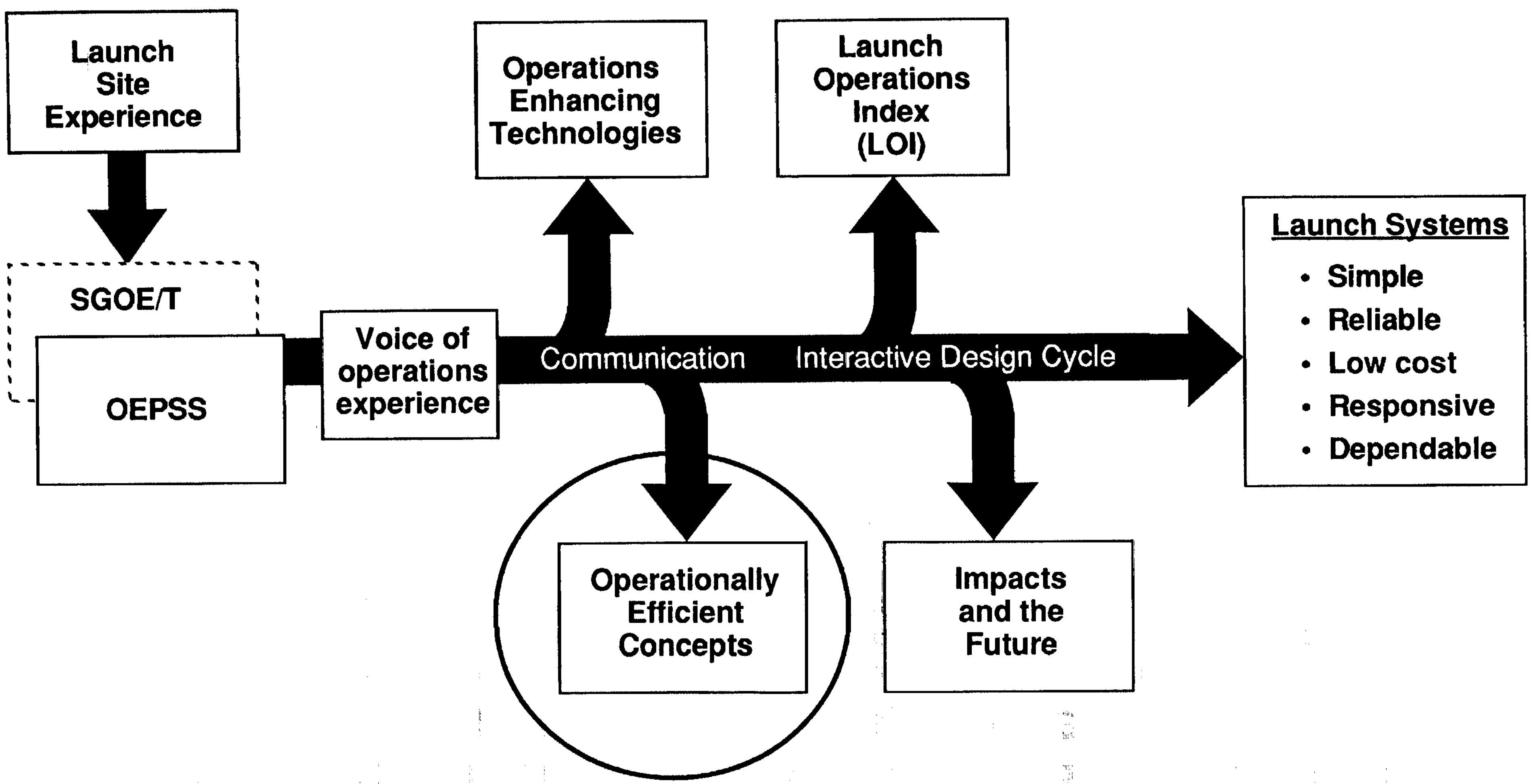
Operationally Efficient Launch Facility



"...Operations interactive in the design cycle will eliminate many launch site activities allowing systems to be available and responsive

The following section describes how several propulsion system architectures achieved operational efficiency by (1) integrating subsystems; (2) applying operations technology to eliminate operations problems; and (3) achieving drastic reductions in the operations support infrastructure

"...Operations interactive in the design cycle will eliminate many launch site headaches..."



Operations-Driven Propulsion System Architecture

This section will describe how simple design and appropriate technology can increase operability and achieve operational efficiency. To illustrate the principles of deliberate "integration" and "continuous process improvement (CPI)," a series of propulsion system architecture will be used. These include the applications for a booster, upper stage and space transfer propulsion systems.

Operations-Driven Propulsion System Architectures

Operations-Experience Based Architecture

In view of the many operations concerns that exist for current launch systems, the OEPSS study endeavored to apply its extensive operations experience base to find ways to greatly simplify and reduce operational requirements in future new systems. Concentrating on the propulsion system, the approach was to address the propulsion system architecture from the propellant tanks and feed system down to the turbopumps and thrust chambers, including all the pneumatic, hydraulic, electrical and avionics/control subsystems.

The architecture study explored how higher operational efficiency could be obtained in future booster (BPM), upper stage (IME) and space transfer (STPOES) propulsion systems. Although the air-augment rocket booster and propellant tank configurations, that will greatly simplify the ground support requirements, will not be described in this section, they are described in the OEPSS Databook, Volume IV - OEPSS Design Concepts. This section will cover the first three propulsion system architectures. Not only operations concerns were specifically addressed, applicable operations technologies also were applied.

Operations-Experience Based Architecture

• Integrated Booster Propulsion Module	BPM
• Integrated Modular Engine	IME
• Space Transfer Propulsion Operational Efficiency Study	STPOES
• Air-Augmented Rocket Afterburning	
• Alternate Propellant Tank Configurations	

Evolving Approach to Operations-Driven Architecture

The evolving nature of the OEPSS propulsion system architecture study is depicted. The operations concerns and technology identified by the study are primary drivers. First addressed in the fully "integrated," booster propulsion module (BPM), and with additional space operations concerns, then addressed in the upper stage "integrated" modular engine (IME)* and the space transfer propulsion system (STPOES). The term "integrated" does not mean packaging a system in the simplest manner; it means ...eliminating major components and subsystems and consolidating functions to achieve quantum reduction in hardware and, therefore, major reductions in operational requirements.

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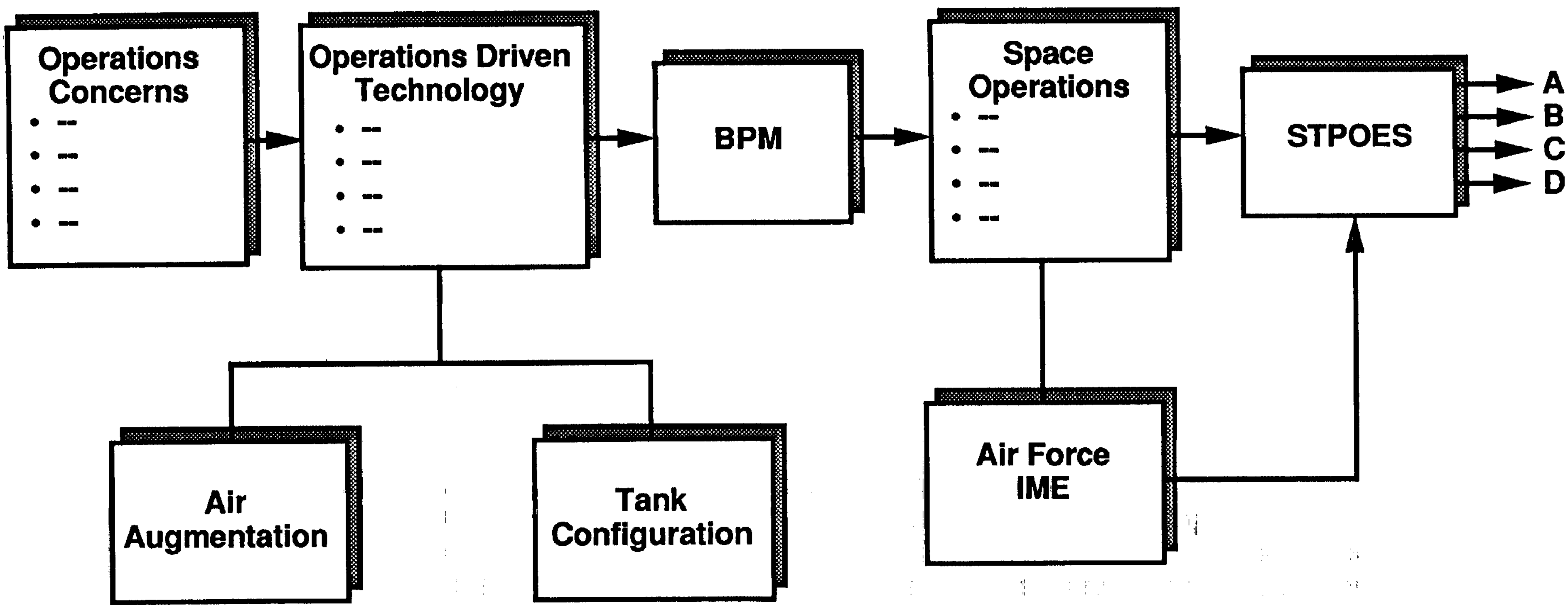
*The IME is a separate Air Force study contract.

Evolving Approach to Operations-Driven Architecture

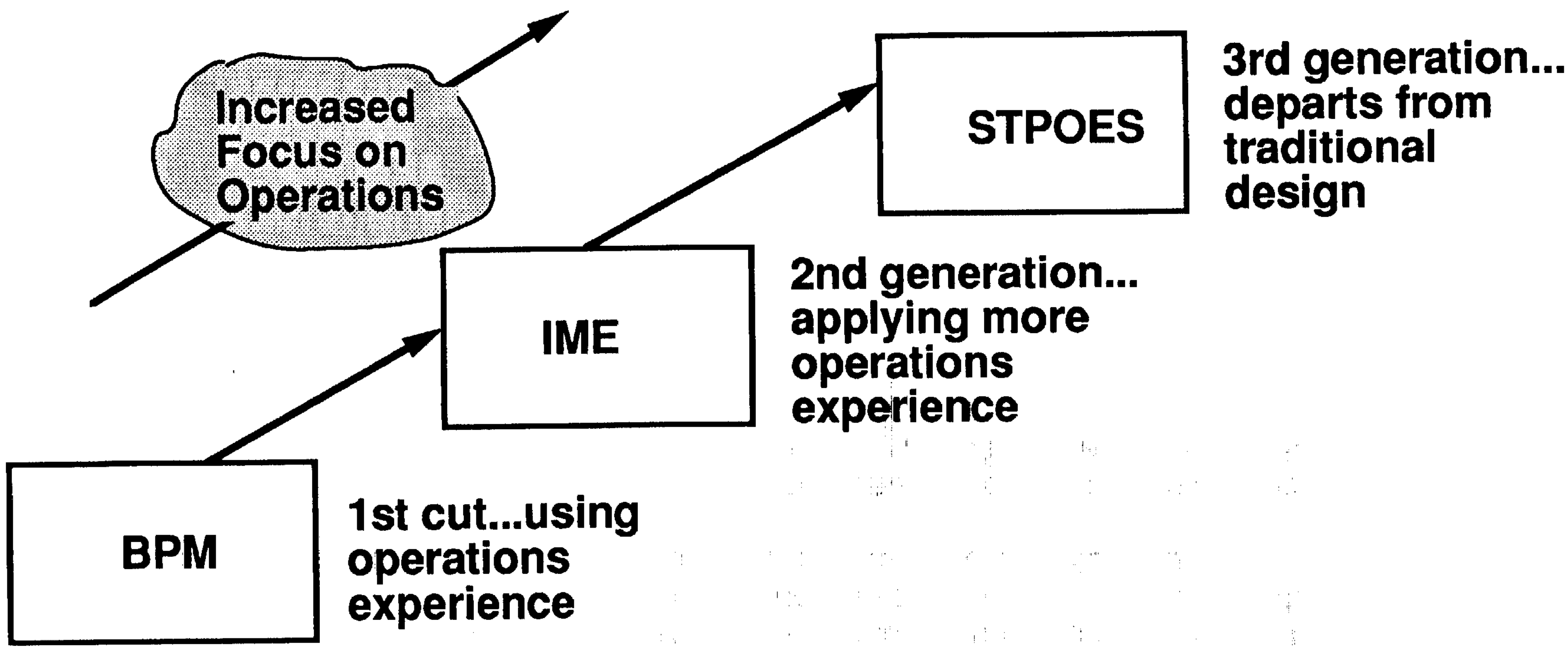


Operational Experience and Principles of Continuous Process Improvement Drive Architecture

In the successive process of exploring the system architecture of the three different propulsion system applications, the benefits of Continuous Process Improvement, or CPI, were most evident. The understanding of the customer's (operator) need; recognizing the great opportunity for reducing operations problems and improving the launch process flow; and making the operations process easier, faster, cheaper and better, all come into play during the OEPSS study.

Moreover, a figure of merit which will also reflect the beneficial gains achieved (measurement) in the CPI process, called the LOI, or launch operations index, was developed in the OEPSS study and will be described in a later section.

Operational Experience and Principles of Continuous Process Improvement Drive Architectures



Operations and Operability Impacts on Booster Propulsion

In the architecture study of a booster propulsion module for a heavy lift launch vehicle, a propulsion system driven by operations concerns early in the design cycle will avoid these concerns later in development. The system architecture will be inordinately simpler and ultimately more operationally efficient.

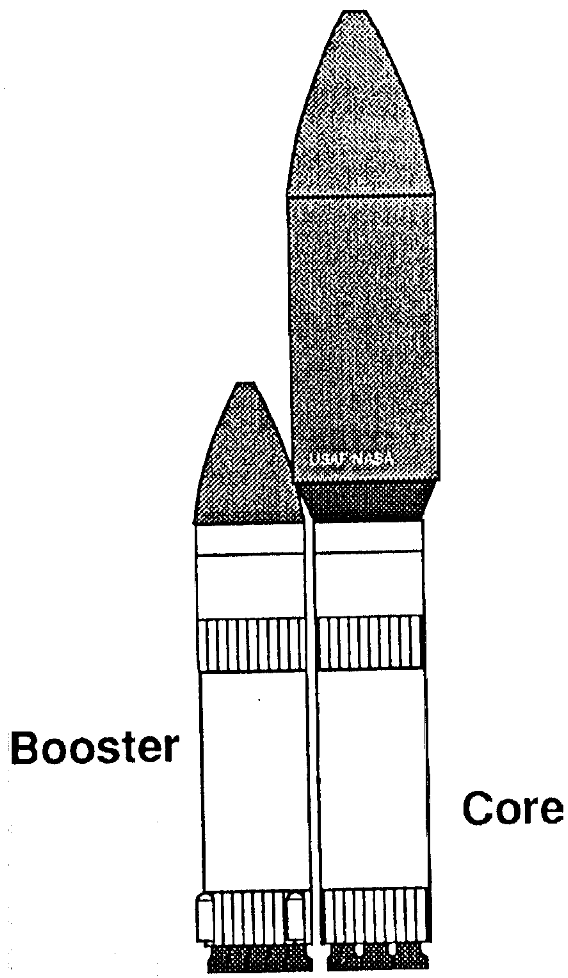
Operations and Operability Impacts on Booster Propulsion

Operations-Driven BPM Architecture

Integrated Booster Propulsion Module

A fully-integrated, operationally efficient booster propulsion module is depicted. A significant reduction in major hardware and a simplified propellant feed system were achieved by utilizing a parallel manifold system of components. The major difference between this system and a conventional system is that a minimum number of turbopumps and subsystems are needed to feed the thrust chambers. The conventional system with autonomous engines will require complete sets of dedicated turbopumps and subsystems for each thrust chamber and, therefore, has no latitude for reducing hardware and simplifying the system or reducing the operational requirements. A detailed discussion of the integrated booster propulsion module is found in the OEPSS Databook Volume IV.

BASELINE ALS VEHICLE



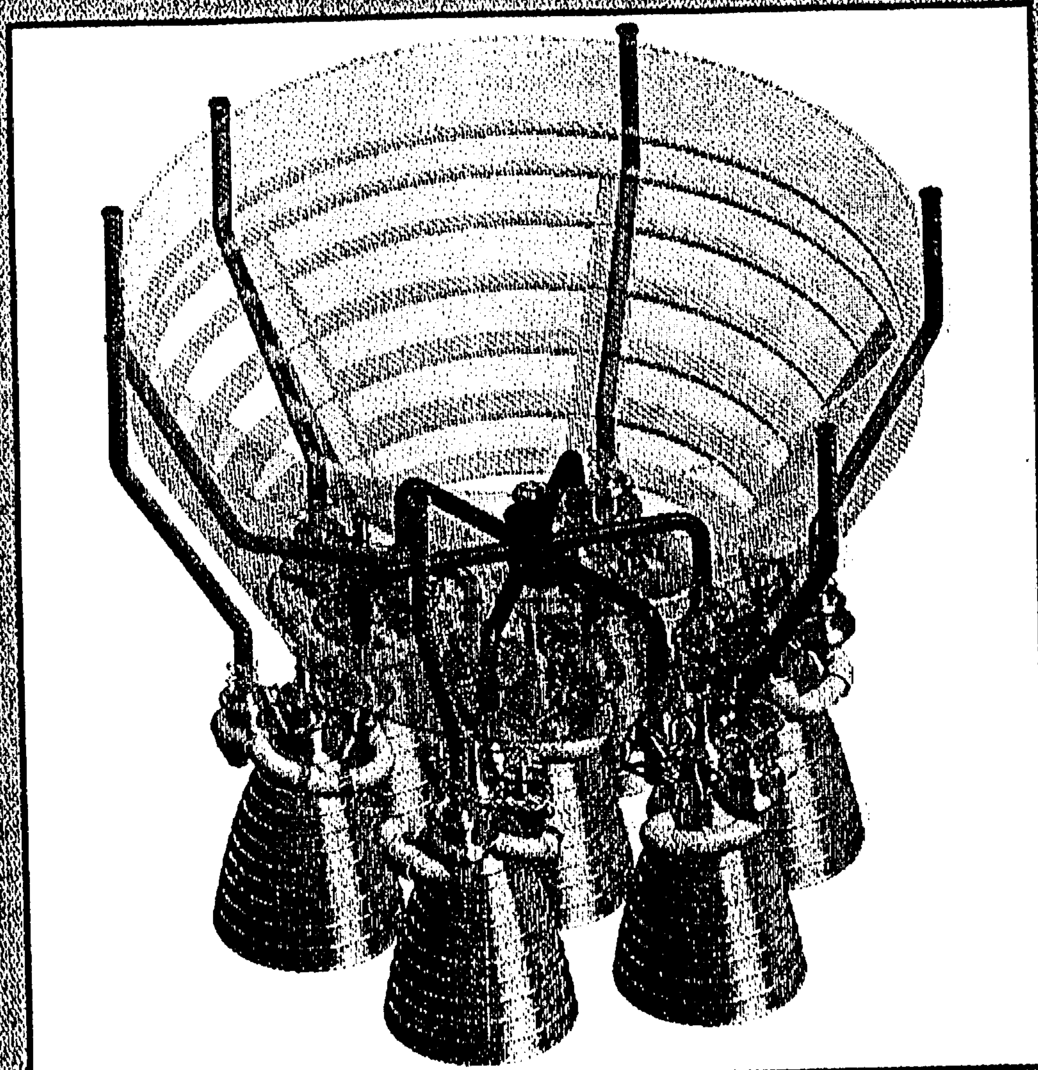
• Payload	120,000 lbs (LEO)
• GLOW	3,500,000 lbs
• Thrust/weight	1.30
• Booster vehicle	150' x 30' dia.
• Core vehicle	280' x 30' dia.
• Booster engines	7
• Core engines	3
• Engine thrust (vac)	580,000 lbs (STME)

Conventional Booster Propulsion System

A typical propulsion module for the ALS booster vehicle is depicted. It consists of seven autonomous, stand-alone engines. Each engine consists of a complete set of dedicated components and sub-systems, and the shutdown of any of which will shut down the autonomous engine. The center engine location presents added operational complexities.

CONVENTIONAL BOOSTER PROPULSION SYSTEM

7 – ENGINE



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Integrated Booster Propulsion Module

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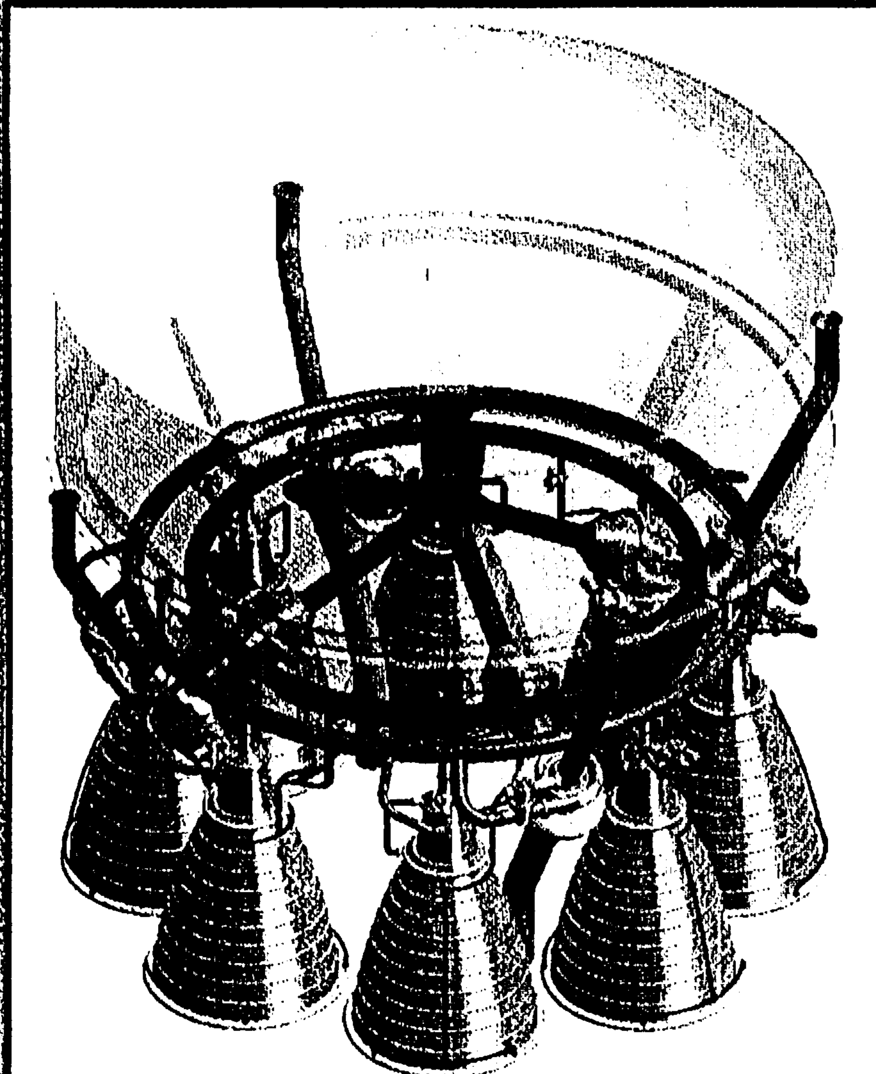
INTEGRATED BOOSTER PROPULSION MODULE – ENGINE

8 – THRUST CHAMBERS



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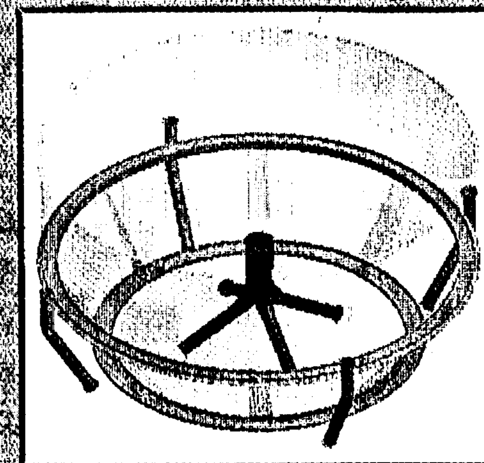
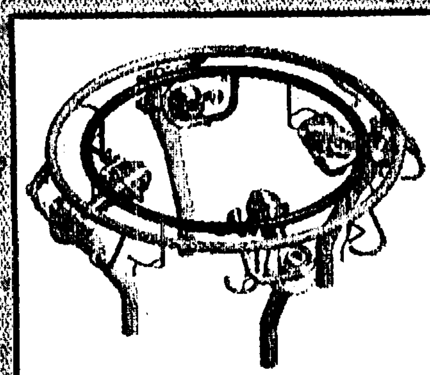
Integrated Propulsion Module
Engine Subsystems

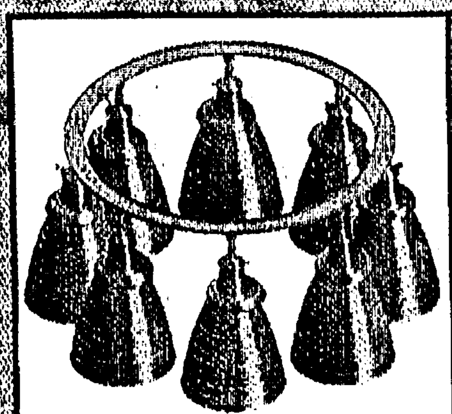
The three major subsystems for the integrated propulsion module are depicted. These are the (1) parallel thrust chamber-manifold subsystem, (2) parallel turbopump-manifold subsystem, and (3) feedline and structure assembly.

Integrated Propulsion Module

Engine Subsystems







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Integrated System has Operating Margin and Fault Tolerant Capability

Adding a thrust chamber to the integrated BPM achieved some significant and unique advantages over a conventional cluster of autonomous engines. First, there is total symmetry between the booster and core. Second, at nominal vehicle takeoff thrust, the thrust chambers and turbopumps all operate at 85% and 90% of its design operating points, respectively. Third, only when there is a thrust chamber shutdown or a turbopump shutdown, or both, will the thrust chambers and turbopumps be operating at their 100% design point conditions.

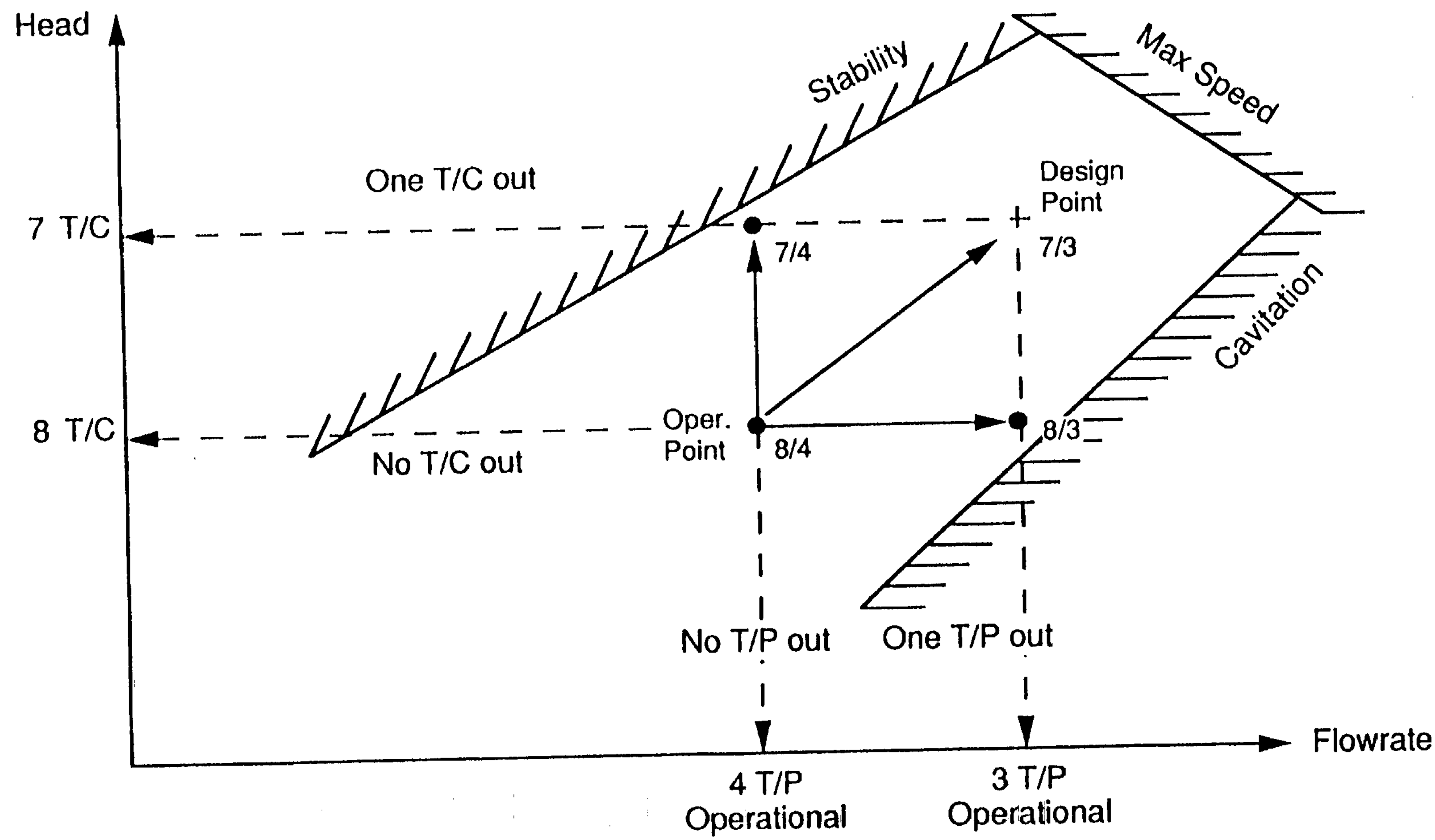
Integrated System Has Operating Margin and Fault Tolerant Capability

Engine Operation	Thrust Chamber (T/C) % Rated Thrust	Turbopumps (T/P) % Rated Speed
Nominal	85	90
T/C - Out	100	97
T/P - Out	85	93
T/C and T/P-Out	100	100

Turbopump Operating Conditions

The turbopump operating map shows the nominal operating margin for the turbopumps in the integrated system. The turbopump operating points under all fault-tolerant conditions described previously fall well within the performance map.

TURBOPUMP OPERATING MARGIN



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SC89c-30-151A

90ALS-150-98

Booster Propulsion Module
Hardware Comparison

A vis-a-vis comparison of component hardware between the integrated and conventional propulsion systems for the ALS vehicle is shown. The operational requirements favors the integrated system with approximately 40% less parts.

BOOSTER PROPULSION MODULE HARDWARE COMPARISON

Separate Engines vs. Integrated System

Engine Elements	Separate Engines	Integrated System (Static)
	No. of Components	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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Backup D to
SC89c-30-151A

90ALS-150-104

Booster Propulsion Module Reliability

The vis-a-vis comparison of system reliability between the integrated and conventional propulsion systems for the ALS vehicle is shown. The system reliability clearly favors the integrated system with fewer component parts. As pointed out earlier, the system reliability for the fault-tolerant integrated system clearly is significantly higher than the conventional system with a single engine-out capability.

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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Backup E to
SC89c-30-151A

90ALS-150-105

Booster Propulsion Module System Weight

The vis-a-vis comparison of system weight between the integrated and conventional propulsion systems for the ALS vehicle is shown. Conservative weight estimates were made for the ring manifold, turbopumps and heat exchangers used for the integrated system. The simpler feed system configuration and fewer component parts appear to favor the integrated system.

BOOSTER PROPULSION MODULE SYSTEM WEIGHT
Separate Engines vs. Integrated System

Engine Elements	Unit Weight Lbs	Separate Engines		Integrated System	
		No. of Components	Weight Lbs	No. of Components	Weight Lbs
Thrust chamber:					
MCC	613	7	4291	8	4904
Injector	364	7	2548	8	2912
Nozzle	2088	7	14616	8	16704
Igniter	31	7	217	8	248
Oxidizer turbopump	1726	7	12082	4	9664 (1)
Fuel turbopump	1421	7	9947	4	7960 (1)
Gas generator	121	7	847	4	484 (2)
Heat Exchanger	101	7	707	2	404 (3)
Start System	35	7	245	1	70 (3)
PCA	82	7	574	1	82
Controller (avionics)	20	7	140	1	20
Gimbal bearing	158	7	1106	0	0
Gimbal actuator	190	14	2660	0	0
Propellant lines	--	14 (1186)	16600	4 (1587)	6348
Flexible inlet lines	734	14	10276	0	0
Fixed inlet lines	668	0	0	8	5344
Main valve/actuator	144	14	2016	24	3456
Prevalve	75	14	1050	0	0
Crossover duct/lines	214	7	1498	0	0
HP T/P discharge lines	360	0	0	8	2880
Ring manifold	3750	0	0	2	7500
HP T/C inlet lines	300	0	0	8	2400
Miscellaneous	585	7	4095	8	4680
Center engine mount	1826	1	1826	0	0
Total Weight			**87,340**		**76,058**

(1) Factor of 1.4; (2) Factor of 1.5; (3) Factor of 2.0

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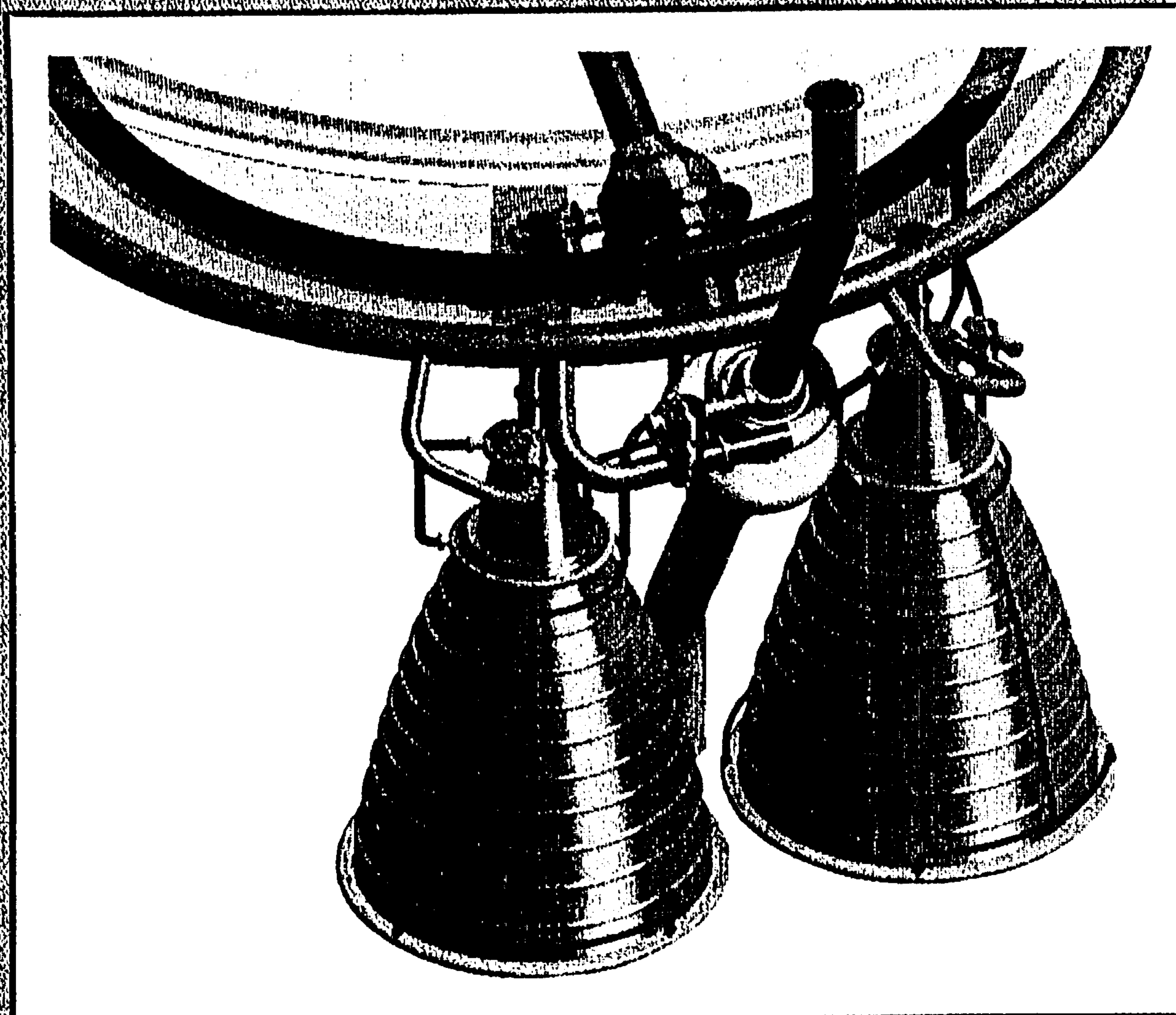
Backup F to
SC89c-30-151A

90ALS-150-107

Integrated Propulsion Module - Engine Element

The simple engine element that allows the integrated BPM parallel configuration to achieve simplicity is depicted. Manifolding these elements allows you to synthesize a booster, or a core, or a vehicle of any thrust level to deliver a wide range of payloads. The engine element approach not only reduces operational requirements, it also has the potential to greatly simplify and reduce the cost of propulsion development.

INTEGRATED PROPULSION MODULE – ENGINE ELEMENT



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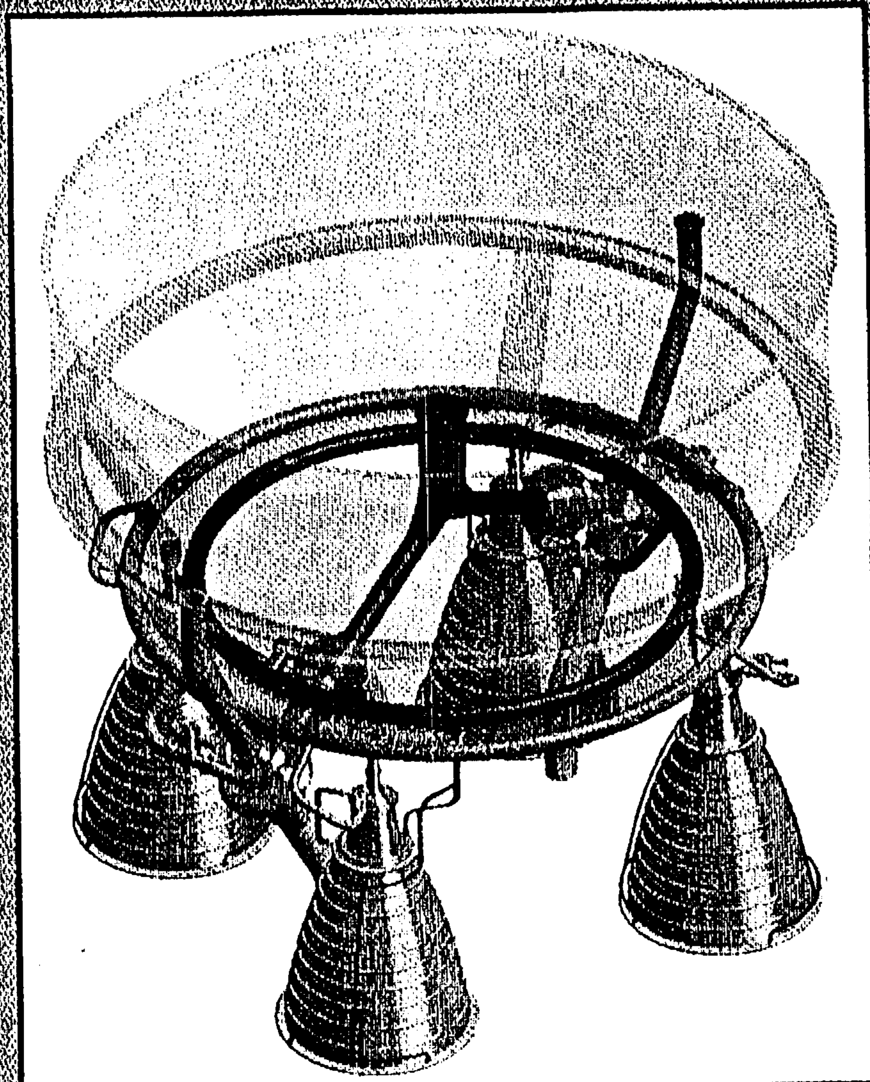
Integrated Core Propulsion Module

Two basic engine-elements is seen to make up the integrated core propulsion module. The core and booster propulsion module have common manifolds, feedlines, valves and thrust structure as well as common turbopumps and thrust chambers.

INTEGRATED CORE PROPULSION MODULE – ENGINE
4 – THRUST CHAMBERS



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Backup A to
SC89c-30-154A

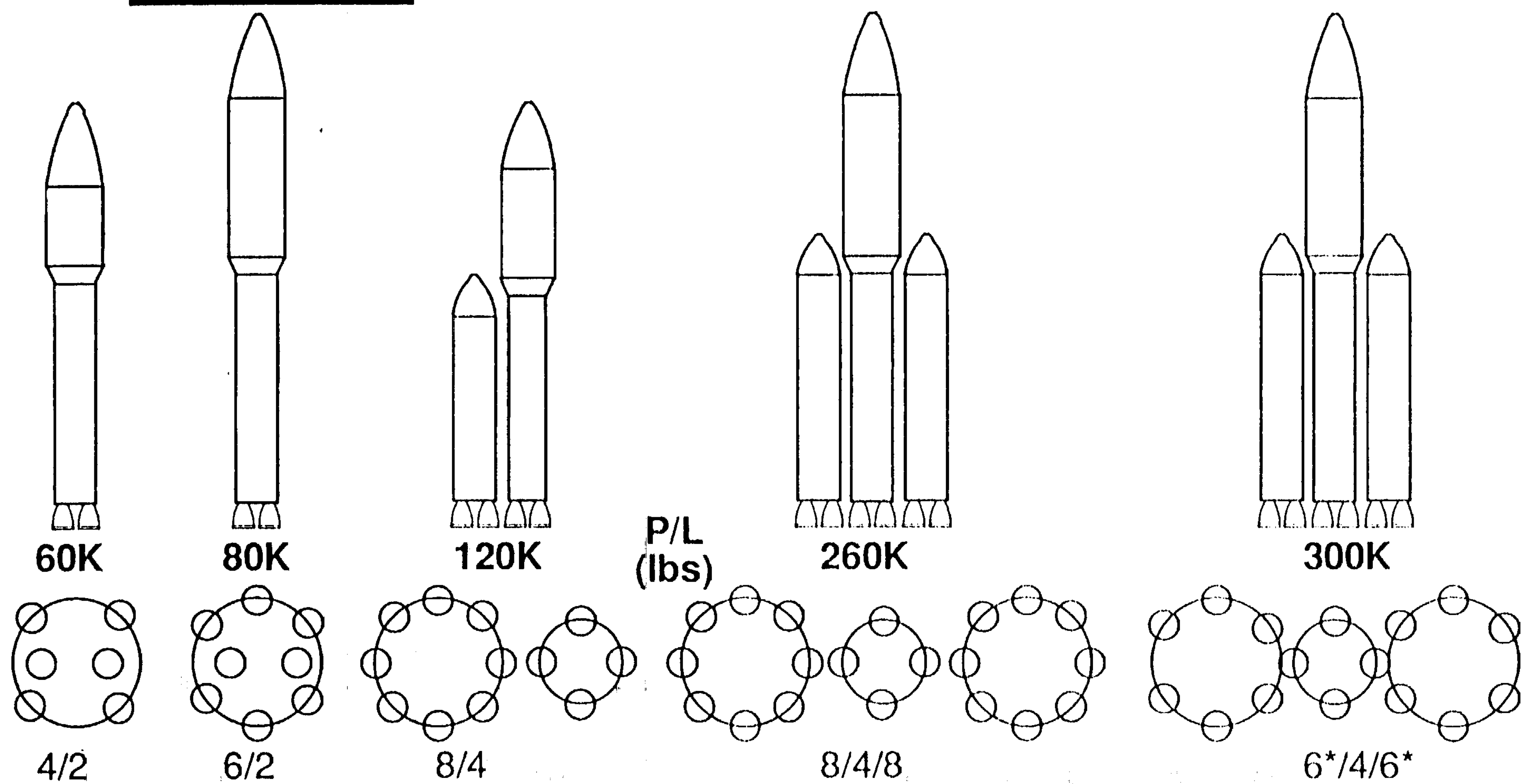
Payload Capability Using Integrated Engine Elements

The basic engine-element illustrated for the BPM has been shown to make up the booster and core propulsion modules for the ALS. In similar fashion, the same basic elements, once developed, can be directly used to synthesize the requisite total vehicle thrust to deliver payloads from 60,000 to 300,000 pounds. Common propellant ring manifolds are used for the boosters and cores, respectively.

PAYLOAD CAPABILITY USING INTEGRATED ENGINE ELEMENTS

Typical ALS Vehicles

- P/L = 60,000 to 300,000 lbs
- 580K STME



* 650K STME

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SC89c-30-154A

91ALS-051-34

Payload Capability Using Integrated Engine Elements

This chart illustrates the number of basic engine-elements that are needed to deliver a range of payloads using thrust chambers based on the 650K STME engine.

PAYLOAD CAPABILITY USING INTEGRATED ENGINE ELEMENTS

- **P/L = 60,000 to 300,000 lbs**
- **STME 580 Klbs thrust chambers**

	Thrust Chambers		Payload Capability, lbs				
Integrated Engine:	Booster	Core	60K	80K	120K	260K	300K
3 - Elements*	4	2	X				
4 - Elements*	6	2		X			
6 - Elements**	8	4			X		
10 - Elements***	8/8	4				X	
8 - Elements****	6/6	4					X

* Staged vehicles
** Side-mounted booster vehicle
*** Two side-mounted LRBs
*** HLLV configuration, 650K STME

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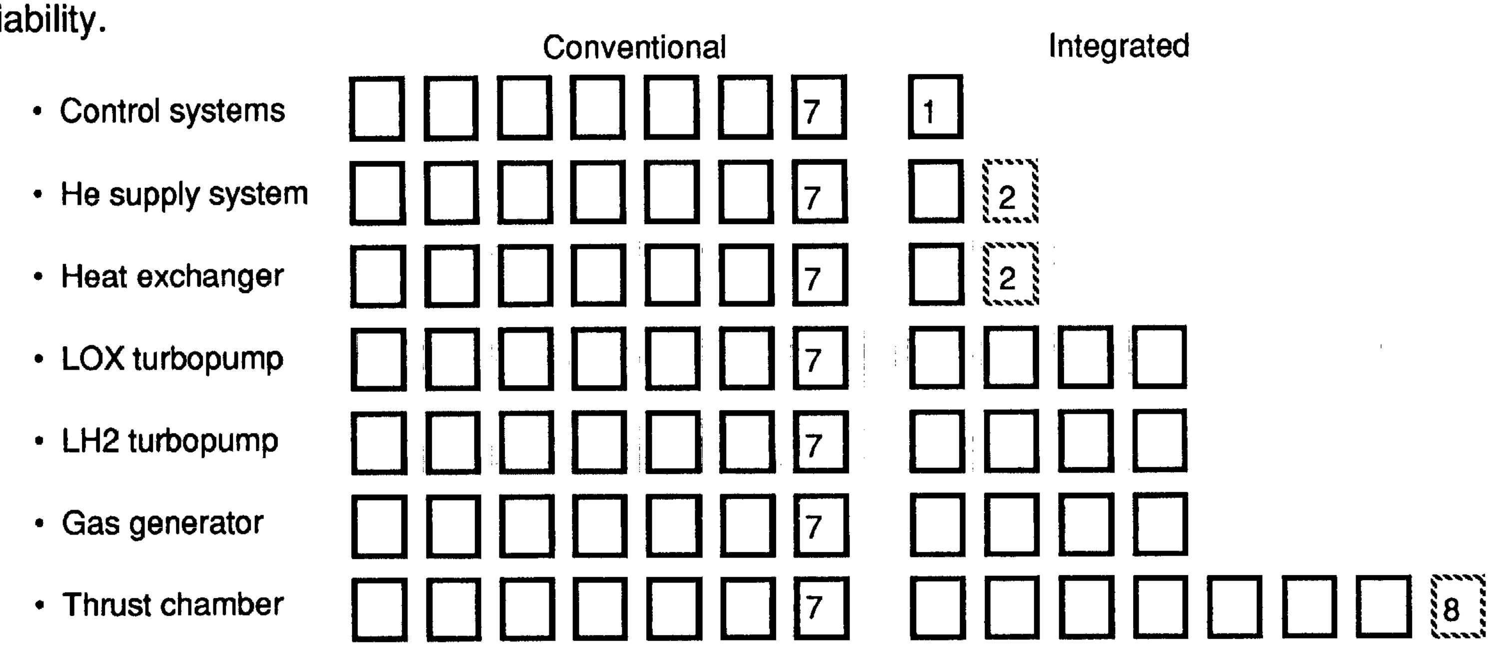
Backup C to
SC89c-30-154A

Integrated Architecture Increases Operability

The integrated BPM allows the use of a single He-pressurization system, a single LOX- pressurization system and a single avionic/control system. Together with the engine-element approach, this results in nearly 50% reduction in primary components and therefore achieves high operability and reduced operational requirements. Moreover, the architecture is robust and fault tolerant and has high system reliability.



Integrated Architecture Increases Operability

- 50% fewer primary components
- High operability
- Operating margin (robust)
- Component fault tolerant capability
- High propulsion system reliability

Integrated BPM Addresses Operations Concerns

The operational efficiency of the integrated BPM architecture is most evident by the number of operations concerns it mitigates or eliminates. At least 14 major operations concerns are shown addressed. The application of operations technology identified by the OEPSS study undoubtedly will reduce these concerns even further.

Integrated BPM Addresses Operations Concerns

No.

1 Closed aft compartments
2 Fluid system leakage
- External
- Internal

3 Hydraulic system
4 Ocean recovery/refurbishment
5 Multiple propellants
6 Hypergolic propellants (safety)
7 Accessibility
8 Sophisticated heat shielding
9 Excessive components/subsystems
10 Lack of hardware integration
11 Separate OMS/RCS
12 Pneumatic systems

No.

13 Gimbal system
14 High maintenance hardware
15 Ordnance Operations
16 Retractable T-O umbilical carrier plates
17 Propellant tank pressurization system
18 Excessive interfaces
19 Conditioning/geysering (LOX tank forward)
20 Preconditioning system
21 Expensive commodity usage -- helium
22 Lack hardware commonality
23 System contamination

BPM addressed 14 concerns

Integrated BPM Generated Many Questions

The integrated propulsion architecture of the BPM was initially conceived to illustrate how a system can be made simpler by avoiding the major operations concerns identified by the OEPSS study. Granted that the system indeed has attractive and distinct operational advantages, but will a manifold-parallel propellant feed system work? Thus, a new transient simulation computer model was developed to investigate potential performance problems, unique to its configuration, and, otherwise, to confirm and validate its operating characteristics and satisfactory transient and stable mainstage performances.

Integrated BPM Generated Many Questions

- Originally conceived only as an "illustration" how launch operations could be greatly "simplified"
- Many questions raised
  - "...BPM sounds good...will it work? It will work...it's blue sky..."
- Operational advantages warrant further analysis
- New transient simulation computer model developed for BPM

Required to establish conceptual credibility

Computer Model Generated for BPM

A fluid dynamic, digital transient computer model of an integrated, parallel propulsion system was developed for CDC mainframe computer and the SUN workstation. Since all STME component designs were used for the integrated system, computer subroutines were written characterizing the performance and geometry of all the components used in the system, including the manifold. Thus, propellant pressures, temperatures and flowrates (for gas generators, pumps, turbines, valves, lines, etc.) throughout the system can be generated for a computer simulation of system transient behavior or steady state operation. A series of computer runs were required to "debug" the new computer model to verify nominal engine balance and steady state operation.

Computer Model Generated for BPM

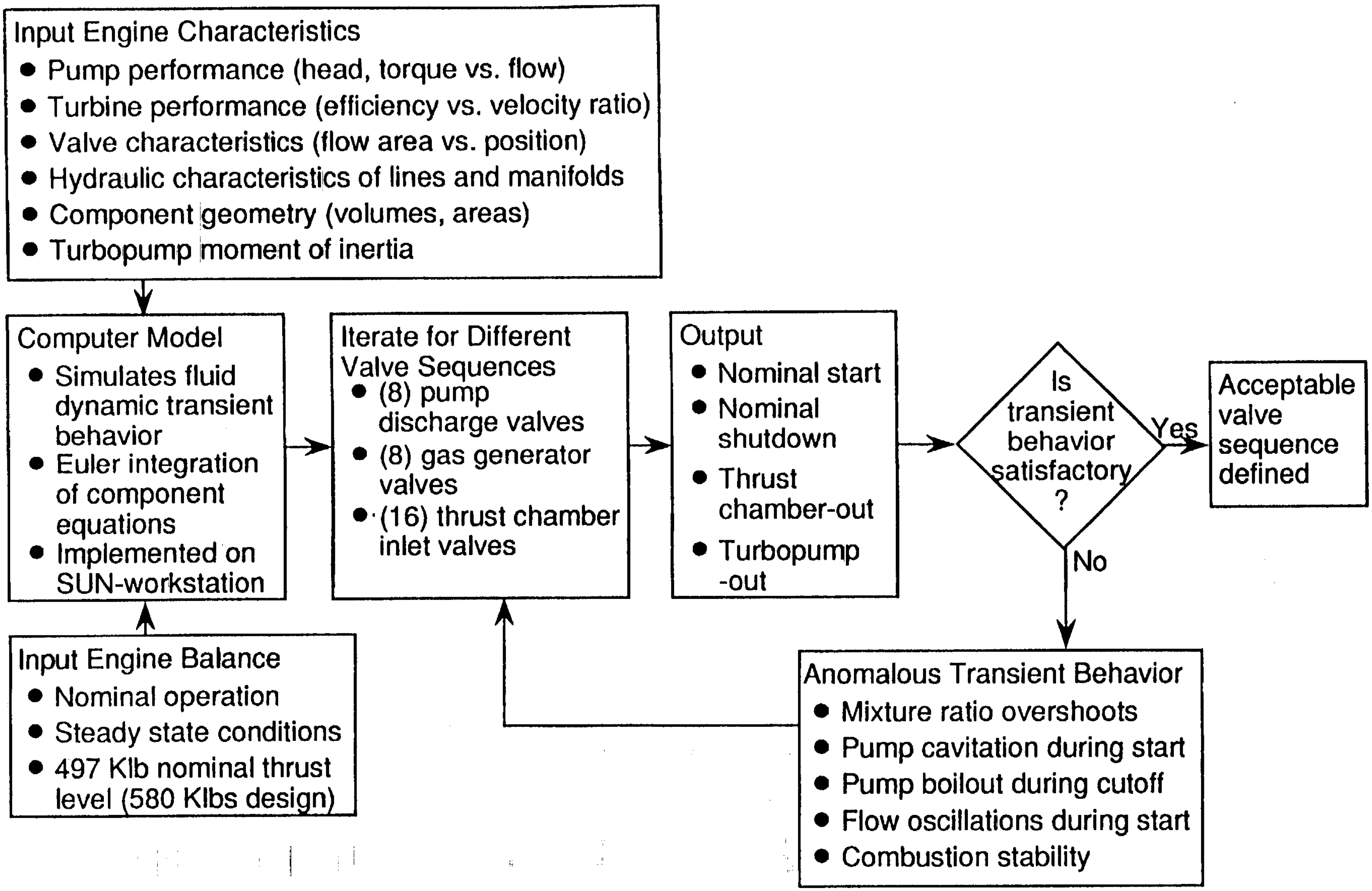
- A fluid dynamic digital transient model developed for CDC mainframe computer and SUN workstation
- Subroutines written characterizing component performances (Propellant pressures, temperatures & flowrates for gas generators, pumps, turbines, valves, lines, etc. throughout the system)
- Successful computer model checkout and operation established by propulsion "system balance" and stable mainstage operation

New computer model applicable to all integrated propulsion systems for any power cycle

Methodology for Transient Simulation Modeling

The computer model developed for the integrated BPM is diagrammatically illustrated. The component characteristics and nominal operation are already system inputs. The output is the system transient behavior obtained during system startup, cutoff, or component malfunction and shutdown. To achieve satisfactory operation, the system must avoid anomalous transient behaviors such as mixture ratio overshoot, pump cavitation (during start), pump boilout (during shutdown) flow oscillations and combustion instability. Variations in valve sequencing is iterated to ascertain if the selected valve sequence has successfully avoided all operating anomalies and achieve stable transient and steady state operations.

METHODOLOGY FOR TRANSIENT SIMULATION MODELING



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Transient Dynamics Simulated for the Integrated Parallel System

The integrated, parallel propulsion system was found to be dynamically stable for a wide spectrum of transient behaviors investigated. Not only acceptable performance was obtained for nominal startup and cutoff, turbopump or thrust chamber or combined turbopump and thrust chamber shutdowns, and variations in valve sequencing, acceptable performance also was obtained for staggered turbopump start, delayed spin start and common pump to pump performance differences. The dynamic operating characteristics of the integrated system has shown to be no different nor more difficult than a conventional propulsion system. The results described are discussed in more detail in OEPSS Databook Volume VIII.

Transient Dynamics Simulated for the Integrated Parallel System

- Nominal start and cutoff transients
- Staggered gas spin (turbopump) start
- Single turbopump shutdown (throttling up)
- Single thrust chamber shutdown (throttling up)
- Combined thrust chamber/turbopump shutdown (throttling up)
- Delayed gas spin start
- Variations in valve sequencing
- Differences in pump-to-pump head and torque characteristics

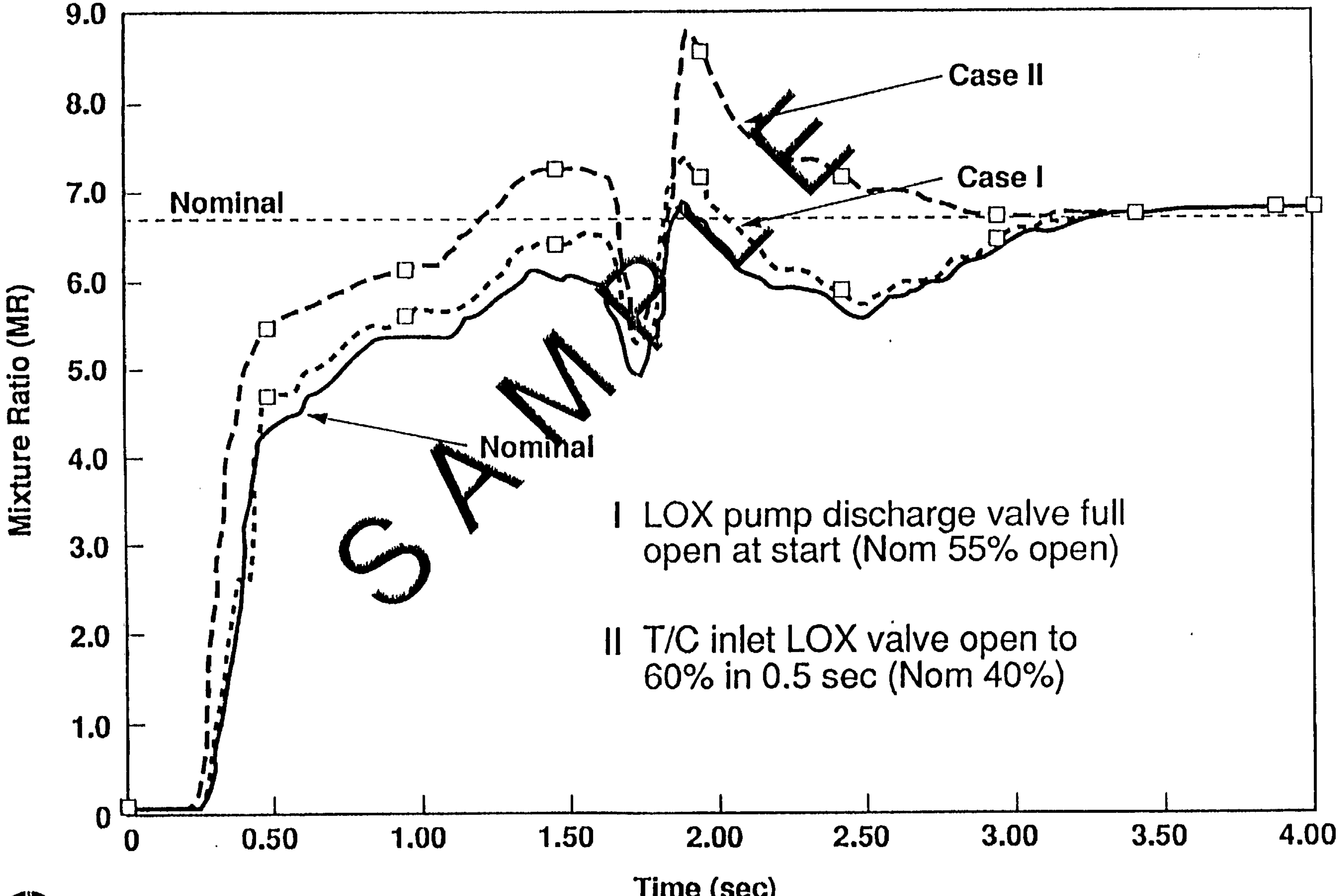
Extensive modeling performed to anchor system dynamics*

*Over 150 computer simulation runs

Effect of Valve Sequence

An example of a computer run is shown investigating the effect of valve sequencing during startup for the integrated propulsion system. All computer simulation runs made are documented in the OEPSS Databook Volume VIII.

EFFECT OF VALVE SEQUENCE ON THRUST CHAMBER MIXTURE RATIO



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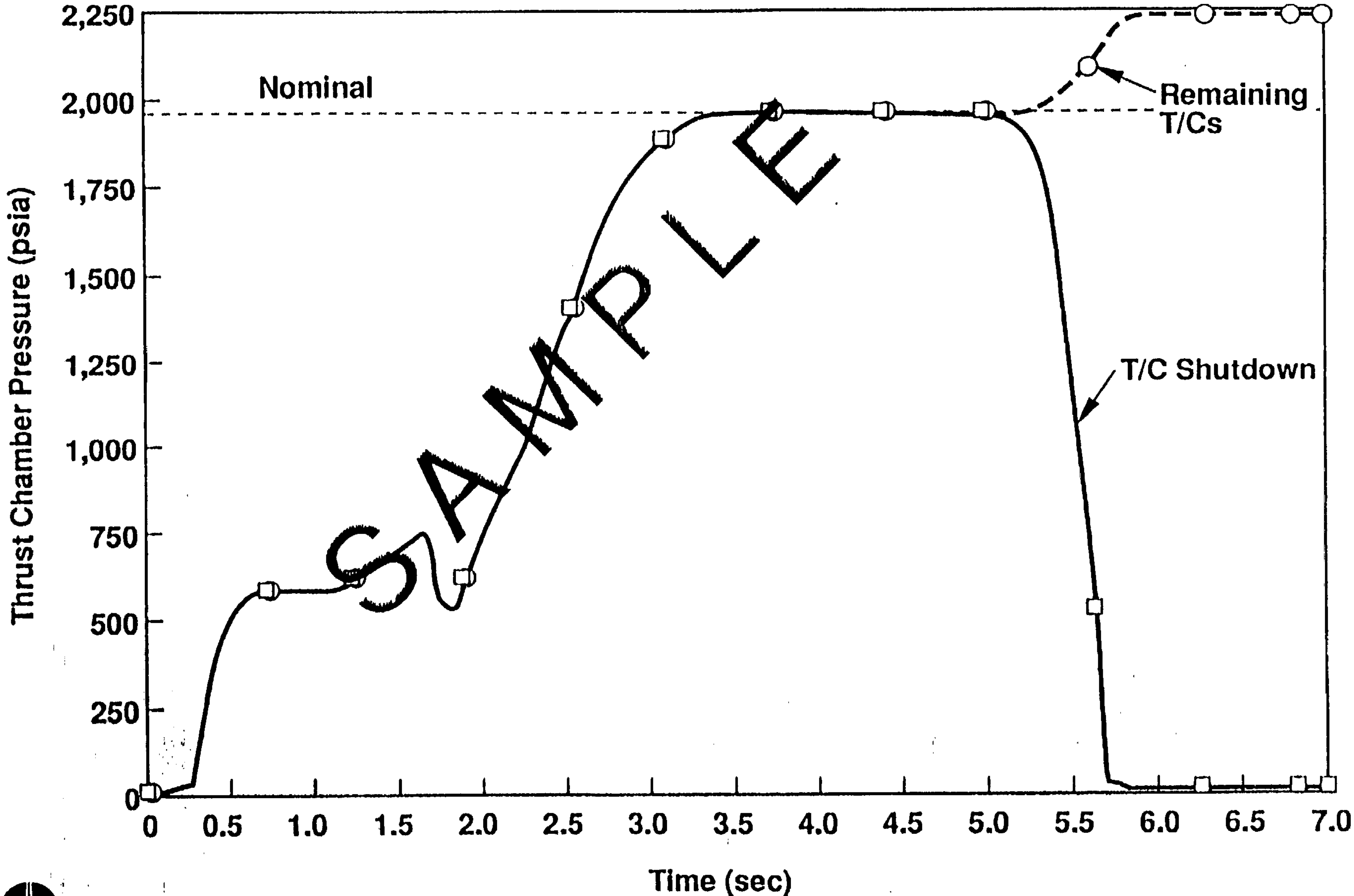
Effect of Thrust Chamber Out

An example of a computer run is shown investigating the effect of a thrust chamber shutdown on the integrated system. All computer simulation runs are documented in the OEPSS Databook Volume VIII.

EFFECT OF THRUST CHAMBER-OUT ON THRUST CHAMBER PRESSURE



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High Reliability and Operational Efficiency

The integrated propulsion architecture did indeed successfully address many operations concerns by reducing the number of major components and subsystems otherwise required and by simplifying the total system to eliminate operational requirements and achieve operational efficiency. No less significant are two important factors achieved by the integrated system that cannot be met by a conventional ALS propulsion module by virtue of fewer parts: (1) the integrated system achieved an inherently higher reliability, and (2) the integrated-parallel system has a higher component fault-tolerant capability (equivalent to two engine-out) to achieve a significantly higher reliability for mission success.

BPM Meets High Reliability and Operational Efficiency

Key Factors	Conventional	Integrated
• Higher reliability	0.988*	0.993*
T/C and T/P out	0**	0.999**
• Higher operational efficiency (LOI)	0.310	0.833
• Fewer components	169	111

* Basic system reliability
** With T/C and T/P shutdown

Operations-Driven BPM Results

The integrated propulsion architecture has addressed over 60% of current operations concerns surfaced by the OEPSS study. Since no component technology is required, the parallel, ring manifold system can be considered at a technology Level IV (or TRL 6) for technology demonstration.

The computer simulation of the integrated system transient and steady state operations, under a variety of off-nominal conditions, were found to be satisfactory.

A propulsion development program for the integrated system, utilizing the basic engine-element (two thrust chambers and a turbopump set), potentially can be shorter schedule and lower cost than that for a conventional system. For the integrated system, fewer hardware (number of engine-elements or engines), fewer system tests (prototype; full scale development, FSD; and flight) and fewer reliability demonstration tests (equivalent mission tests) are required to meet all development program goals. A preliminary development program, meeting the same goals required for the development of the ALS/STME propulsion system, for the Integrated Propulsion Module (IPM) or BPM is described in the OEPSS Databook Volume IX.

Operations-Driven BPM Results

- Addresses 14 operations concerns
- Uses existing hardware technology
- New system architecture technology exercised
- All start and operating dynamics successfully modeled
- Simpler, faster and cheaper development program
- Concept foundation applies to common use transportation systems
  - Booster
  - Upper stage
  - Space based
- Concept credibility established at this Technology Readiness Level

To advance Technology Readiness Level will require hardware experimentation

Preliminary Development Plan Groundrules

A preliminary development plan for the integrated propulsion module (IPM) was generated during the OEPSS study. The development plan used the same ground rules prescribed in the development plan for the STME engines. This included: a phased-approach; prototype system tests; full-scale development test (FSD), including PFC and FFC; acceptance tests; and propulsion modules for the first two flights. Reliability tests to demonstrate 99% reliability at ILC and IOC are also required. The IPM preliminary development plan defines the development schedule, describes component, subsystem, system and reliability test requirements and identifies the hardware needed to support these tests. A direct comparison is made of these same requirements for the STME. A more detailed description of the IPM preliminary development plan is found in OEPSS Databook Vol. IX.

PRELIMINARY DEVELOPMENT PLAN GROUNDRULES
Integrated Propulsion Module

- **Use STME/DDT&E, two sub-phases approach: prototype/FSD**
- **ALS/ADP supports "integrated" approach**
- **Includes integrated P/M for both baseline booster and core vehicles**
- **Reliability demonstration**
  - 99% at 50% confidence at ILC
  - 99% at 90% confidence at IOC
- **Acceptance testing of single engine-element only**
- **Propulsion modules for first 2 flights included**
- **Contractor facilities used for component laboratory testing**
- **Contractor services provided for hot-fire testing (includes test article installation, testing, removal, GSE/STME, maintenance)**
- **Government supplies hot-fire test facilities:**
  - Capable of testing "integrated" sub-systems, single engine-elements and multi engine-elements

Advantages of an Integrated Propulsion Module

By examining the development plan for the integrated system and comparing that to the development plan for a conventional engine, significant advantages were found that could reduce development cost and time. For the IPM, hot-fire testing is done primarily with multi-elements already in the form of a complete propulsion system such that a main propulsion test article (MPTA) program would not be needed. Thus, the test objectives are achieved with significantly fewer hot-fire tests. A similar advantage accrues for the IPM in the number of hot-fire tests required to demonstrate reliability. The results indicate that the development of the IPM could be achieved with nearly 66% fewer system tests and nearly 83% less reliability tests, and the hardware required to support these tests reduced by nearly 36%.

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**

Development Tests and Hardware Required

This chart provides a comparison of system development tests and hardware support for a conventional and an integrated propulsion system. The simplicity of the integrated system (which eliminates the traditional engine/vehicle interface), the reduction in the number of components, and the engine-element approach, not only contributed to the operability of the IPM, but is seen to achieve potential cost savings in the development program.

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

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Space Operations

Recognizing that operations in-space are even more difficult than ground based operations the OEPSS study examined the issues encompassing in-space operations. In-space propulsion systems are defined as including second stage, space transfer, lander and ascent propulsion systems.

Space Operations

Space Operations Goals

The launch and in-space operations goals are similar and synergistic with launch operations goals, i.e., simplified systems and minimized operations. In-space operations and resources will be extremely limited in space therefore space operations goals focus on "eliminating" and "automating" activities and operations. The space operations goals are compatible with the goals resulting from the Space Transportation Vehicle (STV) systems/engine workshop conducted at MSFC.

Space Operations Goals

- Eliminate hands-on, manpower intensive operations in space
    - Eliminate extra vehicular activities (EVA) operations
    - No in-space assembly
    - Eliminate in-space replacement
    - Minimum number of fluids in space
    - No fluid transfer
    - Eliminate inspections
- Dormant standby, monitoring and verification
- Immediate system operational response

Coordinated with STV system/engine workshop, MSFC

Space Propulsion Modular Configuration Assessment

The initial in-space propulsion system assessment focused on a Lunar Excursion Vehicle (LEV) propulsion system. The LEV mission was to perform a Lunar landing and requirements included 20:1 throttling and single and double fault tolerance. Seven integrated modular and independent engine configurations were evaluated. The major difference between integrated modular systems and conventional systems is that conventional autonomous engine systems require complete sets of dedicated turbopumps and subsystems for each thrust chamber and , therefore, has no flexibility for reducing hardware and absorbing a major component failure without losing the entire engine. This top level assessment showed the integrated modular propulsion system approach incorporated the most fault tolerance capability.

Space Propulsion Modular Configuration Assessment

- Seven modular & independent engine configurations reviewed
- Throttling capability evaluated
- Component fault tolerance assessed
  - Single fault tolerance
  - Double fault tolerance

Integrated modular propulsion most flexible

Space Based Propulsion Module

The assumptions and groundrules for the LEV vehicle were 80,000 lbs thrust with throttling capability down to 4,000 lbs thrust (20:1 throttling). The minimum mission required thrust to complete the mission was 40,000 lbs thrust. Thrust below 40,000 lbs thrust due to failures would be defined as losing the mission.

SPACE BASED PROPULSION MODULE

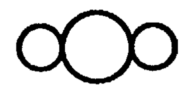
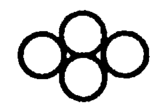
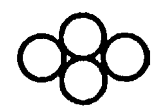
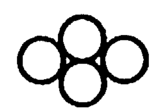
Lunar Excursion Vehicle (LEV)

- **Groundrules**
  - Vehicle thrust — 80 Klbs
  - Minimum thrust — 40 Klbs
  - Mission lost — < 40 Klbs
  - Throttling (20:1) — 4 Klbs
- **Nomenclature**
  - Turbopump — T/P
  - Thrust Chamber — T/C
  - Total system flow — Q_T
  - Individual T/P flow — Q
  - Outboard T/C — O.B.

Space Propulsion Systems

Seven integrated modular and independent engine configurations were postulated and evaluated. These systems included 5 modular and 2 independent engine configurations. The integrated systems had 2, 3 and 4 thrust chambers and 2, 3 and 4 turbopump sets as shown in the Space Propulsion System Matrix. The two thrust chamber configuration was concentrically arranged to keep thrust aligned for a thrust chamber out failure. The three thrust chamber configuration had two variations, a three equal thrust chamber (26,500 lbs thrust each) configuration and a centerline 40,000 lbs thrust chamber with two 20,000 lb thrust chamber on either side configuration. The independent engine configurations were a single 80,000 lbs thrust engine system and four 20,000 lbs thrust engine systems. It was assumed that the loss of an outboard thrust chamber necessitated shutting down the opposing thrust chamber in order to keep vehicle thrust aligned through the vehicle centerline.

SPACE PROPULSION SYSTEMS
Lunar Excursion Vehicle (LEV)

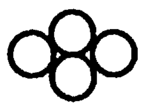
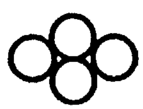
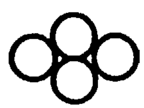
Concept	Configuration T/P - T/C	No. T/C x T/C Thrust (Klbs)	T/C Pattern	T/P Q
1*	1-1	1 x 80		Q_T
2	2-2	2 x 40		$Q_{T/2}$
3	2-3	3 x 26.7		$Q_{T/2}$
4	3-3	2 x 20 +40		$Q_{T/3}$
5	2-4	4 x 20		$Q_{T/2}$
6	4-4	4 x 20		$Q_{T/4}$
7*	4-4	4 x 20		$Q_{T/4}$

* Independent Engine(s)

Integrated Propulsion System Throttling Capability

Throttling capability was assessed with the objective of minimizing the propulsion system operating range. The single engine configuration would have to operate over the entire 20:1 throttling range from 100 percent to 5 percent thrust. The multiple thrust chamber and engine configurations could take advantage of planned thrust chamber or engine system shutdown and reduce the operating range required of the remaining systems. This approach permitted these systems to operate over a smaller throttling range.

INTEGRATED PROPULSION SYSTEM THROTTLING CAPABILITY

Concept	Configuration T/P - T/C	T/C Pattern	Throttling to 4 Klbs: Shutdown T/C	Remaining T/C		Idle T/P	T/C	
				P_c	Q		P_c	Q
1*	1-1		- -	- -	- -	- -	5%	5%
2	2-2		1	10%	5%	1	10%	10%
3	2-3		2(O.B.)	15%	5%	1	10%	10%
4	3-3		2(O.B.)	10%	5%	1 2	10% 10%	7.5% 15%
5	2-4		2 (opposing)	10%	5%	1	10%	10%
6	4-4		2 (opposing)	10%	5%	2 3	10% 10%	10% 20%
7*	4-4		2 (opposing)	10%	5%	2 (opposing engines)	10%	10%

* Independent Engine(s)

engine s)

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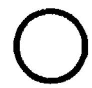
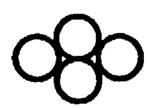
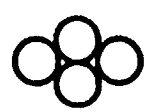
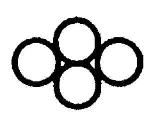
Integrated Propulsion System Single Failure Tolerance

The single failure tolerance assessment showed the single engine and one variation of the three thrust chamber configuration were incapable of accommodating a single major component failure. The three equal thrust chamber system would have insufficient thrust if one outboard thrust chamber shut down. This was due to the need to shutdown the opposing thrust chamber in order to keep thrust aligned through the vehicle centering. All the other configurations could accommodate a single failure without dropping below the minimum 40,000 lbs thrust requirement.

INTEGRATED SPACE PROPULSION SYSTEM
SINGLE FAILURE TOLERANCE

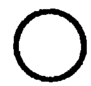
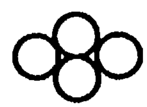
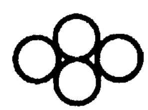
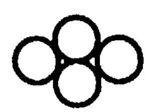
Concept	Configuration T/P - T/C	T/C Pattern	Single Failure: 1 T/C Lost		Single Failure: 1 T/P (LH_2 or LOX) Lost	
1*	1-1		Mission lost	- -	Mission lost	- -
2	2-2		Operational	Remaining T/C F=40K Q=50%	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
3	2-3		• Center T/C fails-operational • O.B. T/C fails-mission lost	• Remaining 2 T/C F=53.4K • Shut opposing T/C, F=26.7K	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
4	3-3		• Center T/C fails-operational • O.B. T/C fails-operational	• Remaining 2 T/C F=40K • Shut opposing T/C, F=40K	Operational	$53.6 \leq F \leq 80K$ $100 \leq Q \leq 150\%$
5	2-4		Operational	Shut opposing T/C, F=40K	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
6	4-4		Operational	Shut opposing T/C, F=40K	Operational	$60 \leq F \leq 80K$ $100 \leq Q \leq 133\%$
7*	4-4		Operational	Shut opposing T/C, F=40K	Operational	Shut opposing engine F=40K

* Independent Engine(s)

Integrated Propulsion System Double Failure Tolerance

The double failure tolerance assessment showed no system configuration of accommodating a two thrust chamber failure condition. However, other double failure scenarios, i.e., one thrust chamber and one turbopump failure, could be sustained by some integrated configurations. The four independent engine systems could not accommodate double failures.

INTEGRATED SPACE PROPULSION SYSTEM
DOUBLE FAILURE TOLERANCE

Concept	Configuration T/P - T/C	T/C Pattern	Double Failure			
			2 T/C's Lost		1 T/C and 1 T/P Lost	
1*	1-1		- -	- -	Mission lost	- -
2	2-2		Mission lost	- -	Operational	F = 40K
3	2-3		• 2 O.B. T/C fail-mission lost • Center & O.B. T/C fail-mission lost	• F = 26.7K • - -	• Center T/C fails-operational • O.B. T/C fails-mission lost	• F =40K • Shut opposing T/C F = 26.7K
4	3-3		• Mission lost	- -	Operational	F =40K Q = 75%
5	2-4		• Mission lost	- -	Operational	Shut opposing T/C F =40K Q = 100%
6	4-4		• Mission lost	- -	Operational	Shut opposing T/C F =40K Q = 67%
7*	4-4		• Mission lost	- -	• Mission lost	• Shut opposing engines F =40K • Shut both engines F =40K • - -

* Independent Engine(s)

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Operations and Operability Impacts on Upper Stage Propulsion

Operations-Driven IME Architecture

IME-Air Force Conceptual Architecture Study

The IME Study was a six-month program to study and conceptually design an operational integrated modular engine (IME). The study defined an IME propulsion system for a National Launch System (NLS) Upper Stage (NLSUS) vehicle. This IME design was used to quantify payoffs and advantages, and to identify key technical areas for further development. The IME program offered the opportunity to build upon the integrated BMP architecture and apply the principles of Continuous Process Improvement to a second generation system. Rocketdyne's approach to include operability in the design process demonstrated that an operations driven design architecture enhances the design. The resulting modular design was found to be adaptable to a wide range of applications and was a highly operable system.

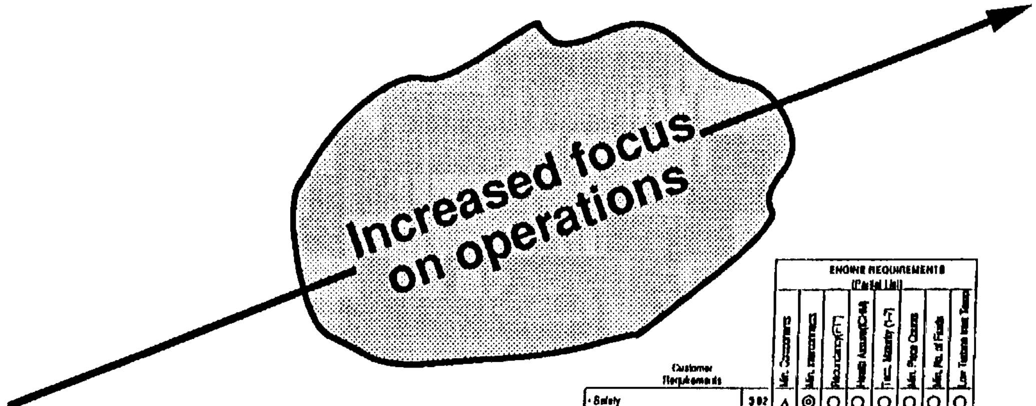
IME-Air Force Conceptual Architecture Study

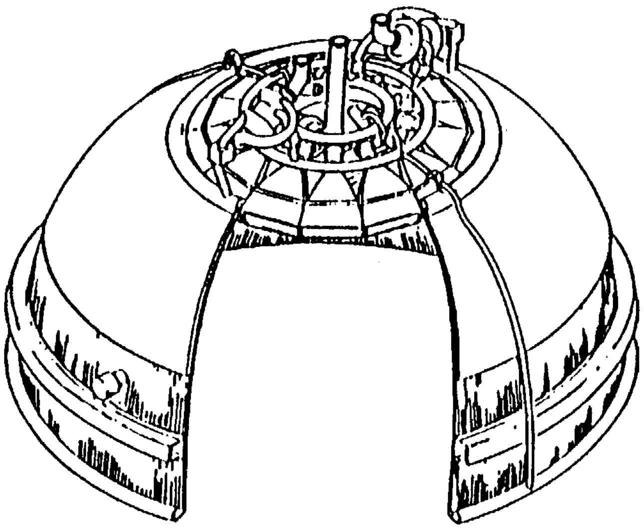
- Define an optimum upper stage engine configuration
- An example of operations-driven architecture
  - Propulsion system paradigm enlarged
  - IME design simplifies propulsion and stage systems
- IME defines a family of systems
  - Number of thrust chambers, turbopumps, etc. are design specific
  - Adaptable to multiple applications
    - Upper stage propulsion
    - In space propulsion

IME Design Evolved through QFD Process

The Quality Function Deployment (QFD) Methodology was used to refine propulsion requirements, evolve design strategies and develop an exceptionally capable propulsion system. The result of customer and Rocketdyne interactions was an enlarged set of requirements, compatible with contract document requirements but more definitive, which emphasized reliability, safety, operability and cost. Applying QFD methodology with its expanded requirements revealed the originally proposed IME concept, a horizontal flow nozzle approach, was not an optimum design. The increased focus on operations drove the design towards a simpler, more operationally efficient design architecture which had lower technical risk. This "enhanced" design, the modular bell design, is adaptable to a wide range of applications via adding or subtracting thrust chamber and turbopump modules.

IME Design Evolved through QFD Process





HORIZONTAL FLOW NOZZLE

Proposed Concept

Customer Requirements		Min. Connections	Min. Interconnects	Redundancy(FT)	Health Assess(CHM)	Tech. Maturity (1-7)	Min. Piece Counts	Min. No. of Fluids	Low Turbine Inlet Temp.
• Safety	3.92	Δ	◎	○	○	○	○	○	○
• Reliability	4.69	◎	◎	◎	◎	◎	◎	○	◎
• High Confidence in Eng. Ignition	4.08			◎	○	◎		○	
• Perf. Values corr. w/Test/Analysis	3.40								
• Cell/Module Out Cap. Assessed	[illegible].85			○	○	○			
• Identify Mixed /Mfl. Tech. Reqmts	3.00					○			
• High Confidence of IVO Cap.	3.62				○	◎			
• High Confidence in Operability	4.08	Δ	○	◎	◎	○	○	○	Δ
		189	165	249	077	038	110	88	110

ENGINE REQUIREMENTS (Partial List)

RELATIONSHIPS

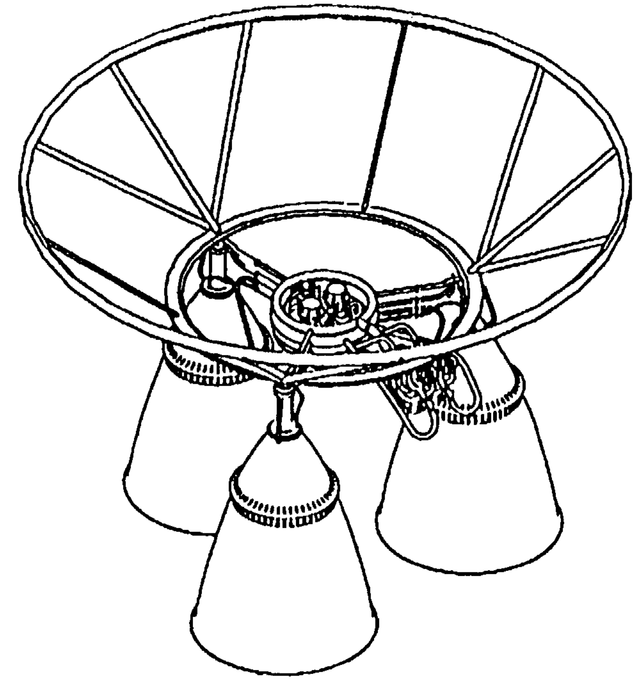
Δ = 1
○ = 3
◎ = 9

IMPORTANCE RATINGS (Example Only)

Engine Concepts	Ratings								Final Engine Score Totals
#1	1	9	1	3	1	3	1	1	2309
#2	9	1	9	9	3	1	3	3	4139
Reference	3	3	3	3	3	3	3	3	2322

IME concepts evaluated using QFD methodology

IME Propulsion System



Enhanced IME

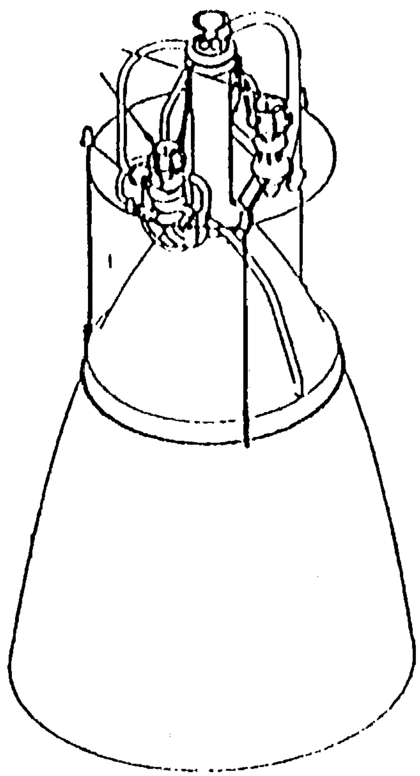
Maximized benefits by driving architecture with operations support as the focus

Expanded Propulsion System Definition Enhanced Operability Opportunities

A key to enhancing the IME design was the recognition that significant improvements to propulsion system reliability, operability, cost and performance could be achieved by driving the design to provide features that would benefit the overall propulsion system and stage. In other words, the propulsion system definition was enlarged to include Thrust Vector Control (TVC), the Reaction Control System (RCS), and the propellant feed system as shown in the figure. This novel approach was implemented by designing the propulsion to eliminate vehicle subsystems which are normally required for engine support and by using the engine to accomplish, more effectively, functions traditionally provided by other susbystems.

Expanded Propulsion System Definition Enhances Operability Opportunities

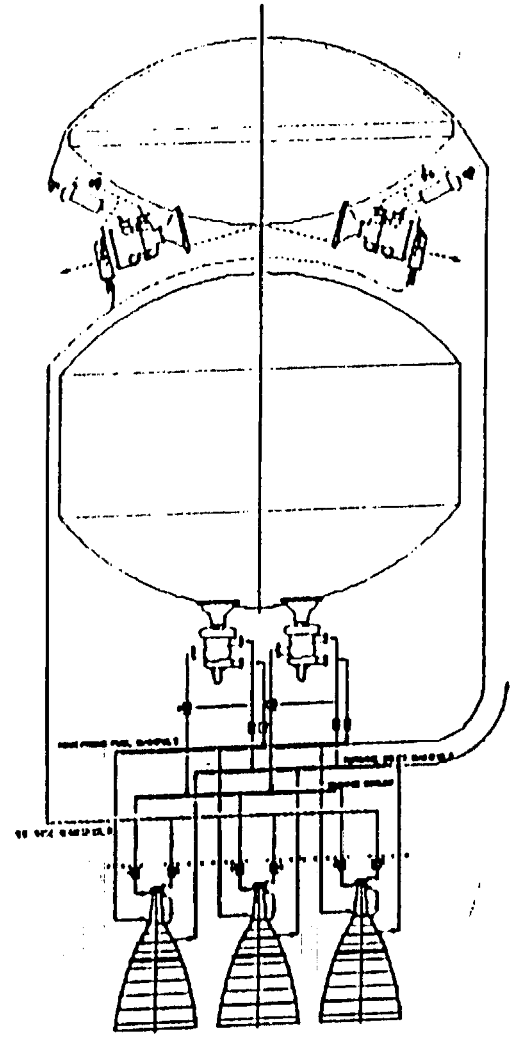
Usual Perception By Most



Current propulsion system definition

IME study propulsion system definition

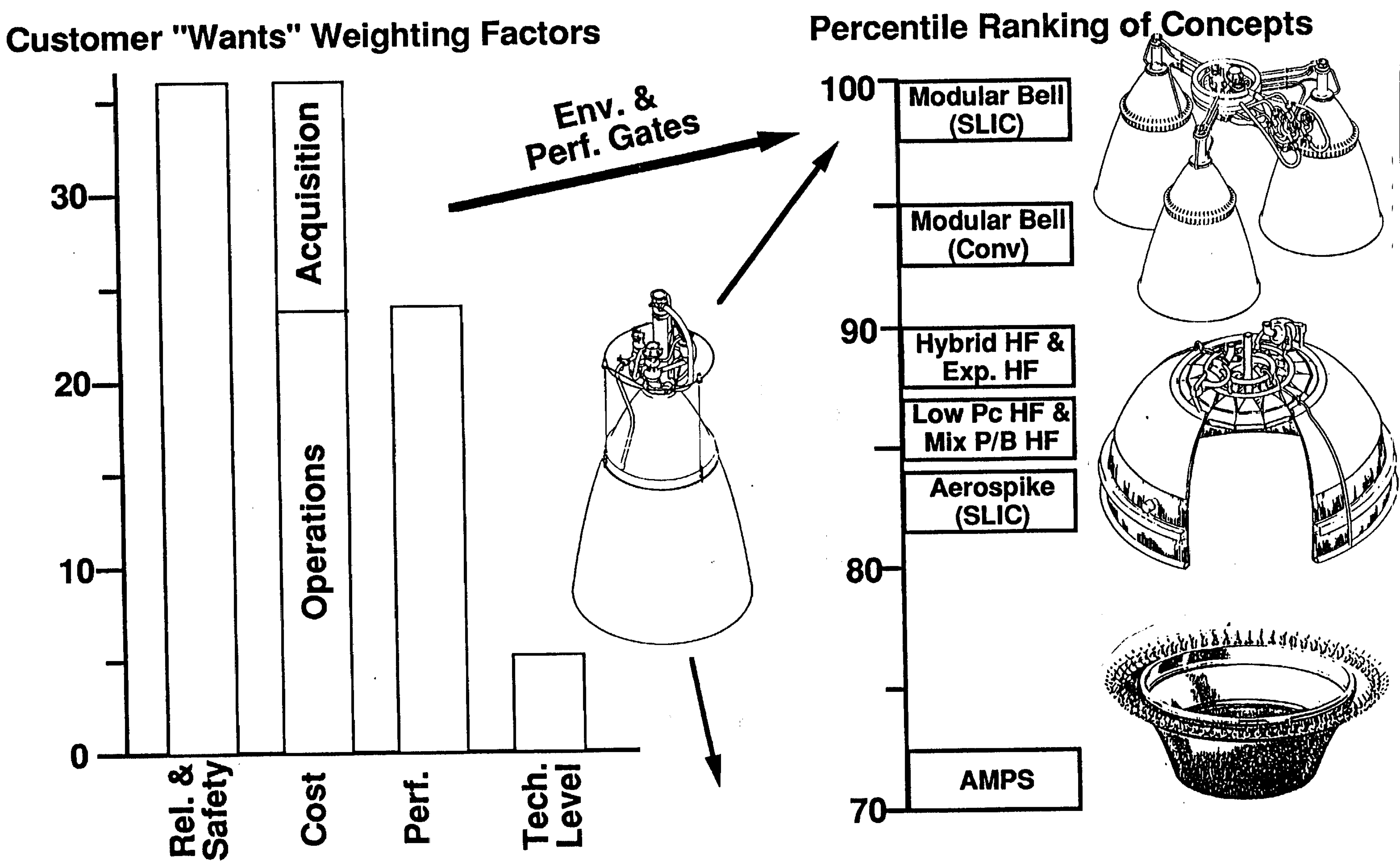
IME Interpretation



Requirements Drive the Architecture Solution

The QFD methodology includes weighting factors on requirements (wants). It was interesting to note that reliability and cost were of equal ranking while performance had a lower weighting factor. The lowest weighting factor was technology level, however, those technologies requiring a lot of development would be excluded for other reasons, such as cost or reliability considerations. These weighted factors, when assessed against different propulsion system design architectures show the relative ranking of each system. This process revealed the originally proposed design , the horizontal flow propulsion system concept, was less able to satisfy customer requirements. The modular bell design was shown to have the highest percentile ranking. Except for the limited length requirement, the IME single bell concept met all the vehicle requirements.

Requirements Drive the Architecture Solution



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Study Tree 4
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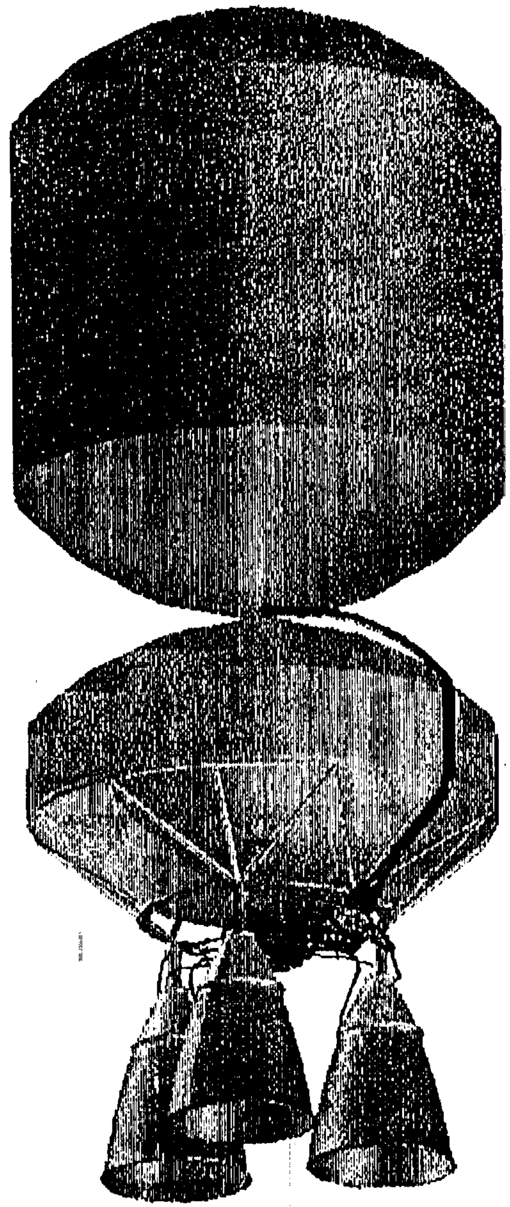
Operations and Operability Enhanced IME Architecture

The resulting IME system as shown met all Air Force Design requirements. The propulsion system attributes of high performance, operability and reliability were achieved without compromising the system.

Operations and Operability Enhanced IME Architecture



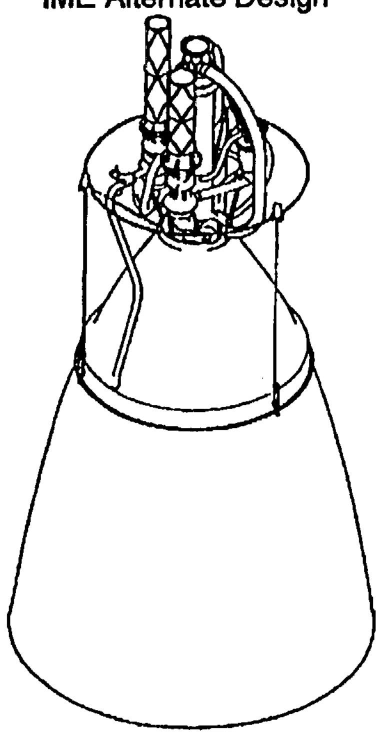
• Thrust	30,000 lbs.
• Specific Impulse	480 sec.
• Reliability	0.9953
• LOI	0.80
• Engine Length	88 in.
• Engine Diameter	136 in.

IME Propulsion Concept Family

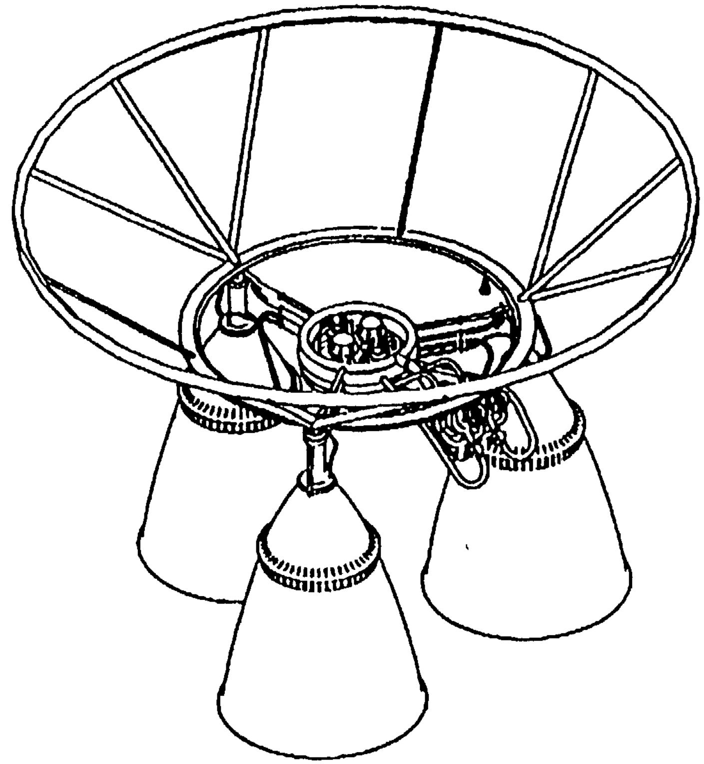
The IME modular propulsion system concept is a flexible architecture in that the design can be adapted to meet emphasis on different requirements. System level flexibility is shown with the alternate propulsion system configurations, i.e., multiple thrust chambers or a single thrust chamber. Stand alone integrated systems or a completely integrated stage with the turbopumps mounted directly to the propellant tanks. What emerged was a unique family of modular propulsion systems which can be tailored to specific design applications by changing the number of thrust chambers turbopumps, ets.

IME Propulsion Concept Family

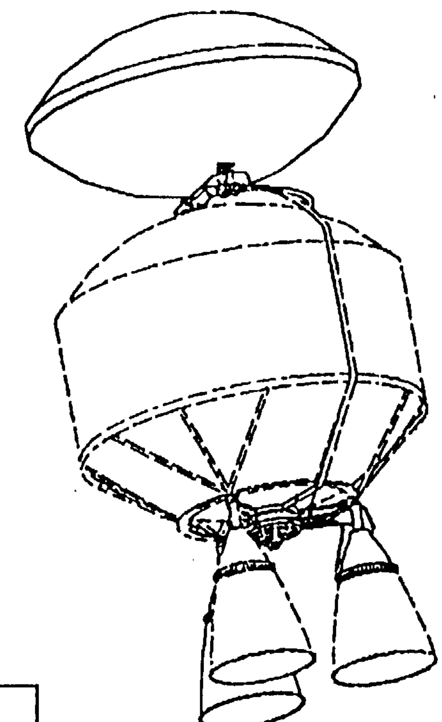
Single Thrust Chamber
IME Alternate Design



IME Multiple Thrust Chamber Propulsion System



LOX Tank Forward
No. 2 Alternate IME Design*
(Both propellant enhanced childown)



Non-constraining requirements allowed creative system approaches and flexibility

IME Operations-Driven Features

The IME is a two fluid (LOX and LH2) system using three thrust chambers and two turbopump sets. The number of bell thrust chambers is requirements driven. One turbopump set is operational with the second set in a standby mode. Thrust vector control is by differential throttling. The engine features a hybrid cycle with an expander cycle driving the hydrogen turbopump and a LOX-rich preburner driving the oxygen turbopump. Interpropellant seals and purges between the pump and turbines are not required. The oxidizer pumps are tank mounted. Tank mounting the turbopump allows automatic pump preconditioning when LOX is loaded. An alternate configuration would also allow tank mounting the hydrogen pump and automatic fuel pump preconditioning. The propulsion system eliminates purges, pneumatics, and hydraulics. The propulsion system also supplies gaseous hydrogen and oxygen for tank pressurization (if needed). In addition, the gaseous hydrogen and oxygen could also be used to supply small GH2 and GO2 RCS thrusters, eliminating the need for a storable propellant(s) (hydrazine or MMH and NTO) RCS.
The IME system would reduce by orders of magintude the launch site support requirements

IME Operations-Driven Features

- Two-fluid system LOX/LH_2
- All-welded design minimizing leakage
    - Unique weld joint for component replacement
- GOX/GH_2 RCS system
- Hypergolic propellants eliminated
- EMA valves
- Pneumatics eliminated
- Hydraulic APU eliminated
- Helium eliminated
- Differential throttling TVC
- Gimbal system eliminated

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IME Operations-Driven Features (Contd.)

- Propellants pressurized with GOX and GH_2 from propulsion system (only if needed)
- Interfaces, components minimized
- Preflight checkout minimized
  - No gimbal checks
  - No pump torque/deflection checks
  - Automated valve checks
- Umbilical has LO_2, LH_2, and electrical
- LOX pump attached to tank automatically preconditions pump when LOX is loaded
- Fuel pump attached to tank automatically preconditions pump when LH2 is loaded
- Heat shielding reduced, LOX turbopump module mounted forward

Orders of magnitude decrease in launch and vehicle support

Major operations cost reduction

IME Focused on OEPSS Operations Concerns

The IME design approach recognized that system improvements would result by focusing on incorporating operability enhancements which would mitigate or eliminate operations concerns. The resulting design addressed 18 of the 23 OEPSS study developed operations concerns.

IME Focused on OEPSS Operations Concerns

No.	
1	Closed aft compartments
2	Fluid system leakage • External • Internal
3	Hydraulic system
4	Ocean recovery/refurbishment
5	Multiple propellants
6	Hypergolic propellants (safety)
7	Accessibility
8	Sophisticated heat shielding
9	Excessive components/subsystems
10	Lack of hardware integration
11	Separate OMS/RCS
12	Pneumatic systems

No.	
13	Gimbal system
14	High maintenance hardware
15	Ordnance Operations
16	Retractable T-O umbilical carrier plates
17	Propellant tank pressurization system
18	Excessive interfaces
19	Conditioning/geysering (LOX tank forward)
20	Preconditioning system
21	Expensive commodity usage -- helium
22	Lack hardware commonality
23	System contamination

IME addresses 18 concerns

Operations-Driven IME Results

The design approach that is operations driven and treats the engine as an integrated part of the upper stage results in significant operability, reliability and cost benefits.

The operationally efficient propulsion system that evolved from the IME study was a modular propulsion system that best met the customer requirements because; (1) it provided the highest reliability and safety as reflected by its simpler design, fewer parts, and lowest piece count; (2) it has the highest rating in performance confidence and operability due to its mature thrust chamber design, its simple turbomachinery, and the lack of gimbal accessories and purge-gas systems; (3) it provided the highest performance on account of its straightforward bell nozzle design which provides uninterrupted, low-loss expansion of the hot gases, (4) its overall simplicity of design will result in both low development and low production cost, and (5) its modularity and component sizes are readily adaptable to other planned applications.

In short an operations driven upper stage architecture such as the IME is doable, drives design simplicity, and is affordable.

Additional information on the IME propulsion system is presented in the Operational Integrated Modular Engine Contract No. F04701-91-C-0076 Final Report, SMC TR-92-51, by T. J. Harmon and R. P. Pauckert.

Operations-Driven IME Results

- OEPSS experience base applied to an upper stage study contract
- Uses BPM concept and space operations goals as point of departure
- Addresses 18 operations concerns
- Utilizes operations driven technology
- IME defines a family of systems
  - Highly operable
  - More operationally efficient
  - Enlarged paradigm
  - Simple, more reliable, cost-effective

Operations driven upper stage architecture *is doable*, drives design simplicity, and is affordable

Operations-Driven Space Transfer Propulsion Operational Efficiency Study (STPOES) Task

The Space Transfer Propulsion Operational Efficiency Study task studied, evaluated and identified design concepts and technologies which optimized in-space vehicle propulsion system operability and minimized launch and in-space operations. NASA defined a Lunar Lander mission/vehicle as the propulsion system to apply operability methodology and conceptualize an operable in-space propulsion system. The STPOES task design effort built upon the foundations of the BPM and IME propulsion systems and continued the CPI process into a third generation system. The four design concepts that were developed were driven by operational considerations and each iteration provided a more operable concept. These operationally efficient designs revealed the necessary technologies to allow development of that concept.

Study task elements included acquiring operations databases from four current and past flight systems, initiating and defining a process to produce an in-space operations index, conceptualizing four operations driven lunar lander propulsion system designs and recommending technologies which require development in order to bring these operational designs to fruition. The final design iteration is highly operable and the supporting technologies are doable and would support a 2005 Lunar mission schedule. A final report on the results of this study effort is presented on the OEPSS Databook Volume VI, the Space Transfer Propulsion Operational Efficiency Study Task Final Report.

Operations and Operability Focus on Space Propulsion

Operations-Driven Space Transfer Propulsion Operational Efficiency Study (STPOES) Task

Propulsion System Energy Requirements

The STPOES propulsion system conceptual design requirements were defined by NASA. The mission / Vehicle was a Lunar Lander Descent Stage. The major energy requirements are shown in the table.

Propulsion System Energy Requirements

Mission:	Lunar Lander Descent Stage
Thrust:	60,000 to 80,000 lbs.
Propellants:	LOX/LH_2
Throttling:	10 to 1

STPOES Conceptual Design Requirements

The propulsion system design characteristics and requirements are shown in the figure. These requirements were derived from information from the First Lunar Outpost (FLO) workshop, held at NASA JSC on August 13-14,1993.

STPOES Conceptual Design Requirements

- **Mission/Vehicle Requirements:**
  - Application: Lunar Lander -- descent stage evolution
  - Staging: Two-stage (separate descent and ascent prop. modules)
  - Mission profile: Circularization burn, de-orbit burn, terminal descent & landing
  - Descent payload: 35 MT (includes ascent stage, plus crew, plus payload)
  - Hardware reuse: Expendable
  - Total stage vac. thrust: 266.9 to 355.9 MN (60,000 to 80,000 lbf)
  - Propellants: LOX/LH2
  - Fault tolerance: Zero fault tolerance for descent stage (single fault tolerance for ascent stage)
  - Throttling: 10:1
  - Stage Diameter: 10 meters (32.8 ft.) not including legs

- **Operational Requirements:**
  - Operability: Operations index >0.9
  - Reliability: >0.99
  - Cost: Lowest recurring and non-recurring cost

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Lunar Lander Operational Attributes

The primary design objective was to eliminate or mitigate propulsion system operability concerns and issues, both launch and in-space. Four propulsion system design architectures were developed. All four Lunar lander architectures incorporated the operational attributes listed in the table.

Lunar Lander Operational Attributes

- Open propulsion compartment
- Automated checkout
- Non-intrusive propellant gaging system
- Two-fluid system -- LOX/LH_2
- O_2/H_2 RCS
- Laser ignition (engines & ordnance)
- EMA actuators
- Differential throttling TVC (no gimbal)
- Zero NPSH pumps (no tank pressurization)
- No turbopump preconditioning (interfaced directly to propellant tanks)
- No hydraulics, pneumatics, helium, hypergolics, monopropellants, APU's, gimbal systems, flex lines

Operations-Driven STPOES Architecture

The propulsion system operations-driven architecture objective was to develop conceptual designs which minimized operability concerns and issues. The operations driven architecture explored how higher operational efficiency could be designed into a lunar lander propulsion system. The propulsion system paradigm was the same as that used on the IME project, i.e., the propulsion system included propellant tanks, propellant distribution and the rocket engines. Several design concepts were developed and evaluated. Each postulated design incorporated additional operations enhancing features. This design effort represents a first cut at an operationally efficient propulsion system meeting the requirements of a Lunar lander vehicle. Additional design studies and system optimization studies would yield further improvements.

Operations-Driven STPOES Architecture

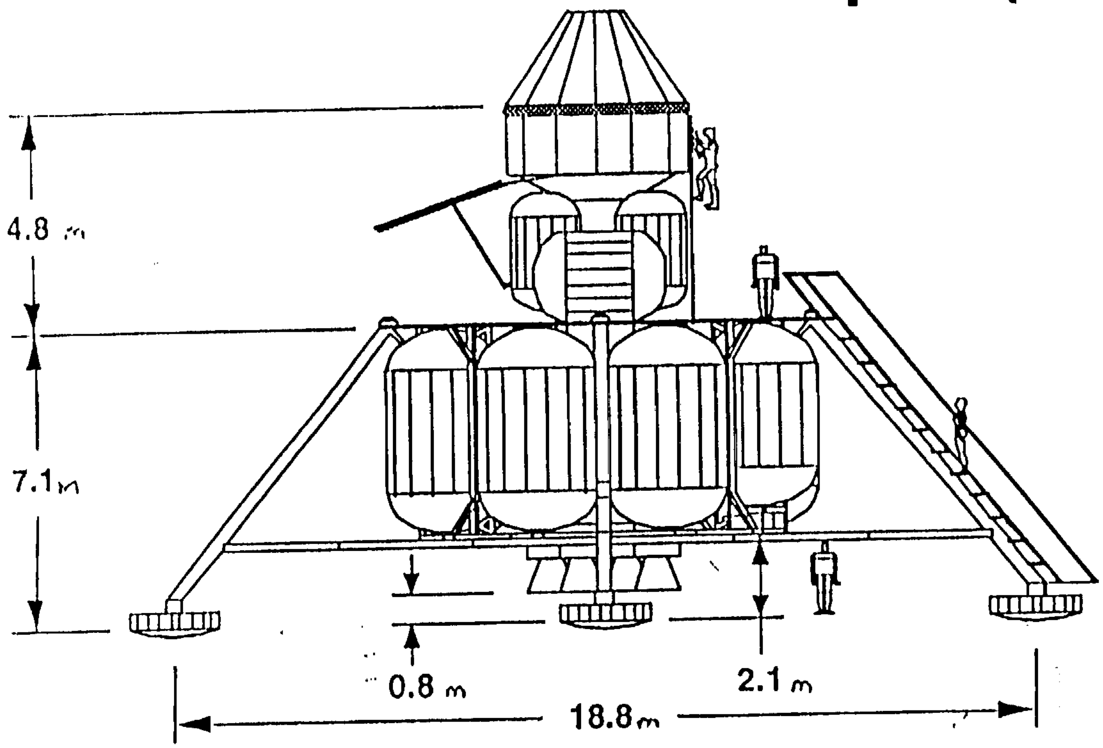
- Minimize launch and in-space operations
- Operations enhancements evolved from BPM & IME foundation
- Four design concepts developed and evaluated
- Enlarged propulsion system paradigm resulted in:
  - High propulsion system reliability
  - Robust design
  - Inherent fault tolerance
  - Highly operable and operationally efficient
  - Transportation system fully integrated

A space-based propulsion system concept was developed that is operable, responsive and available

First Lunar Outpost (FLO) Concept

NASA defined a Lunar Lander mission/vehicle. These requirements were derived from information from the First Lunar Outpost (FLO) workshop, held at NASA JSC on August 13-14,1993. The propulsion system sketch shown in the figure was used as the point of departure configuration for the STPOES task propulsion system design. This sketch is somewhat misleading however as neither the launch or mission operations support infrastructure is shown. This propulsion system is not a stand alone system.

First Lunar Outpost (FLO) Concept



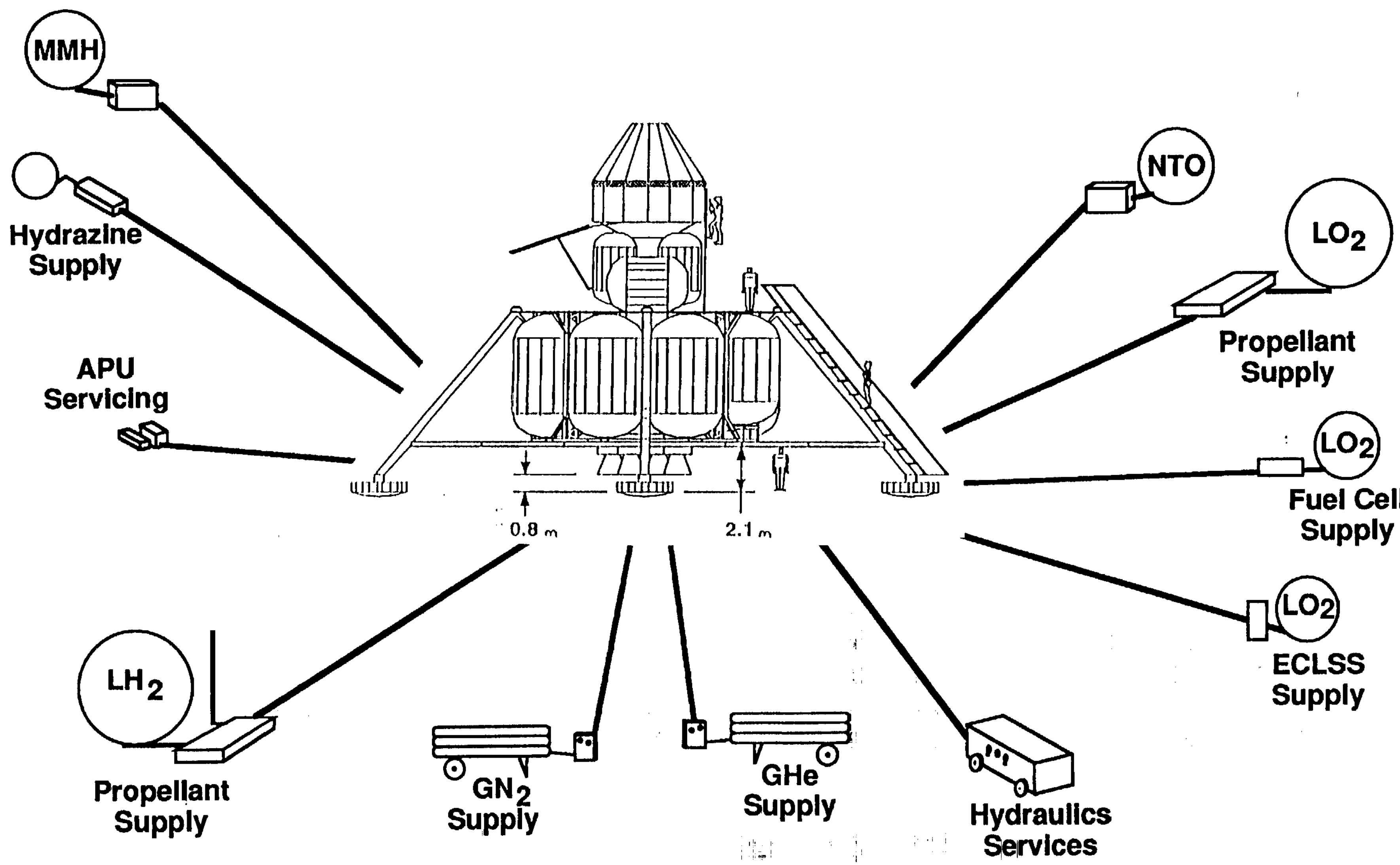
Study Point of Departure Architecture

- "FLO" study objective--Develop viable propulsion system alternatives
- STPOES task used "FLO" as propulsion system

Traditional Launch Facility

The launch facility required to support the point of departure (FLO propulsion system) Lunar lander propulsion systems is schematically depicted. The extensive ground support infrastructure shown must be serviced and maintained, and must operate reliably to support the launch successfully. There is also a massive infrastructure required in specialized equipment and trained personnel. Future propulsion system launch facility operations support systems must be greatly simplified.

Traditional Launch Facility



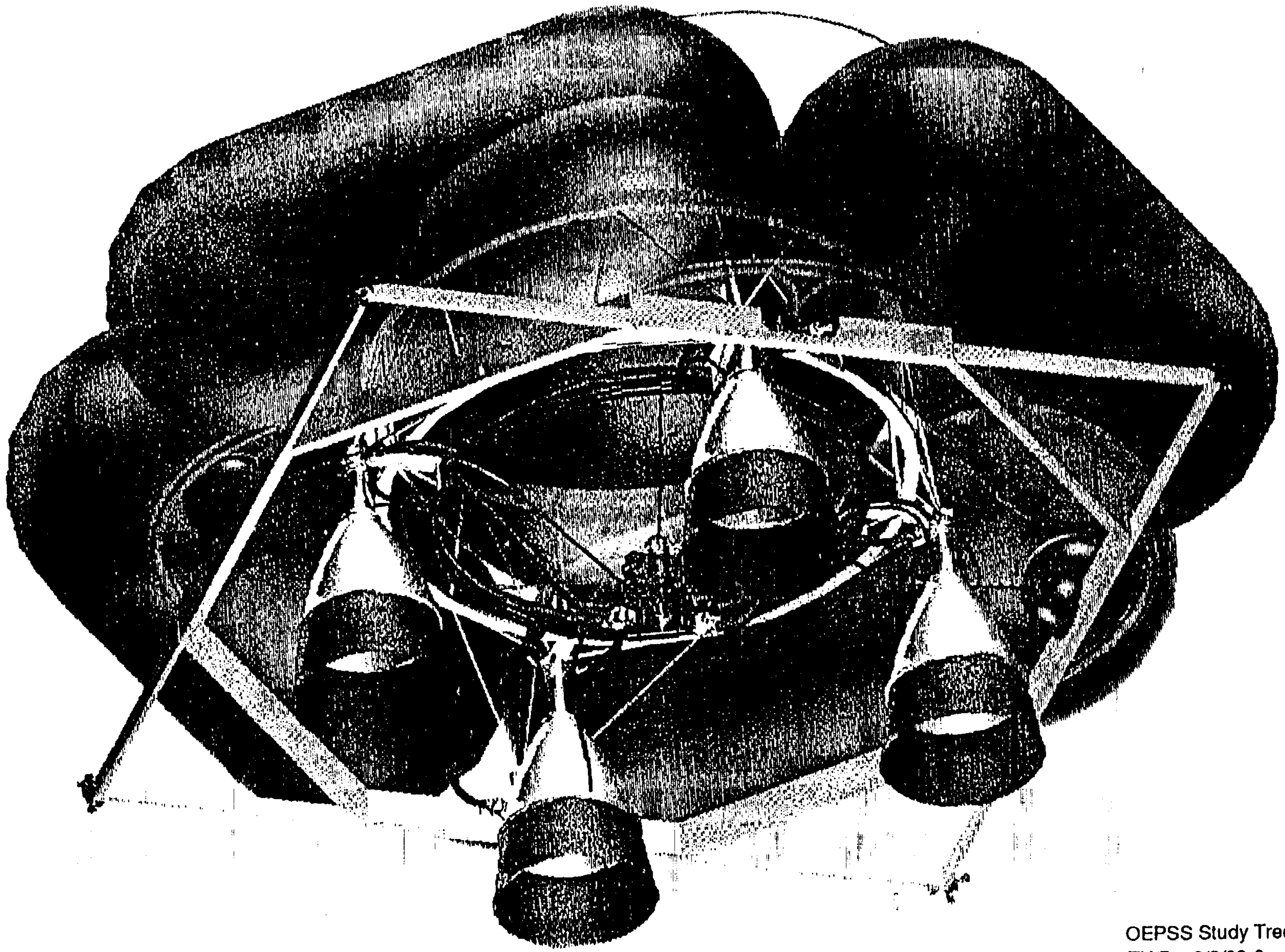
STPOES Concept A--Integrated Modular Propulsion System

Integrated (engine and conventional propellant tanks) System

Concept A consists of four thrust chambers and two sets of turbopumps integrated into a modular configuration with four hydrogen tanks and a single oxygen tank as show in th figure. The propulsion system uses a LOX/LH2 hybrid power cycle with an integral Reaction Control system (RCS) and is capable of throttling to 10 Percent of the nominal thrust. This hybrid cycle uses a hydrogen expander cycle to power the fuel turbopump and an ox-rich preburner to power the oxygen turbopump. The hybrid cycle simplifies the propulsion system eliminating the need for turbopump seals and purges. Gaseous Oxygen and Hydrogen RCS thrusters provide vehicle reaction control, replacing a separate storable monopropellant or hypergolic propellant systems. This approach eliminates the use of multiple propellants on the vehicle. In addition, the high pressure gaseous RCS propellants can be used to spin start the turbopumps (if necessary) , increasing the available power to start the turbines.

STPOES Concept A -- Integrated Modular Propulsion System

Integrated (Engine & Conventional Propellant Tank) System



STPOES Concept A--Integrated Modular Propulsion System

Integrated (engine and conventional propellant tanks) System (part 2)

The Concept A propulsion system design addresses 20 launch operations concerns within the basic design. There are, however, other major operations element which must be addressed. These are the in-space operations concerns. The In-Space Operations listed in the figure represents an initial cut at operations concerns areas resulting from the STPOES task study. It is planned for this list to be expanded as in-space operations issues are uncovered and addressed. Concept A addresses 10 in-space concerns. Major operations concerns that Concept A did not address were propellant acquisition and propellant liquid vapor handling.

Concept A is a two fluid system, i.e., only the Hydrogen and Oxygen propellants are required, which simplifies the launch facility.

Concept A -- Integrated Modular Propulsion System

Integrated (Engine & Conventional Propellant Tank) System

Launch Operations

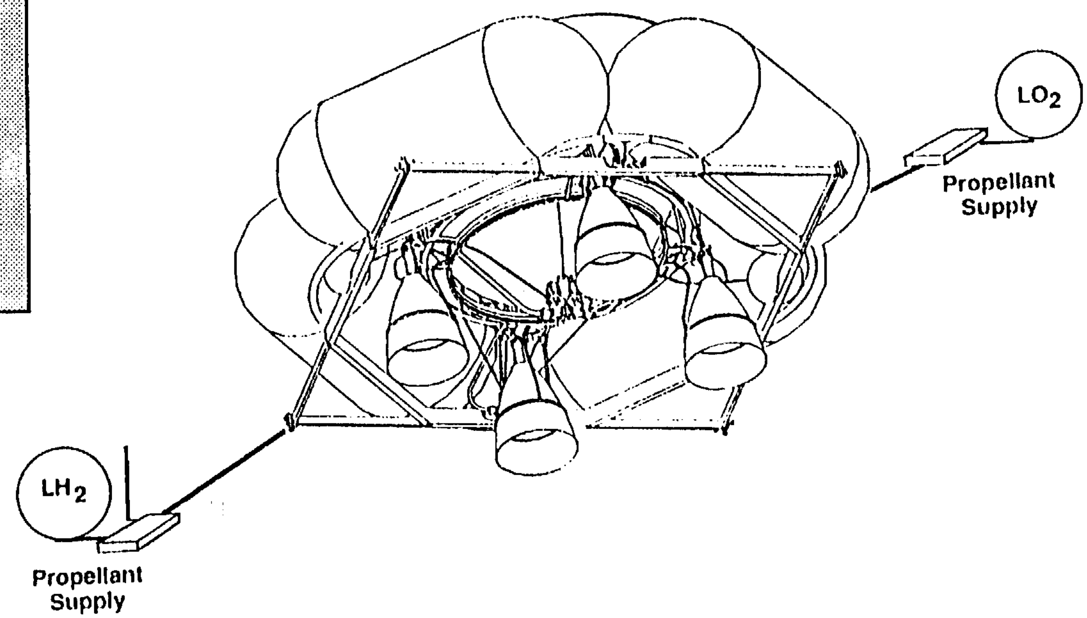
- Eliminates 20 launch concerns

In-Space Operations

- Integrated RCS
- Fluid Transfer In-Space
- Fluids In-Space
- In-Space Assembly
- In-Space Replacement
- Hardware Dependability
- Maintenance
- Fault Tolerance
- Extra Vehicular Activity
- Inspection

- Propellant Loading
- Common Propellant Tanks for RCS, etc.
- Turbopump Simplification
  (Eliminates Boost Pumps)
- Limited Commodities
- Liquid Vapor
  - Propellant Acquisition
  - Propellant Gaging
  - Zero G Venting
  - Propellant Loss

Operations addressed in positive direction



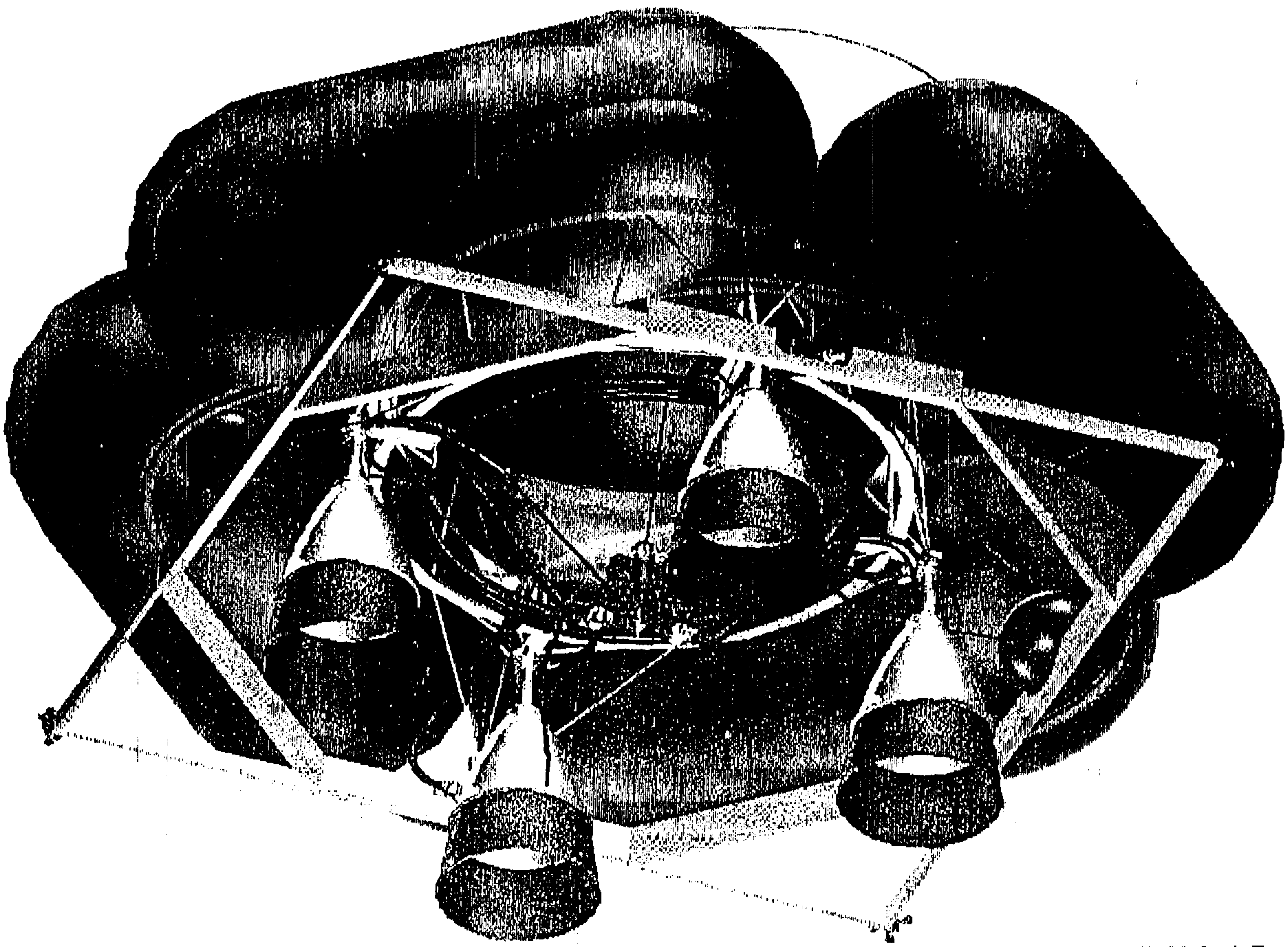
Greatly simplifies launch facility

STPOES Concept B--Integrated Modular Propulsion System
Supercritical Propellant Tanks

Concept B is a design variation of Concept a using supercritical cryogenic propellant tanks. Using supercritical propellants eliminates concerns with propellant acquisition, propellant settling, and sloshing and propellant liquid/vapor separation issues. Propellant tank pressures of 200 and 750 psia were assumed for the hydrogen and oxygen supercritical tanks. The higher pressure tanks simplify the propulsion system by eliminating boost pumps and separate RCS GH2 and GOX tanks. The use of supercritical tanks incurs a weight penalty which is mitigated to some extent by the elimination of boost bumps and separate RCS system propellant tanks.

STPOES Concept B -- Integrated Modular Propulsion System

Supercritical Propellant Tanks



STPOES Concept B--Integrated Modular Propulsion System
Supercritical Propellant Tanks (part 2)

The Concept B propulsion system design, like the Concept A design, addresses 20 launch operations concerns. Concept B, with its supercritical tanks, addresses 14 of the 15 listed in-space operations concerns. The major operations area that Concept B does not address is propellant loading, i.e., supercritical propellant tank loading for conventional propulsion system sized tanks needs additional study.

Concept B is a two fluid system, i.e., only the Hydrogen and Oxygen propellants are required, which simplifies the launch facility..

Concept B -- Integrated Modular Propulsion System
Supercritical Propellant Tanks

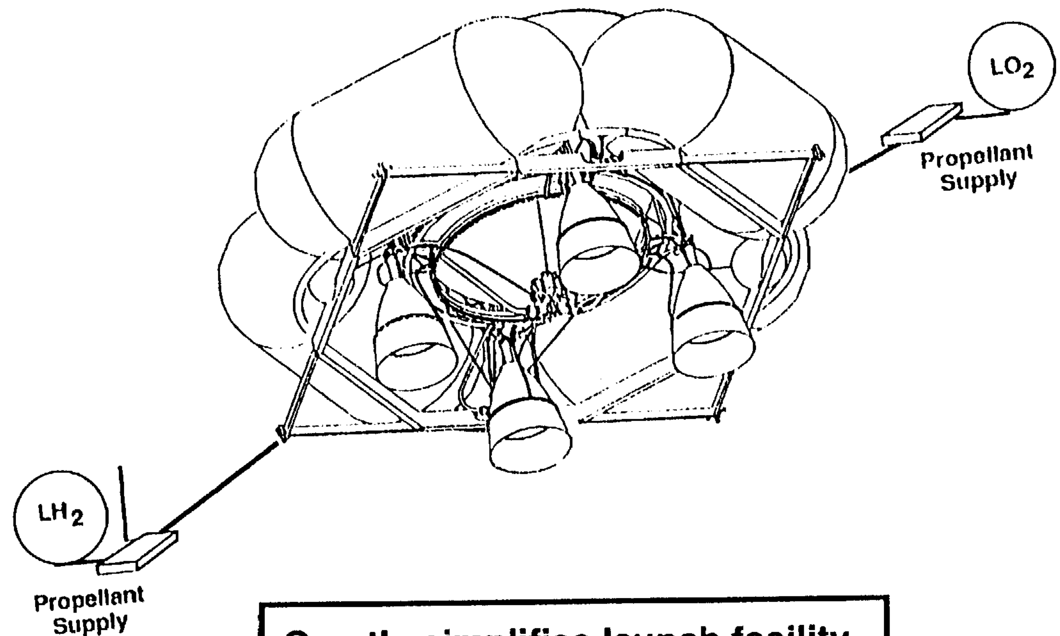
Launch Operations

- Eliminates 20 launch concerns

In-Space Operations

- Integrated RCS
- Fluid Transfer In-Space
- Fluids In-Space
- In-Space Assembly
- In-Space Replacement
- Hardware Dependability
- Maintenance
- Fault Tolerance
- Extra Vehicular Activity
- Inspection
- Common Propellant Tanks for RCS, etc.
- Turbopump Simplification
  (Eliminates Boost Pumps)
- Limited Commodities
- Liquid Vapor
    - Propellant Acquisition
    - Propellant Gaging
    - Zero G Venting
    - Propellant Loss
- Propellant Loading

Operations addressed in positive direction

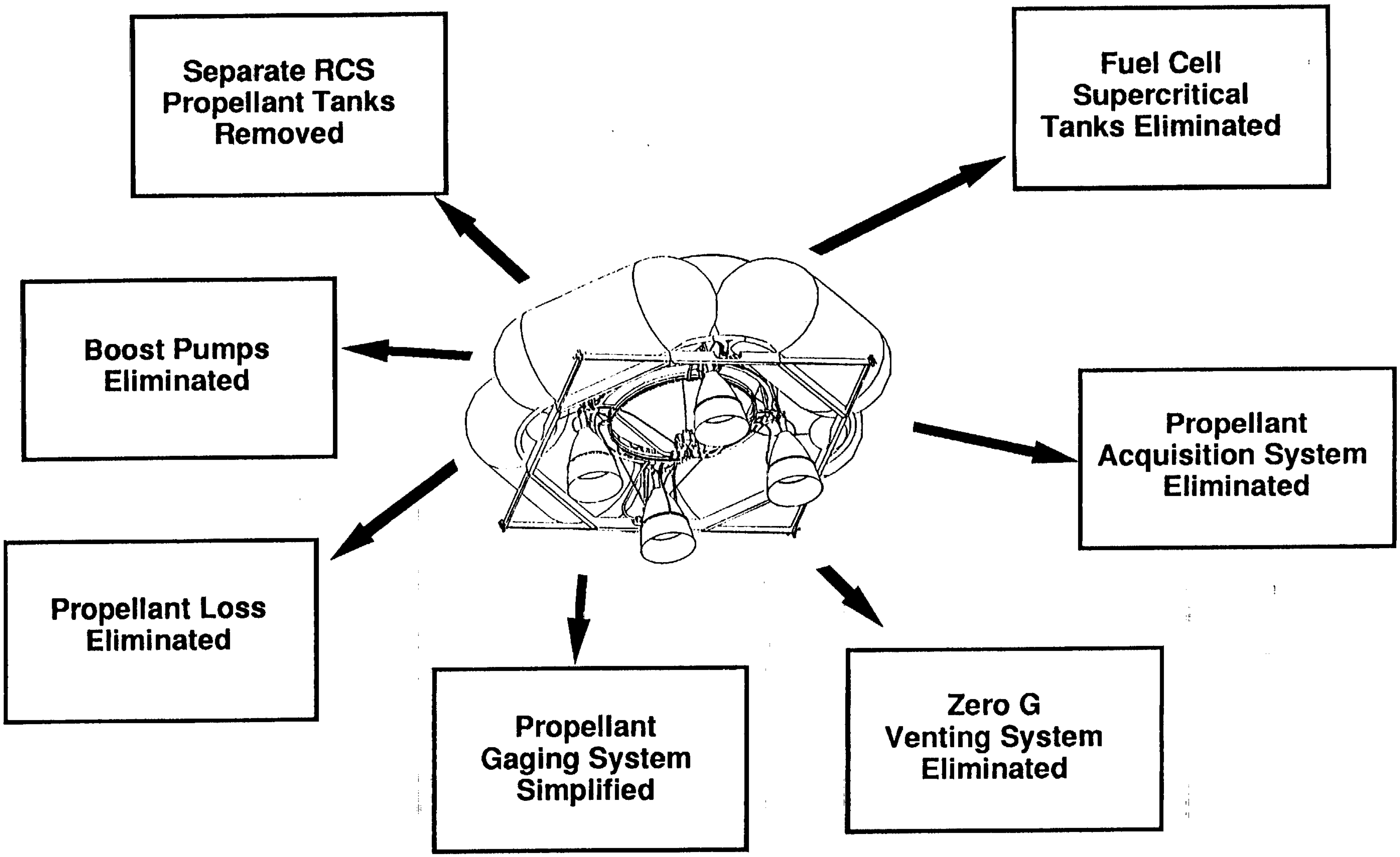


Greatly simplifies launch facility

Concept B - In-Space Systems Simplification

Concept B, with its supercritical tanks, addresses 14 of the 15 listed in-space operations concerns. The in-space operations that are addressed is shown in the figure. Eliminated are boost pumps, zero G venting system,separate propellant tanks for the RCS system and propellant acquisition systems. The supercritical main propellant tanks can be used to supply the vehicle fuel cells. The propellant gaging system would be simplified (both fewer systems and fewer measurements) and propellant loss would be minimized. These vehicle enhancements simplifies both launch and in-space operations. The major operations area that Concept B does not address is propellant loading, i.e., supercritical propellant tank loading needs additional study.

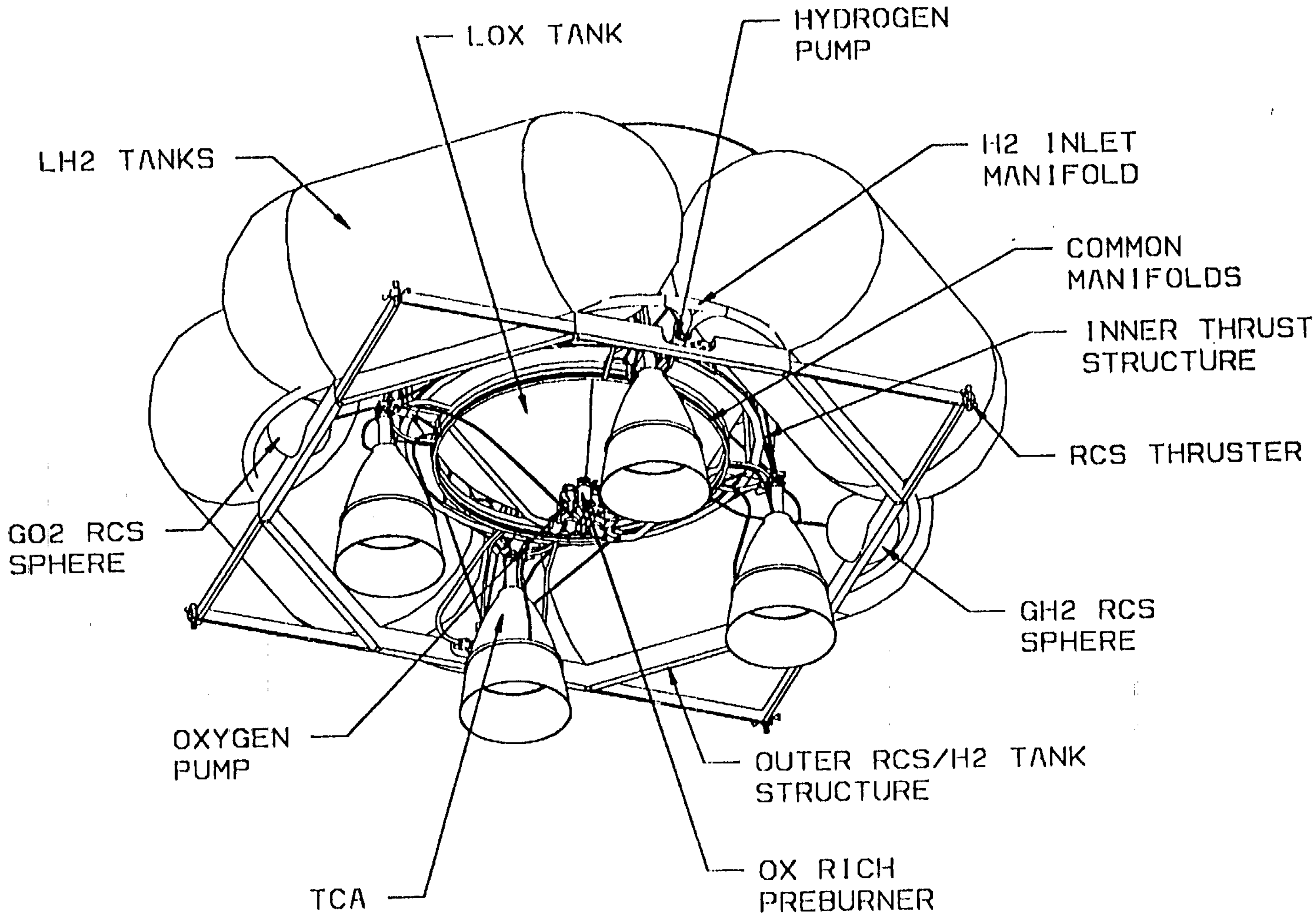
Concept B -- In-Space Systems Simplification



Lunar Lander Concepts A and B

Concepts A and B are similar in configuration and subsystem layout. The propellant tanks are similar except the supercritical tanks would be heaver due to the increased tank pressures required to maintain propellants supercritical. Delta weight increases of 1267 lbs for each hydrogen tank and 12364 lbs for the oxygen tank were calculated. Mitigating this weight increase are weight reductions from eliminating the RCS propellant tanks, fill and drain valve reduction (only one set would be needed), eliminating propellant acquisition systems and eliminating boost pumps. Task funding and schedule did not permit a total propulsion system delta weights evaluation.

Lunar Lander Concepts A & B



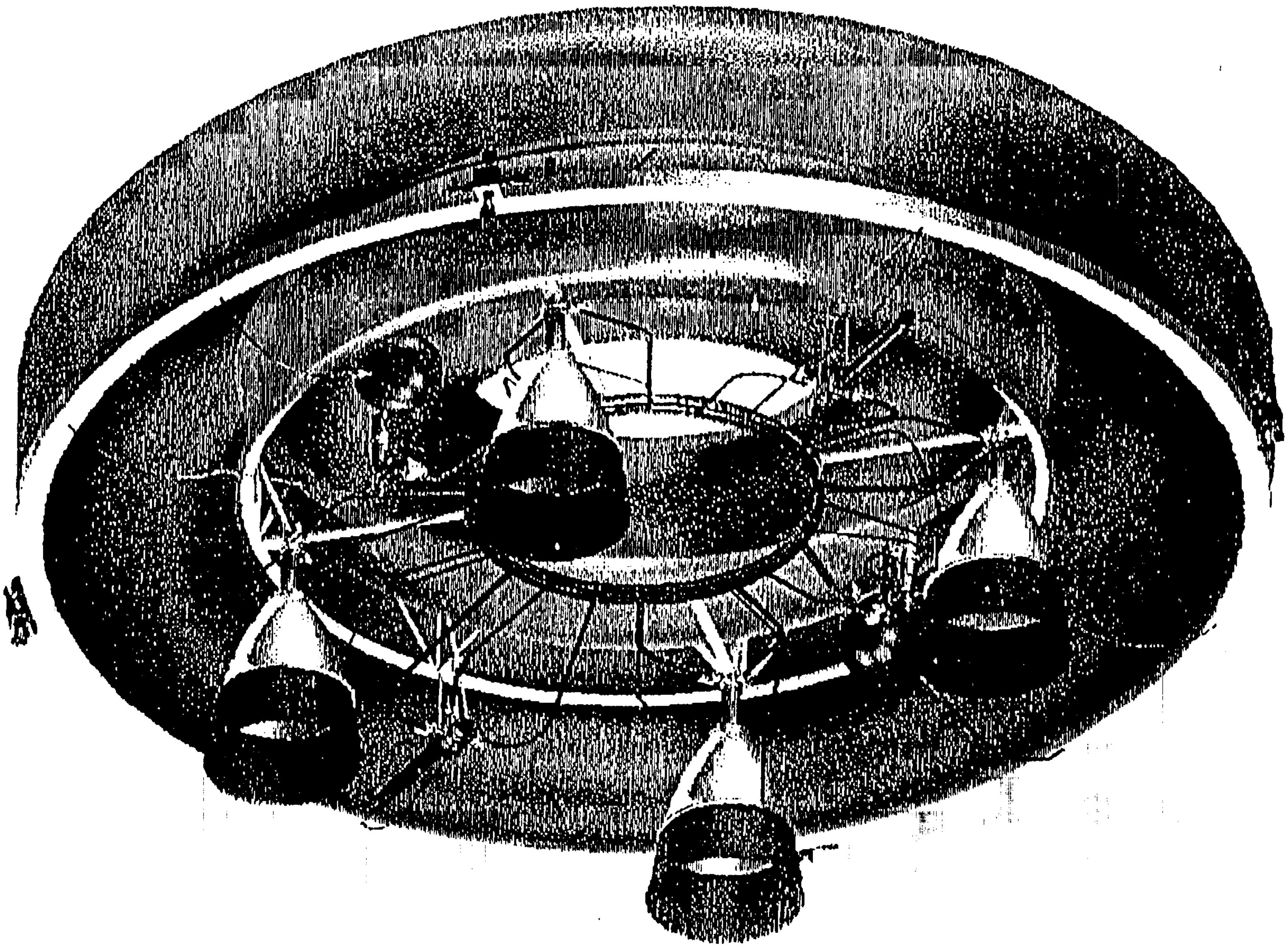
Concept A -- Conventional Tanks
Concept B -- Supercritical Tanks

Backup A to
OEPSS Study Tree 2
TH/BV 8/23/93-86

STPOES Concept C - Integrated Modular Propulsion System
Dual Concentric Propellant Tanks

Concept C modifies the original concept by substituting concentric toroidal cylindrical tanks for conventional cylindrical tanks. The toroidal tank arrangement allows tank mounted turbopumps, eliminates multiple propellant tanks, simplifies propellant tank loading and venting, and incorporates an open central core for the ascent engine. The toroidal tanks were sized to contain the same volume of propellants as Concept A. The overall height is greatly reduced with this concept and a large open area is provided in the center for the ascent engine and "fire in the hole" ascent operation.

STPOES Concept C -- Integrated Modular Propulsion System
Dual Concentric Propellant Tanks



STPOES Concept C - Integrated Modular Propulsion System
Dual Concentric Propellant Tanks (part 2)

The Concept C propulsion system design, like the Concept A design, addresses 20 launch operations concerns. Concept C, with its concentric tank arrangement, addresses 11 of the 15 listed in-space operations concerns. The single tank configurations for oxygen and hydrogen propellants would greatly simplify propellant loading which previous configurations were deficient.

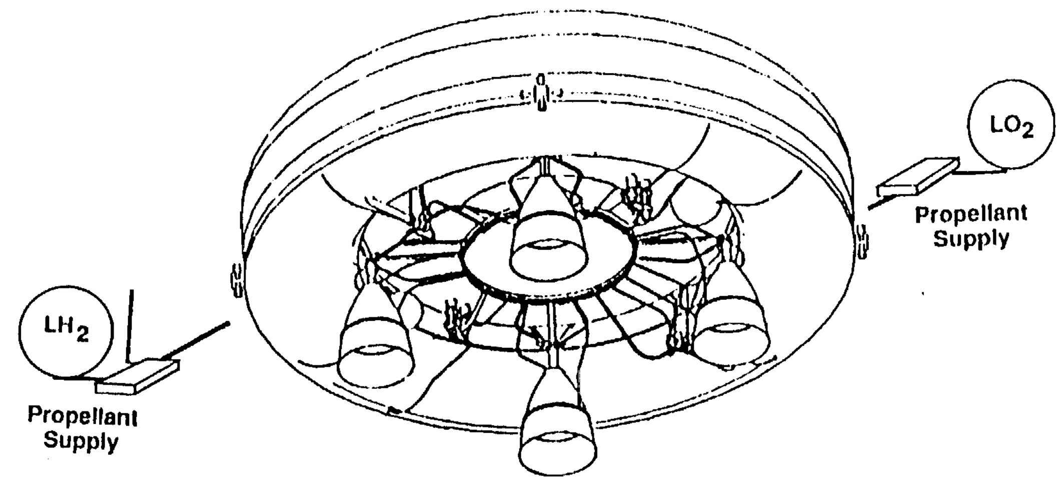
Concept C is also a two fluid system, i.e., only the Hydrogen and Oxygen propellants are required, which simplifies the launch facility.

Concept C -- Integrated Modular Propulsion System
Dual Concentric Propellant Tanks

Launch Operations
- Eliminates 20 launch concerns

In-Space Operations
- Integrated RCS
- Fluid Transfer In-Space
- Fluids In-Space
- In-Space Assembly
- In-Space Replacement
- Hardware Dependability
- Maintenance
- Fault Tolerance
- Extra Vehicular Activity
- Inspection
- Propellant Loading
- Common Propellant Tanks for RCS, etc.
- Turbopump Simplification (Eliminates Boost Pumps)
- Limited Commodities
- Liquid Vapor
  - Propellant Acquisition
  - Propellant Gaging
  - Zero G Venting
  - Propellant Loss

Operations addressed in positive direction



Greatly simplifies launch facility

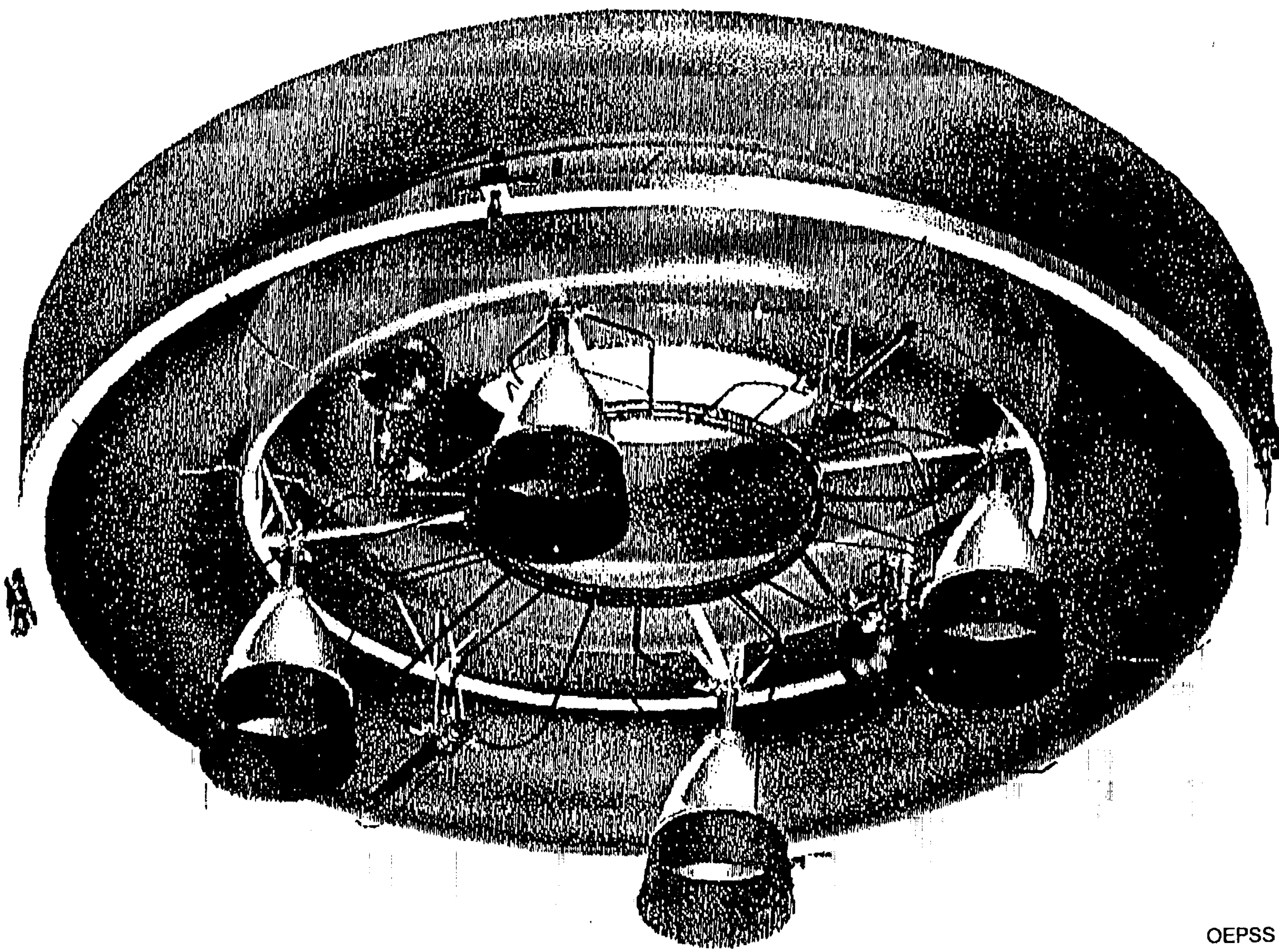
Fire in Hole Capability for Ascent Stage

STPOES Concept D - Integrated Modular Propulsion System
Enlarged Concentric Tanks for Descent & Ascent

Concept D is similar to Concept C except the propellant tanks are sized for a single descent and ascent lunar lander stage. A combined descent and ascent propulsion system would have a higher, total vehicle, overall operations index as a complete vehicle (and its associated operations) would be eliminated.

STPOES Concept D -- Integrated Modular Propulsion System

Combined Descent & Ascent Stages



STPOES Concept D - Integrated Modular Propulsion System
Enlarged Concentric Tanks for Descent & Ascent (part 2)

The Concept D propulsion system design, like the Concept A design, addresses 20 launch operations concerns.

Concept D is also a two fluid system, i.e., only the Hydrogen and Oxygen propellants are required, which simplifies the launch facility.

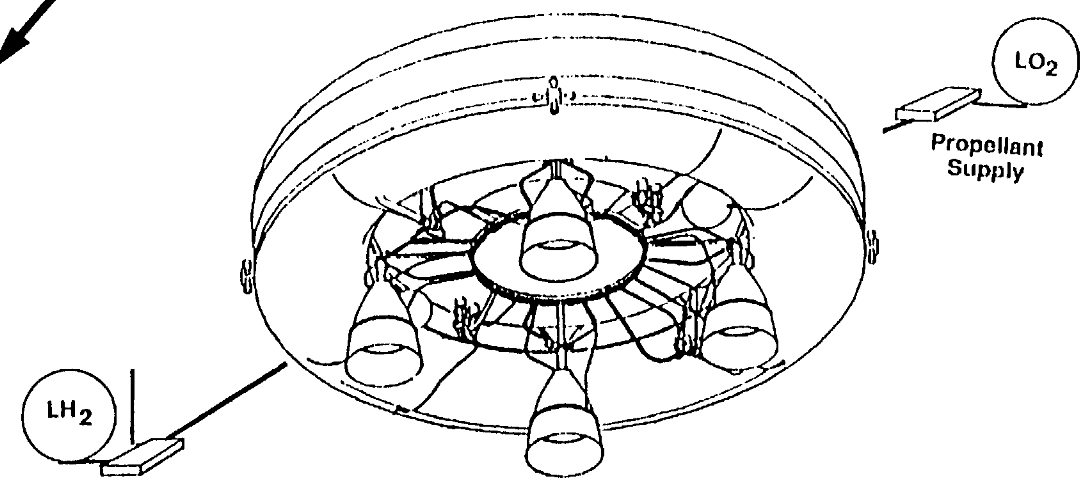
Concept D -- Integrated Modular Propulsion System
Combined Descent & Ascent Stages

Launch Operations
- Eliminates 20 launch concerns

In-Space Operations
- Integrated RCS
- Fluid Transfer In-Space
- Fluids In-Space
- In-Space Assembly
- In-Space Replacement
- Hardware Dependability
- Maintenance
- Fault Tolerance
- Extra Vehicular Activity
- Inspection
- Propellant Loading

- Common Propellant Tanks for RCS, etc.
- Turbopump Simplification
  (Eliminates Boost Pumps)
- Limited Commodities
- Liquid Vapor
  - Propellant Acquisition
  - Propellant Gaging
  - Zero G Venting
  - Propellant Loss

Operations addressed in positive direction



Greatly simplifies launch facility

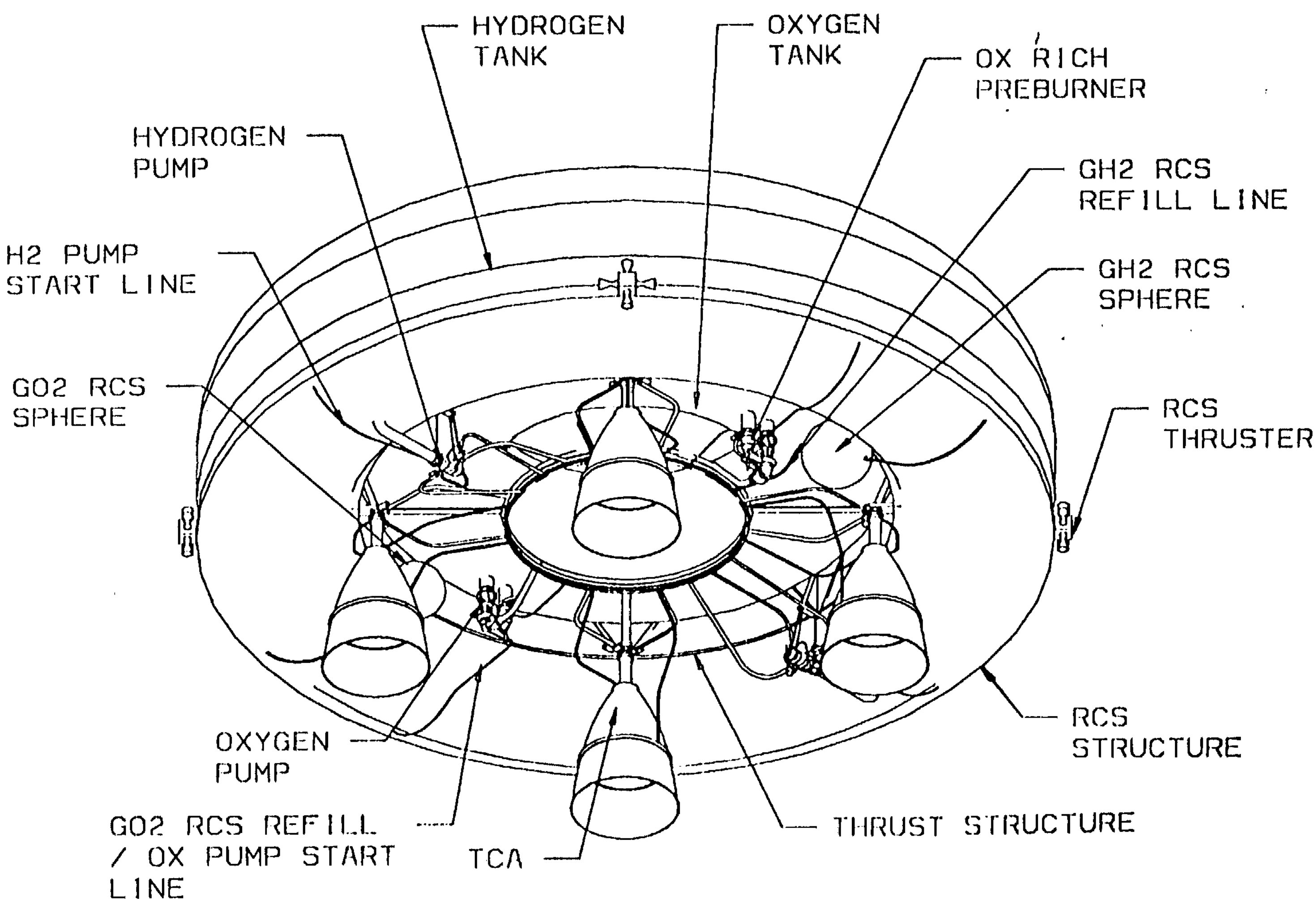
Ascent Stage Launch & In-Space Operations Eliminated

Combined stages greatly simplify operations

Lunar Lander Concepts C and D

Concepts C and D are similar in configuration and subsystem layout. The propellant tanks for concept D would be larger to accommodate propellant required for the ascent phase of the mission.

Lunar Lander Concepts C & D



Concept C -- Lunar Lander Tanks Only
Concept D -- Larger Tanks for Landing & Return

Backup A to
OEPSS Study Tree 2
TH/BV 8/23/93-86

Lunar Lander Operations-Driven Architecture Evolution

The Space Transfer Propulsion Operational Efficiency Study task studied, evaluated and identified design concepts and technologies which minimized launch and in-space operations and optimized in-space vehicle propulsion system operability. These objectives were realized while maintaining reliability and performance goals. The four design concepts that were developed were driven by operational considerations and each iteration provided a more operable concept. The final design iteration is highly operable and the supporting technologies are doable and would support an early year 2000 Lunar mission schedule.

Lunar Lander Operations-Driven Architecture Evolution

Operations-Driven STPOES Results

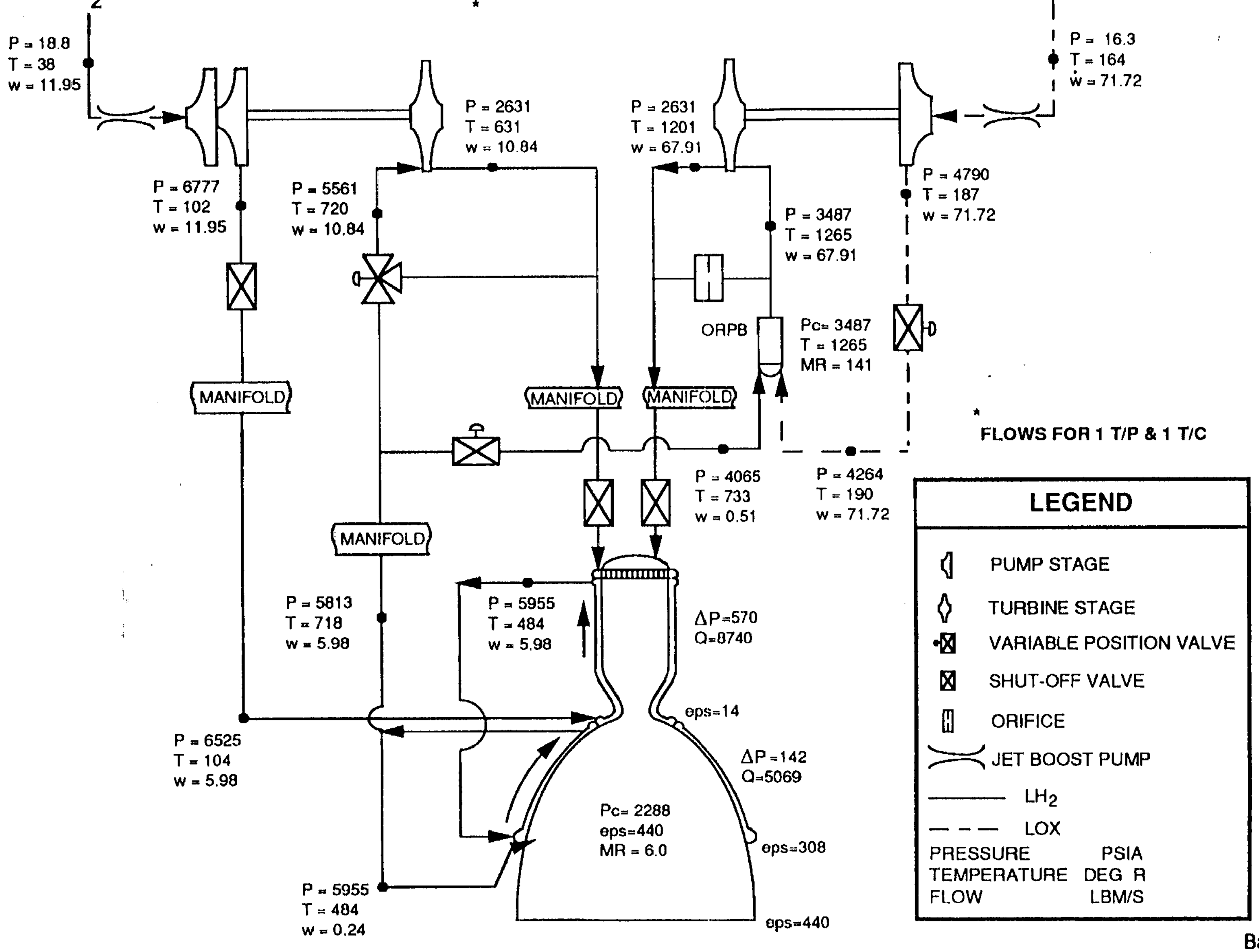
- High engine system reliability (Re) -- Exceeds reliability goal 0.994
- High performance (Isp) -- No decrease in performance 478 sec.
- Pump component out capability incorporated
- Supercritical propellant tanks (Concept B) enhancements
  - Simplifies gaging system, venting, turbopump conditioning
  - Propellant acquisition, settling concern eliminated
  - Reduces commodities loss
  - Simplifies support infrastructure
- Toroidal tanks (Concept C) enhancement
  - Simplified, tank propellant loading
  - Open center core for ascent propulsion
- Large toroidal tanks (Concept D) enhancement
  - Descent & ascent propulsion combined
  - Total vehicle operability enhanced
  - Eliminating a stage simplifies ground operations

Further combinations need to be evaluated

STPOES - Hybrid Cycle

An engine balance at the on-design full thrust condition is presented in the figure. The hybrid power cycle attains a chamber of 2288 psia and delivers a vacuum Isp of 478 sec. with a nozzle expansion ratio of 440:1.

STPOES - HYBRID CYCLE
2 T/P + 4 T/C* (Fvac=80000 klb Isp=478.1 sec)



Backup A to
OEPSS Study Tree
TH/BV 8/23/93-86

STPOES Reliability Prediction

The STPOES reliability prediction for the engine components was determined by the parts count method. A reliability goal of .99 was specified for the propulsion system. All conceptual designs exceeded this reliability goal. This reliability assessment was conducted assuming a traditional engine system. Indeed the reliability goal of .99 is for a traditionally defined engine system. While reliability benefits are accounted for with the integrated engine system design, the total propulsion system, as defined by this study (tanks, lines, RCS system, turbopumps, thrust chambers, etc.), was not evaluated. That type of reliability assessment was beyond the study scope.

STPOES Reliability Prediction

9-Oct-92		SSME Anology	SSME Rel.	Failure Rate (10^3)	Weighed Factor (Reduce F.R. by)	STPOES Reliability (Adjusted)	Failure Rate (10^3) (Adjusted)	Configuration: Thrust vectoring:	STPOES 4 T/C & 2 T/P no T/C out diff throttle (Stand-by) (Adjusted)	STPOES # of Units 4 T/C & 2 T/P configuration
Thrust Chamber Assembly										
	Injector	main injector	0.998653	1.35	0.85	.999798	0.20			4
	Combustion chamber	MCC	0.997382	2.62	0.80	.999476	0.52			4
	Nozzle	nozzle	0.997382	2.62	0.85	.999607	0.39			4
	Fuel throttle valve	prop. control	0.999890	0.11	0.85	.999984	0.02			4
	Oxidizer throttle valve	prop. control	0.999890	0.11	0.85	.999984	0.02			4
								Per TCA:	0.998849	
								Total TCA:	0.995404	
Turbomachinery Assembly										
	Fuel boost pump	LPFTP	0.999496	0.50	0.70	.999849	0.15			2
	Fuel SLIC pump	HPFTP	0.995680	4.31	0.70	.998707	1.29			2
	Fuel pump isolation valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
	Fuel turbine by-pass isolation valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
	Fuel turbine isolation valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
	Ox boost pump	HPOTP	0.997808	2.19	0.35	.998574	1.43			2
	Ox SLIC pump	LPOTP	0.999853	0.15	0.35	.999904	0.10			2
	Ox turbine isolation valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
								Per TMA:	0.996511	
								Total TMA:	0.999994	
Controls										
	Controller	electronics	0.999530	0.40	0.75	.999885	0.12			1
	Sensor	sensor	0.997800	2.19	0.75	.999452	0.55			TBD
	Health Monitoring	electronics	0.999538	0.46	0.75	.999885	0.12			1
								Total CA:	0.999221	
Integrating valves, ducts, and manifolds										
	High pressure fuel manifold	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel turbine inlet manifold	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel turbine outlet manifold	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox outlet manifold	ducting	0.999855	0.14	0.80	.999971	0.03			1
(Fuel)	Fuel inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	High pres. fuel pump discharge duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Thrust chamber coolant duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel turbine inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel turbine outlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel turbine bypass loop duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Fuel injector duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
(Oxidizer)	Oxidizer inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox pump discharge duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox turbine inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox turbine outlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox turbine bypass loop duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
	Ox injector duct	ducting	0.999855	0.14	0.80	.999971	0.03			1
								Total IA:	0.999507	
Hybrid-related components										
	Preburner	preburner	0.999076	0.92	0.60	.999630	0.37			2
	Preburner fuel valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
	Preburner ox valve	prop. control	0.999890	0.11	0.85	.999984	0.02			2
	Fuel preburner inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			2
	Ox preburner inlet duct	ducting	0.999855	0.14	0.80	.999971	0.03			2
			0.978789					Overall R:	0.994132	
								Overall FR (10^3):	5.87	

Backup B to
OEPSS Study Tree 2
TH/RV 9/2/93-7

STPOES Addresses Operations Concerns

The STPOES design approach recognized that system improvements would result by focusing on incorporating operability enhancements which would mitigate or eliminate operations concerns. Continuation of CPI processes through the operations-driven BPM and IME system architectures further refined and enhanced the STPOES concept. The resulting designs addressed 20 of the 23 OEPSS study developed operations concerns.

STPOES Addresses Operations Concerns

No.	
1	Closed aft compartments
2	Fluid system leakage • External • Internal
3	Hydraulic system
4	Ocean recovery/refurbishment
5	Multiple propellants
6	Hypergolic propellants (safety)
7	Accessibility
8	Sophisticated heat shielding
9	Excessive components/subsystems
10	Lack of hardware integration
11	Separate OMS/RCS
12	Pneumatic systems

No.	
13	Gimbal system
14	High maintenance hardware
15	Ordnance Operations
16	Retractable T-O umbilical carrier plates
17	Propellant tank pressurization system
18	Excessive interfaces
19	Conditioning/geysering (LOX tank forward)
20	Preconditioning system
21	Expensive commodity usage -- helium
22	Lack hardware commonality
23	System contamination

STPOES addresses 20 concerns

Operations-Driven Propulsion System Architecture Simplification Drives Technology Development Needs

Lists of operational concerns were generated for the STPOES and related programs. These lists were compared to identify concerns which are common to propulsion systems. In the STPOES study the propulsion system includes the vehicle tanks, lines, RCS system, turbopumps, thrust chambers etc. Candidate technologies were evaluated This enlarged propulsion system definition suggests that identified technologies should be demonstrated in a propulsion system environment. The resultant selected technologies for development were: oxidizer-rich preburner, SLIC turbopump, jet boost-SLIC turbopump module and a integrated propulsion module testbed.

Technologies recommended herein, as well as by future studies, should be demonstrated as soon as possible to provide a firm foundation for subsequent development efforts. An overall plan should be implemented so that synergistic technologies can be implemented together. A test bed is mandatory for demonstrating system technology maturation. This test bed would provide convincing technology demonstration in the system environment.

Operations-Driven Propulsion System Architecture Simplification Drives Technology Development Needs

- Oxidizer-rich preburner
  - Simplifies pump (eliminates seals, purges)
  - Enables 10:1 throttling
- SLIC turbopump
  - Minimum parts, simple construction, hydrostatic bearing
- Jet Boost Pump/SLIC turbopump module
  - Demonstrates zero NPSH, simplifies vehicle
- Integrated propulsion module testbed
  - System level demonstration of technologies
- H_2/O_2 RCS propulsion running on same tanks
- EMA's
- Above are examples and are not meant to limit technology development

Pursuit of operations enhancing technologies will prepare for development of more affordable space vehicles

STPOES Operations-Driven Results

Conceptual designs were devised which minimized operability concerns and issues for a Lunar Lander propulsion system. Twenty of twenty-three launch operations concerns were addressed and all identified initial space operation goals were met. The propulsion system designs used the enlarged paradigm of the propellant tanks, propellant distribution and the necessary rocket engine components. Major operability enhancing features were a two fluid (LOX/LH2) system, integrated designs including RCS, differential throttling for thrust vector control, zero NPSH pumps (no tank pressurization), turbopumps interfaced directly to propellant tanks, and no hydraulics, pneumatics, helium, hypergolics, monopropellants, gimbal systems or flex lines.

A parameter was developed by the OEPSS study to provide a measure for launch operations efficiency. This Launch Operability Index (LOI) is a measure value similar to a reliability measure. Comparisons between the four Lunar Lander propulsion system concepts, the IME concept, and current in-space LOX/LH2 propulsion systems (Centaur & S IV-B) were completed. The IME was found to have a LOI value of 0.80 and the STPOES had a LOI value of 0.82. This compares with LOI percentages in the mid 30's for current in-space LOX/LH2 propulsion systems. The immaturity of the In-Space Operations Index precluded propulsion system comparison against in-space concerns. The NASA requirement to achieve an Operations Index greater than 0.9 was not achieved, indicating additional work focused toward achieving this goal should be pursued.

STPOES Operations-Driven Results

- Addresses 20 operations concerns
- Addresses all identified initial space operations goals
- Process improvements in operations evolved from BPM and IME
- Innovative, simple, and operationally efficient
  - Current LOI $\approx$ .38 compared to study LOI $\approx$ .82
- Figure of Merit for in-space operations is needed
- Enlarged paradigm enhances transportation system operational efficiency and is very doable

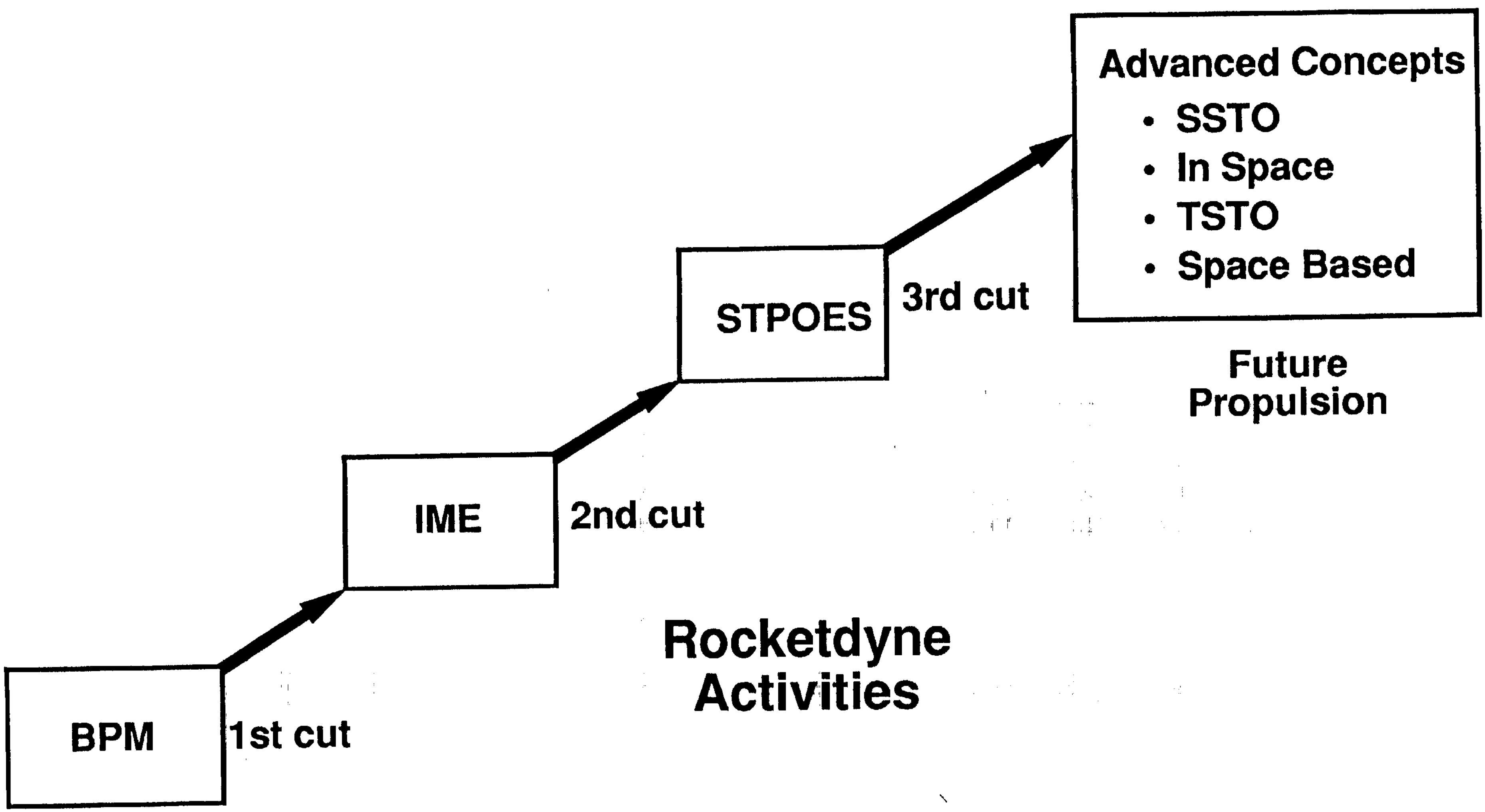
Operations-driven concepts must be applied to in-space systems if they are to be affordable

Operations Experience Continuously Applied to all Future Propulsion Concepts

Operations experience continuously applied to all future propulsion concepts must be the primary focus of conceptual architectures. Continued advancement in the operational efficiency area is mandatory if routine in-space missions are to be achieved. These efforts should include analysis, design, technology development, and group communications among those involved in design, operations and programmatics.

Operations Experience Continuously Applied to all Future Propulsion Concepts

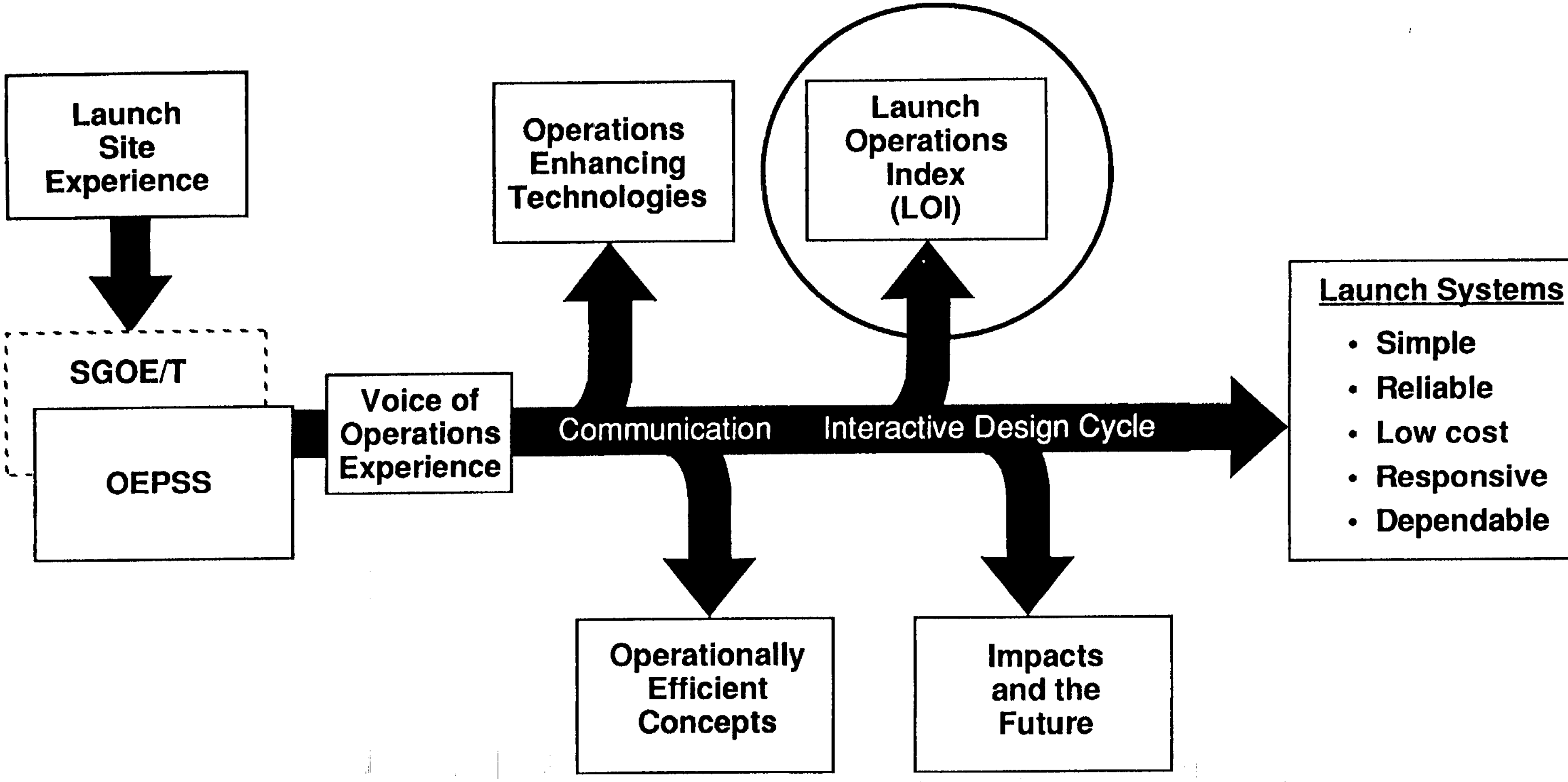
Must be Primary Focus of Conceptual Architectures



LOI: A Tool for Evaluating Operations Efficiencies

The following section describes how the LOI tool for evaluating launch operations Efficiency evolved into a strategic tool for assessing new propulsion system designs.

LOI: A Tool for Evaluating Operations Efficiencies



Launch Operations Index

In this section is presented one of the products developed in OEPSS study called the Launch Operations Index or, as it is more often referred to: the LOI.

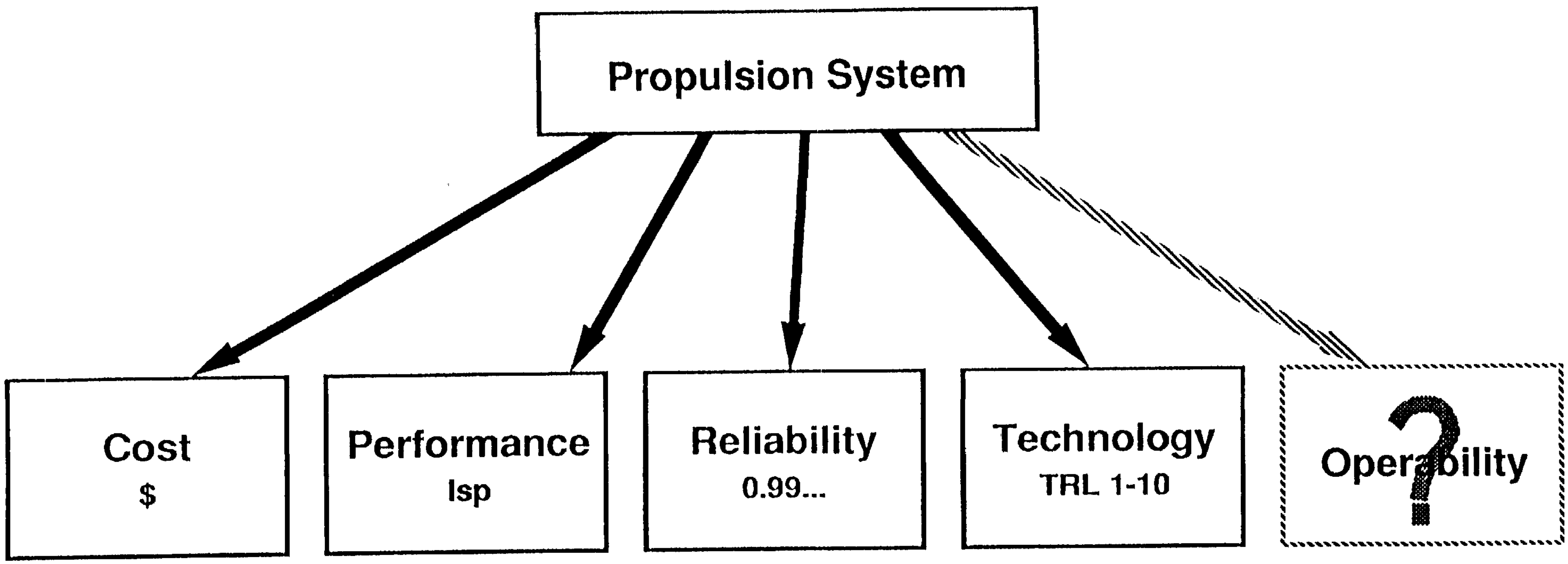
Launch Operations Index

Why is LOI Needed?

We in this industry have a need to quantify the characteristics of a propulsion system such that a more complete and accurate assessment of performance and cost of the total system can be made at the beginning of the design process. Universally understood measures are available for many of these characteristics. For example: cost can be expressed in a given year's dollars for development, for recurring expenses, or for total life cycle costs. Several methods can be used to define performance: total impulse, I_{sp}, thrust per pound of system weight, etc. Reliability can be MTBF, success probability, etc. Technical maturity is expressed as a value from 1 to 10.

However, we have never had a standard for operability.

Why is LOI Needed?



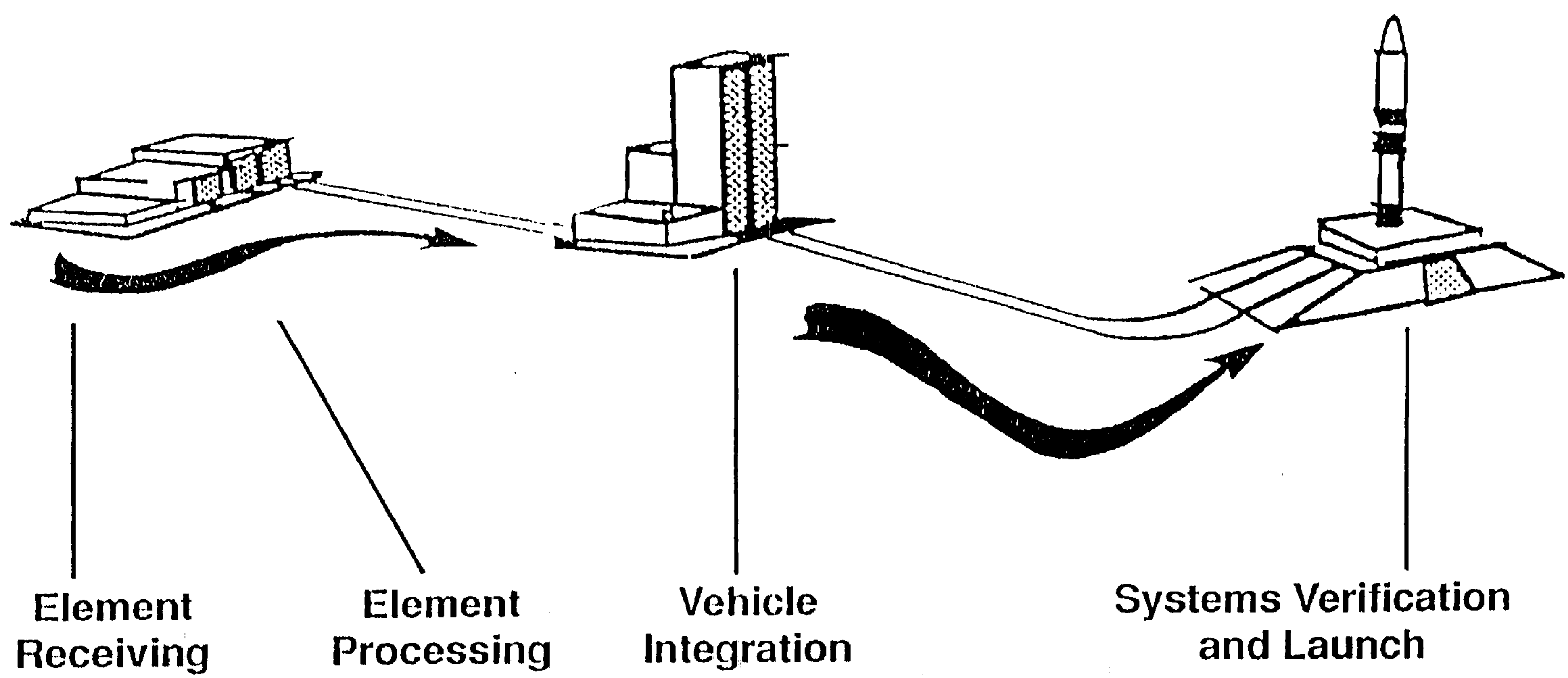
Cost, performance, reliability, and technology maturity, are quantified; but the important and critical measurement of operations is missing

LOI Addresses Complete Launch Operations

In order to be effective, a launch operations index should consider how propulsion designs impact all phases of ground processing prior to launch. Shown here is a typical processing flow - from receiving, processing, integration, verification, to launch.

LOI Addresses Complete Launch Processing

Flight Checkout and Verification



What is LOI?

The LOI is a parameter or a figure of merit which allows us to quantify propulsion system operations. It could be used by conceptual designers to compare different propulsion system designs based on their impact on launch operations. This ensures that launch operations is a factor that is critically addressed early in the design process.

Those who must evaluate propulsion designs in program design reviews or during proposal evaluation will find the LOI a very useful parameter in their assessment of these systems. Program managers will find the LOI a means of showing a credible assessment of operability in their propulsion system designs.

The LOI will improve the design process by making sure direct launch operations experience is a necessary feedback into any design process.

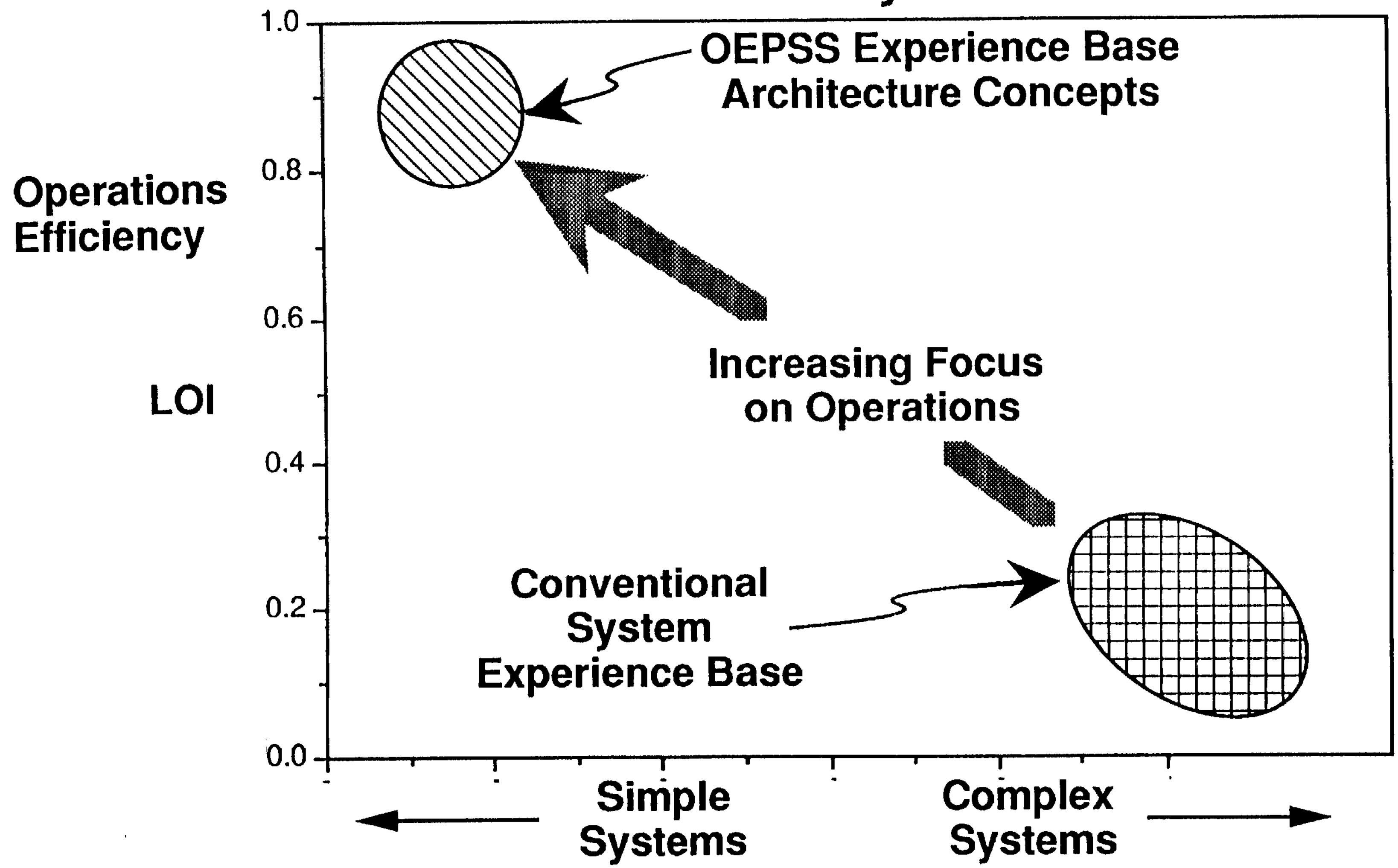
What Is LOI?

- Figure of Merit to quantify system operability
- LOI program is a tool for estimating the Figure Of Merit
- Used by conceptual designers
  - Evaluate options early in design process
- Used by evaluators
  - Design review
  - Proposal evaluation
- Used by program managers
  - Show operability of their products

A tool is needed for measuring system operations efficiency

In view of the need for making operations an important factor in the design process, a design tool was developed during the OEPSS study that will allow the operability of the propulsion design to be measured. This design tool, called the Launch Operations Index, or LOI, is a figure-of-merit that relates "operations efficiency" to system "complexity." Conventional systems, for which many of the OEPSS concerns apply, which are complex will have correspondingly low operations efficiencies, while simple, integrated systems, exemplified by the OEPSS propulsion system architectures, will have high LOI's. This is depicted in the illustration.

"A tool is needed for measuring system operations efficiency..."



The Launch Operations Index "LOI" is an effective, strategic tool

Initial Index Approach Focused on Launch Processing

The first attempt at establishing a credible, meaningful operations index focused on what we know about all the complex tasks involved with processing a vehicle for launch. A processing tree with several levels of checkout and verification was formulated. From the tree was developed a concept in which criteria ratings were applied to the Level 3 elements. The index was based on summing all these criteria ratings.

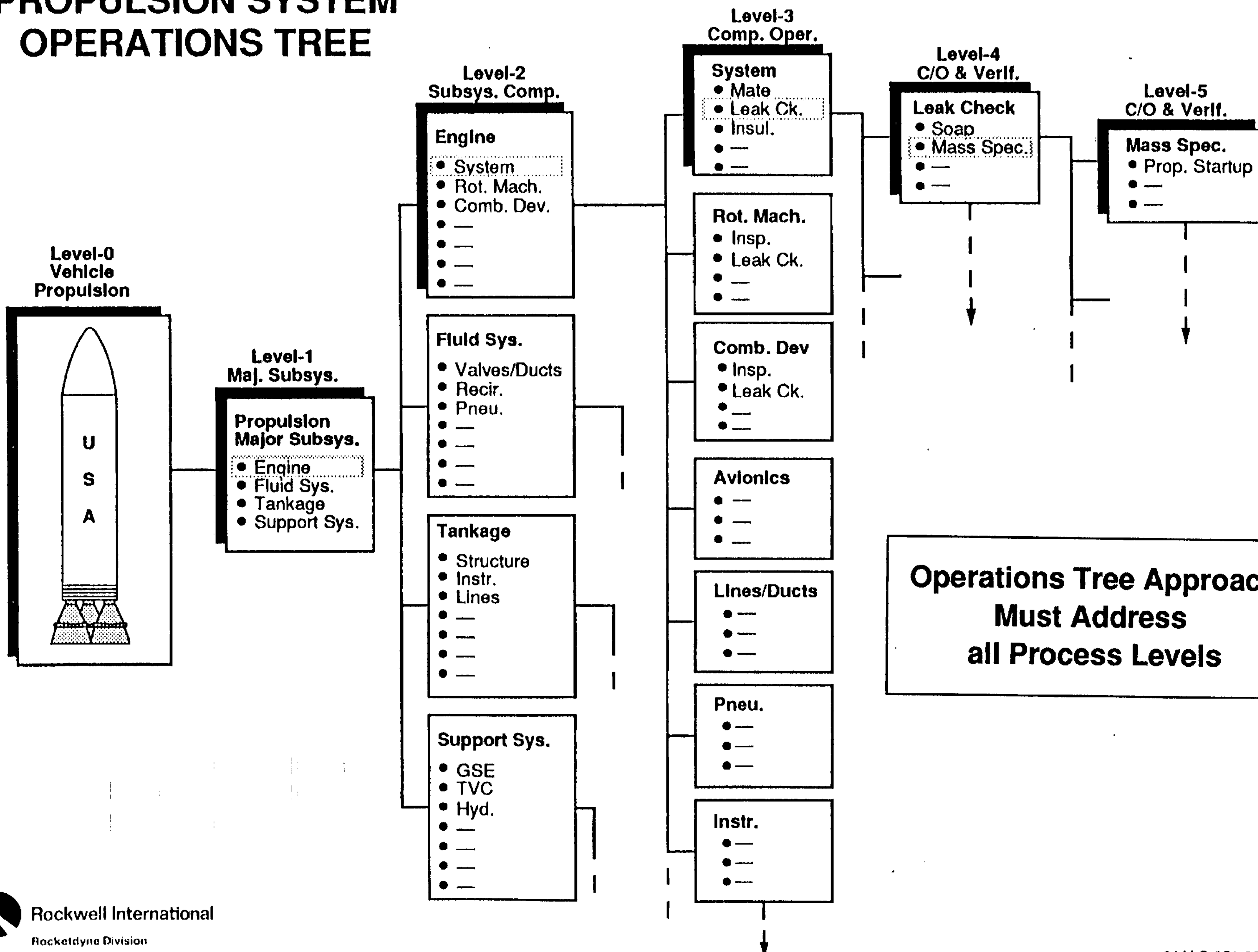
Initial Index Approach Focused on Launch Processing

- Multi-level flight checkout & verifiction processing trees developed
- Criteria ratings applied to level 3 elements of tree
- Index based on summartion of all criteria ratings

Operations Tree

Shown is the Operations Tree with its various levels from the vehicle propulsion system, through major subsystems, subsystems, and components. It is further broken down into detailed operations and even check-out techniques.

PROPULSION SYSTEM OPERATIONS TREE



Operations Tree Approach Must Address all Process Levels

Rockwell International
Rocketdyne Division

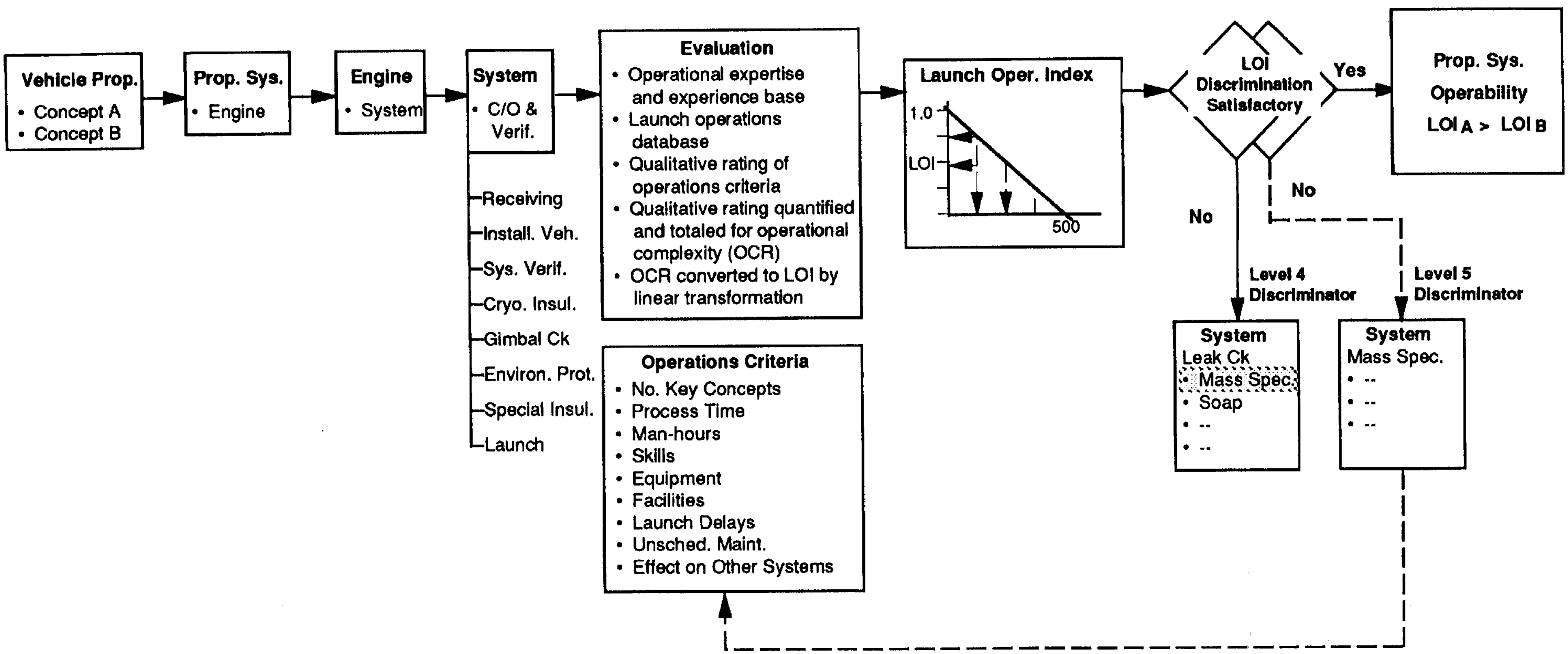
91ALS-051-86

Backup B to Ops Driven Des.

Methodology for Evaluating Ops
Prop Sys Ops Tree

This is the methodology by which an index could be developed from the propulsion system operations tree. It focuses on level 3 and lower. Key to the credibility of this approach is the completeness of the Operations Criteria on which the Evaluation is based. It can be seen that a large amount of data is required to accurately identify the process time, man hours, skills, equipment, etc., etc., that forms the criteria for each process. Multiply this by the total number of operational processes involved in a complete system, and the required amount of data becomes tremendous.

Methodology for Evaluating Operability of Propulsion Systems Operations Tree



Development Effort is Extensive in Nature, but Has Merit

Rockwell International
Rocketdyne Division

Eval. Prop. Sys Ops Tree
TH/Bv 9/9/93
Backup C to
Ops Driven Des.

Operations Tree Approach to LOI Not Completed

It was hoped that the ops tree approach to developing an operational index would develop an index anchored in actual processing data. However, this was not completed during OEPSS. It was found that obtaining the sheer volume of data needed to produce credible results was beyond the scope of the study.

Operations Tree Approach to LOI Not Completed

- Requires evaluation of all levels of processing
- Credible results require gathering and evaluating large quantities of processing data
    - Data unavailable for many elements
- Effort required to develop index anchored in actual launch processing data beyond scope of study

LOI Approach Developed

During the OEPSS study, an LOI was envisioned which would be based on actual launch processing data and evaluation of all levels of processing. Because of the magnitude of the effort needed to obtain the necessary data and because data are not available for many processing elements, this approach was found to be beyond the resources available to OEPSS.

Therefore, an approach was developed for the LOI which is based on the OEPSS experience-based operations concerns list. This approach utilized the collective experiences of the general propulsion community in place of the unavailable hard data on launch processing.

Based on the operations concerns list approach, a prototype computer program for calculating LOI has been completed addressing liquid propulsion systems. This prototype program is available for both IBM compatible and Macintosh platforms.

LOI Approach Developed

- Effort required to develop an operations index anchored in actual launch processing data
    - Beyond scope of study
    - Requires evaluation of all levels of processing
    - Data unavailable for many elements
- Alternate LOI approach based on OEPSS concerns list
    - Required operations experience inputs from general propulsion community
    - Prototype LOI program completed
        - Addresses liquid booster propulsion systems
        - Beta (prototype) program available for both IBM compatible and Macintosh

Original Design Features List

The first step in the LOI development was to convert the OEPSS concerns list to a design features list. Shown here is the original design features list prior to inputs from the propulsion community. The numbers in parentheses following each feature is the original weighting factor (used in the LOI calculation) for that feature.

Original Design Features List

1. Compartment Configuration (8)
2. Degree Of Checkout Automation (9)
3. Number/Type Of Propellants (9)
4. Recovery Method (7)
5. Auxiliary Propulsion Type (8)
6. Ordnance Systems (7)
7. Actuator System Type (6)
8. Heat Shield Type (6)
9. Purge System Type (5)
10. TVC System Type (5)
11. Fluid Ground Interface Type (5)
12. Tank Pressurization Systems (4)
13. Preconditioning Requirements (4)

(X) = Weighting Factor

Conceptual LOI Developed from Experience Base

The LOI has credibility because it represents the collective experience of a wide range of propulsion interests. Initially the OEPSS team, representing NASA-KSC, Rocketdyne, and Rockwell Space Systems Division, formulated the method and assigned the ratings and weighing factors needed in calculating the operations index.

Extensive operations workshops were then held at NASA-KSC, NASA-MSFC, and NASA-JSC. The workshop at JSC was also attended by representatives from Stennis Space Center, Air Force, NASA-LeRC, and NASA-MSFC. Based on inputs from these operations workshops, the LOI was further updated and refined to its present form.

Conceptual LOI Developed from Experience Base

- OEPSS team
  - NASA - Kennedy Space Center
  - Rocketdyne, Rockwell International
  - Space Systems Division, Rockwell International

- Workshops
  - NASA - Kennedy Space Center
  - NASA Marshall Space Flight Center
  - NASA Johnson Space Center
    - Stennis Space Center
    - Air Force
    - Lewis Research Center
    - Marshall Space Flight Center

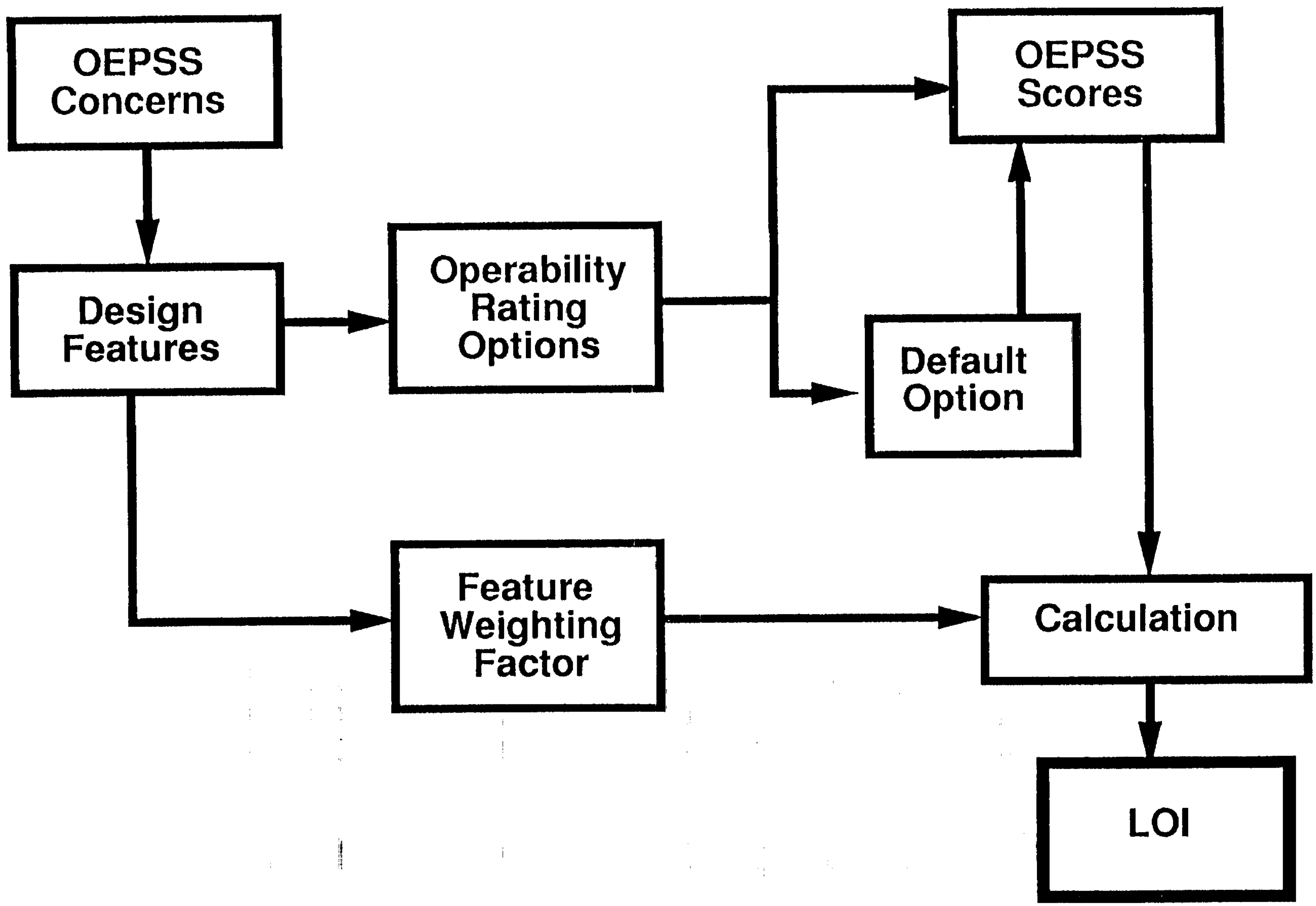
LOI Computational Methodology

The method used in the LOI program starts with the transformation of the OEPSS operations concerns list into a corresponding list of propulsion design features. Each of the features is then assigned a weighing factor based on operations experience which represents that feature's impact on overall operability.

For each of these design features, a list of candidate design options is developed. The options are arranged in order of operability and each assigned a rating from 1 to 10. A default option is selected which is typical of current systems. This default is used when a system is immature and has not yet defined an option for that design feature.

Operability ratings are combined with the weighing factors to yield the operations index.

LOI Computation Methodology



Example of LOI Calculation

Here is how a typical LOI is calculated. The program contains the complete list of design features with weighting factors (WF) and maximum possible operability ratings (OR) for each feature. It calculates the product of the WF and max OR for each and a sum of the products for all the features.

The user selects an option (or accepts the default option) for each feature. The program calculates the product of the corresponding OR for that option and the WF for that feature. A sum of all the (WF X selected OR) is calculated and then divided by the sum of all the (WF X max OR) which results in the LOI.

Example LOI Calculation

Design Feature	1	2	3			. . . . . .	17	18
Weighting Factor	8	9	10				8	8
Operability Rating	5	6	3				6	7
WF X OR	40	54	30				48	56
Σ(WF X OR) = 581								

$$\text{LOI} = \frac{\text{CALCULATED } \Sigma(\text{WF X OR})}{\Sigma(\text{WF X MAXIMUM OR})} = \frac{581}{1340} = 0.433$$

Propulsion Design Features Based on Operations Concerns

As previously stated, for the purpose of developing the LOI, the OEPSS operations concerns list was transformed into a list of design features to be assessed for a given system. Shown here is the current design features list after the three LOI workshops. Significant changes from the original list that were suggested by the workshops include addition of: TVC power, separation of fuel and oxidizer pressurization systems, separation of fuel and oxidizer preconditioning, addition of GSE requirements, and adding number of main engines.

The weighing factor shown in parenthesis for each feature represents that feature's contribution to system complexity and potential for launch delay. As can be seen, the features with the most impact on the operations index are: number/type of propellants, degree of checkout automation, accessibility, and leakage potential.

Propulsion Design Features
Based on Operations Concerns

No.		No.	
1	Compartment configuration (8)	11	Fluid ground interface type (5)
2	Degree of checkout automation (9)	12	Oxidizer tank press. system (2)
3	Number/type of propellants (10)	12A	Fuel tank press. system (2)
4	Recovery method (7)	13	Oxidizer preconditioning (2)
5	Auxiliary propulsion type (8)	13A	Fuel preconditioning (3)
6	Ordnance systems (7)	14	Component subsystem accessibility (9)
7	Valve actuator type (5)	15	Potential for leakage (9)
8	Heat shield type (6)	16	Degree of hardware integration (7)
9	Purge system type (5)	17	Ground support requirements (8)
10	TVC system type (3)	18	Number of Main Engines (8)
10A	TVC power (4)		

(10) = Weighting factor

Design Feature #1 -- Compartment Configuration

This design feature significantly affects the propulsion system's operability. As shown, the best aft compartment is essentially no compartment at all, with no liquid or vapor traps and with easy access to the system. The default option, closed compartment with access through large doors is typical of current systems.

Design Feature #1 -- Compartment Configuration

Operability Rating	Design Options
10	Completely open -- no compartments or traps
9	Completely open before flight -- single simple cover added for launch
8	Completely open before flight -- multiple simple covers added for launch
7	Open but small trap area
6	Open but multiple or large trap areas
5	Open except few small closed compartments
4	Open except many or large closed compartments
3*	Completely closed compartment -- access through large easily utilized doors
2	Completely closed compartment -- access through multiple small hatches
1	Completely closed compartment -- access through single small hatch

*Default for this feature = 3 (reflects current typical configuration)

Design Feature #2 - Checkout Automation

Checkout automation is one of the strongest drivers in reducing ground operations because it directly affects not only the speed at which check-out can be accomplished, but equally important, the number of people needed to perform the check-out.

Design Feature #2 - Checkout Automation

Operability Rating	Feature Option
10	No using site checkout required
9	Totally automated - single command required for complete checkout
8.5	Totally automated except multiple manual commands required for complete checkout
5	Functional checks of all active components automated - most leak checks automated
4	Functional checks of all active components automated - some leak checks automated
2	Functional checks of all active components automated - leak checks performed manually
1.5*	Functional checks of some active components automated - leak checks performed manually
1	No automation - all checkout performed manually

* Default for this feature = 1.5

Design Feature #3 - Number/Type of Propellants

This feature, is felt by the community to be the single most important factor influencing ground operations and it was therefore assigned a weighting factor of 10. It is easy to understand how much more difficult system servicing and checkout is for those options lower down the operability scale than those near the top.

Design Feature #3 - Number/Type of Propellants

OPERABILITY RATING	FEATURE OPTION
10	Prepackaged, sealed propellants - no GSE
9.5	Single, ambient temperature, non-toxic propellant
6.5	LH2
6	Multiple non-toxic, non-hazardous propellants
5	LO2 with hydrocarbon fuel
4	LH2, LO2
1.7	LO2, LH2, and hydrazine mono-propellants
1.5*	LO2, LH2, and hypergolic bi-propellants
1.2	LO2, LH2, hypergolic bi-propellants, and hydrocarbons
0.5	Extremely hazardous/toxic propellants (e.g.: fluorine, flox, pyrophorics, etc.)

* Default for this feature = 1.5

Design Feature #4 - Reusability Potential

The options in this feature affect operations in their impact on turnaround after a mission is complete. Clearly the expendable system scores the highest because it has no turnaround.

Design Feature #4 - Reusability Potential

OPERABILITY RATING	FEATURE OPTION
10	Expendable - no recovery
8	Horizontal land (soft landing), powered
7	Horizontal land (soft landing), non-powered
1	Ocean recovery with complete exposure protection
0.5	Ocean recovery with no exposure protection

* Default for this feature = 10

Design Feature #5 - Auxiliary Propulsion

Auxiliary propulsion systems contribute to operations complexity especially if they require propellant different from that used by the main engines. Toxicity of the propellants is also an important factor.

Design Feature #5 - Auxiliary Propulsion

OPERABILITY RATING	FEATURE OPTION
10	No auxiliary propulsion
9	Auxiliary propulsion prepackaged & sealed
8.5	Single auxiliary propulsion system using main engine propellants from same tanks
8	Multiple auxiliary propulsion systems using main engine propellants from same tanks
5	Single auxiliary propulsion system using main engine type propellants loaded or charged separately from me propellants
4.5	Multiple auxiliary propulsion system using main engine type propellants loaded or charged separately from me propellants
2	Single auxiliary propulsion system using a toxic or hazardous propellant
1.5*	Multiple auxiliary propulsion systems using a common toxic or hazardous propellant
1	Multiple auxiliary propulsion systems, each with different type toxic propellants

* Default for this feature = 1.5

Design Feature #6 - Non-propulsive Ordnance Systems

This design feature addresses ordnance other than solid rockets. The impact of such systems is strongly influenced by safety considerations, especially when personnel clearing dictates serial operations.

Design Feature #6 - Non-propulsive Ordnance Systems

OPERABILITY RATING	FEATURE OPTION
10	No ordnance
9	Pre-installed benign ignition (e.g.: laser)
8	Pre-installed electrical ignition
6	Launch site installation - clearing of personnel not required
4	Single launch site installation operation - clearing of personnel required
1	Multiple launch site installation operations - clearing of personnel required

* Default for this feature = 1

Design Feature #7 - Valve Actuator Type

Propulsion valves are typically distributed throughout the system. Actuation systems for these valves can therefore be complex. If these actuation systems require significant checkout and servicing (such as hydraulics and pneumatics do), then major operations effort is needed to provide this checkout and servicing. On the other hand, if the actuation system is purely electrical, operations are substantially reduced because of the greater potential for automated checkout.

Design Feature #7 - Valve Actuator Type

OPERABILITY RATING	FEATURE OPTION
10	No actuators
8	All EMA
7.5	All EHA
5	Pneumatic
4.5	EMA with pneumatic back-up
3	Distributed hydraulics
2*	Distributed hydraulics with pneumatic back-up

* Default for this feature = 2

Design Feature #8 - Heatshield Type

Heat shields play a role in operations not only because they require installation and servicing, but also because they can obstruct accessibility to other subsystems and components. Ease of installation and removal are therefore important design considerations.

Design Feature #8 - Heatshield Type

OPERABILITY RATING	FEATURE OPTION
10	No heatshield
6.5	Spray on foam heatshield
7	Gimbal plane heatshield + engine blankets
6	Gimbal plane & engine blankets
7	Local shielding of critical components
2*	Aft heatshield with dynamic seal to accommodate engine gimballing

* Default for this feature = 2

Design Feature #9 - Pneumatic System

The effort required to service and checkout a pneumatic system is a function of the number of components in that system. The number of active components (such as valves) obviously has a greater impact than fluid lines or other passive components.

Design Feature #9 - Pneumatic System

OPERABILITY RATING	FEATURE OPTION
10	No pneumatic system
8	Pre-packaged system - no GSE
7	Single ground only purge. ground supplied & controlled.
6.5	Multiple ground only purges. ground supplied & controlled.
5	Multiple ground only purges. vehicle provides on-off control.
4	Multiple ground only purges. vehicle provides regulation & distribution.
3	Simple storage & distribution provides few flight purges.
2.5	Simple storage, distribution, & regulation provides few flight purges.
2*	Storage, distribution, & regulation for multiple flight purges <u>or</u> simple valve pneumatic control system.
1.5	Pneumatic storage, regulation & distribution. multiple ground & flight purges. some pneumatic valve control
1	Complex pneumatic storage, regulation & distribution. multiple ground & flight purges. extensive pneumatic valve control system

*Default for this feature = 2

Design Feature #10 - TVC System Type

As with other design features, the impact on operations of a thrust vector control (TVC) type is dependent on that feature's complexity. The most simple, and therefore the most operable is TVC by differential throttling of the main engines. In this approach there is no added hardware required for the TVC function.

Design Feature #10 - TVC System Type

OPERABILITY RATING	FEATURE OPTION
10	Differential throttling - fixed main engine nozzles
7.5	Auxiliary thrusters - all engine nozzles fixed
7	Vanes
6	Fluid injection - fixed main engine nozzles
5.5	Main engine nozzles fixed - auxiliary thrusters gimballed
4	Main engines hinged
3*	Main engines gimballed

* Default for this feature = 3

Design Feature #10A - TVC System Power Source

For the TVC power source, operability is a function of hardware complexity and the number and handling difficulty of any required fluids.

Design Feature #10A - TVC System Power Source

OPERABILITY RATING	FEATURE OPTION
10	None required
8	Engine power take off (EPTO) directly powers electric TVC
7.5	Batteries directly power electric TVC
7	EPTO directly provides hydraulic power
6	EPTO powered electric APU provides hydraulic power
5	Hydrazine APU provides electric power
4	Battery powered electric APU provides hydraulic power
3	Bi-propellant APU provides electric power
2*	Hydrazine APU provides hydraulic power
1	Bi-propellant APU provides hydraulic power

* Default for this feature = 2

Design Feature #11 - Fluid Ground Interface Type

Operations impact of the fluid interface type is a function of the umbilical systems requirements for service and especially refurbishment after a launch.

Design Feature #11 - Fluid Ground Interface Type

OPERABILITY RATING	FEATURE OPTION
10	FLUIDS ONLY - EXPENDABLE, RISE OFF CONNECTIONS LOCATED ON BASE OF VEHICLE, ZERO EXTERNAL LEAKAGE DESIGN
6	MULTI-FLUID - EXPENDABLE, RISE OFF CONNECTIONS LOCATED ON BASE OF VEHICLE
5	Expendable mast
4	Multi-fluid - pull away connections located at vehicle base and other conventional vehicle / ground interface points requiring QD protection
2*	Multi-fluid - retract at commit, connections located at conventional vehicle / ground interface points, requiring tail service mast infrastructure, towers and swing arm infrastructure, and reusable, sophisticated QD configuration requiring extensive maintenance / refurbishment

* Default for this feature = 2

Design Feature #12 - Oxidizer Tank Press Systems

As with many of the other design features, the oxidizer tank pressurization system's operability increases with decreasing system complexity.

Design Feature #12 - Oxidizer Tank Press Systems

OPERABILITY RATING	FEATURE OPTION
10	None
9	Tank self pressurized
6	Autogenous - fixed orifice control
5.5	Ambient helium - fixed orifice control
5	Autogenous - open loop control valve
4	Ambient helium - closed loop flow control valve
3*	Autogenous - closed loop flow control valve
1	Cold helium, heat exchanger - fixed orifice control
0.5	Cold helium, heat exchanger - closed loop flow control valve

* Default for this feature = 3

Design Feature #12A - Fuel Tank Press Systems

Again, reducing complexity increases operability.

Design Feature #12A - Fuel Tank Press Systems

OPERABILITY RATING	FEATURE OPTION
10	None
9	Tank self pressurized
6	Autogenous - fixed orifice control
5.5	Ambient helium - fixed orifice control
5	Autogenous - open loop control valve
4	Ambient helium - closed loop flow control valve
3*	Autogenous - closed loop flow control valve
1	Cold helium, heat exchanger - fixed orifice control
0.5	Cold helium, heat exchanger - closed loop flow control valve

* Default for this feature = 3

Design Feature #13 - Oxidizer Preconditioning

The difficulty in providing oxidizer preconditioning to satisfy engine start requirements is dependent on the propellant, the engine start requirements, and the feed system design. The proper selection of these requirements can force a complex preconditioning system or permit a very simple one such as use of natural convection.

Design Feature #13 - Oxidizer Preconditioning

OPERABILITY RATING	FEATURE OPTION
10	No preconditioning required
9	Preconditioning through natural convection
8.7	Preconditioning through engine external passive bleed/leakage overboard
8	Preconditioning by helium injection
4	Preconditioning by passive feed line bleeds to tanks
3	Preconditioning by passive feed line bleeds to ground
2	Ground pumps required for preconditioning
1*	Flight pumps required for preconditioning

* Default for this feature = 1

Design Feature #13 A- Fuel Preconditioning

Requirements for fuel preconditioning are similar to those for oxidizer preconditioning.

Design Feature #13 A- Fuel Preconditioning

OPERABILITY RATING	FEATURE OPTION
10	No preconditioning required
9	Preconditioning through natural convection
8.7	Preconditioning through engine external passive bleed/leakage overboard
8	Preconditioning by helium injection
4	Preconditioning by passive feed line bleeds to tanks
3	Preconditioning by passive feed line bleeds to ground
2	Ground pumps required for preconditioning
1*	Flight pumps required for preconditioning

* Default for this feature = 1

Design Feature #14 - Component/Subsystem Accessibility

Access to components may be required for checkout, servicing, maintenance, or replacement. The ease with which this access possible has an important contribution to operability. Ease of access must also consider support equipment requirements to gain the access.

Design Feature #14 - Component/Subsystem Accessibility

OPERABILITY RATING	FEATURE OPTION
10	Each component & subsystem completely accessible without removal of any other parts or use of any support equipment (stands, platforms, etc.)
7	Each component & subsystem completely accessible without removal of any other . Support equipment required for access to some items.
5	Access to some components or subsystems requires removal of panels. Each component & subsystem completely accessible without removal of any other . Limited support equipment required.
3*	Access to some components or subsystems requires removal of panels. Access to some LRU's requires removal of other hardware. Support equipment required for access to some items.
2	Access to most components or subsystems requires removal of panels. Access to some LRU's requires removal of other hardware. Support equipment required for access to some items.
0.5	Access to any component or subsystem requires removal of structural panels. access to many LRU's requires removal of other hardware. Extensive support equipment must be used.

* Default for this feature = 3

Design Feature #15 - Fluid System Leakage Potential

Fluid system leakage has been a major factor in low propulsion system operability. Clearly reducing this problem by eliminating all possible fluid leak points is very desirable.

Design Feature #15 - Fluid System Leakage Potential

OPERABILITY RATING	FEATURE OPTION
10	Hermetic sealing of all fluid systems
7	Few static seals only used in fluid systems.
5	Many static seals only used in fluid systems.
3*	Extensive use of static seals in all fluid systems. few dynamic seals used.
1	Extensive use of static & dynamic seals in all fluid systems

* Default for this feature = 3

Design Feature #16 - Hardware Integration

Lack of subsystem integration reduces operability by precluding simultaneous servicing or checkout of the various propulsion subsystems. Differing requirements between separate subsystems also reduces operability.

Design Feature #16 - Hardware Integration

OPERABILITY RATING	FEATURE OPTION
10	Fully integrated - essentially a single subsystem
7	Physical integration of major subsystems - common requirements where possible
5	Modular, self contained subsystems
3*	Little physical integration - some common subsystem requirements
1	No integration - each subsystem has differing requirements

* Default for this feature = 3

Design Feature #17 - Ground Support Requirements

Ground support equipment (GSE) requirements is an important, and sometimes overlooked factor in a flight system's operability. Complex GSE requires maintenance and servicing and should be eliminated wherever possible.

Design Feature #17 - Ground Support Requirements

OPERABILITY RATING	FEATURE OPTION
10	No ground support equipment required
7	Only simple standard tools and equipment required for ground support
5	Complex equipment required but all common usage with little maintenance needed
3*	Some specially development equipment equipment needed with significant maintenance required
1	Complex specially developed equipment needed with extensive maintenance requirements

* Default for this feature = 3

Design Feature #18 - Number of Main Engines

The number of main engines is one of the most important factors in the overall propulsion system's complexity and therefore its operability.

Design Feature #18 - Number of Main Engines

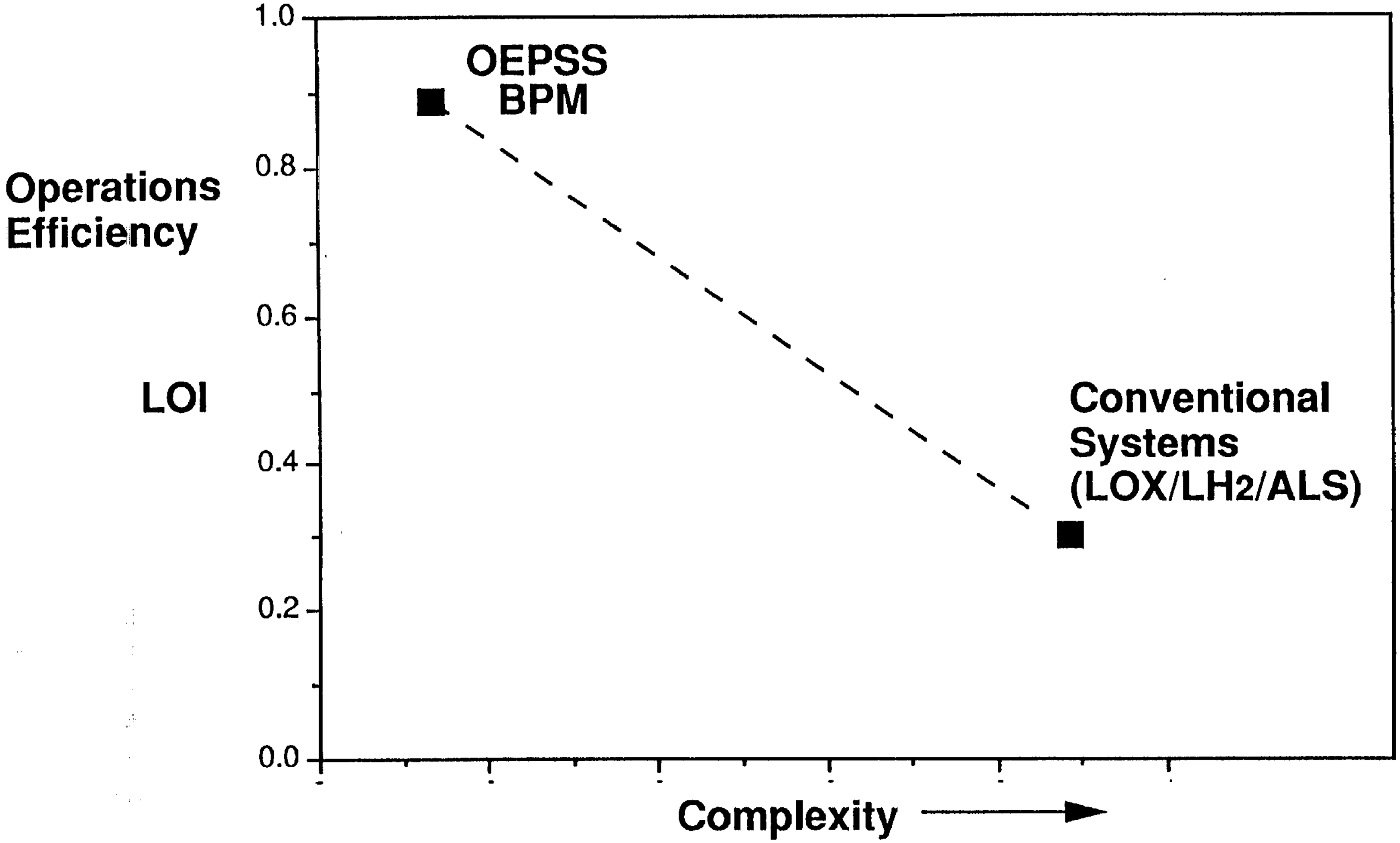
OPERABILITY RATING	FEATURE OPTION
10	Single main engine
7	Two main engines
5*	Three main engines
3	Four main engines
1	Five or more main engines

* Default for this feature = 3

Operations Efficiency for Booster Propulsion Systems

The application of the LOI as a design tool is illustrated for a conventional booster propulsion system and a propulsion system that has been simplified by eliminating operations concerns or operational requirements. The efficacy of the LOI, as a credible discriminator, based primarily on design features and operational experience, is clearly depicted as it relates operations efficiency to system complexity (reflected by operations concerns and problems). The LOI, being in a conceptual development phase, has shown to be useful and undoubtedly in time will be refined and improved.

Launch Operations-Driven Architecture with CPI Meets Operations Efficiency for Booster Propulsion Systems

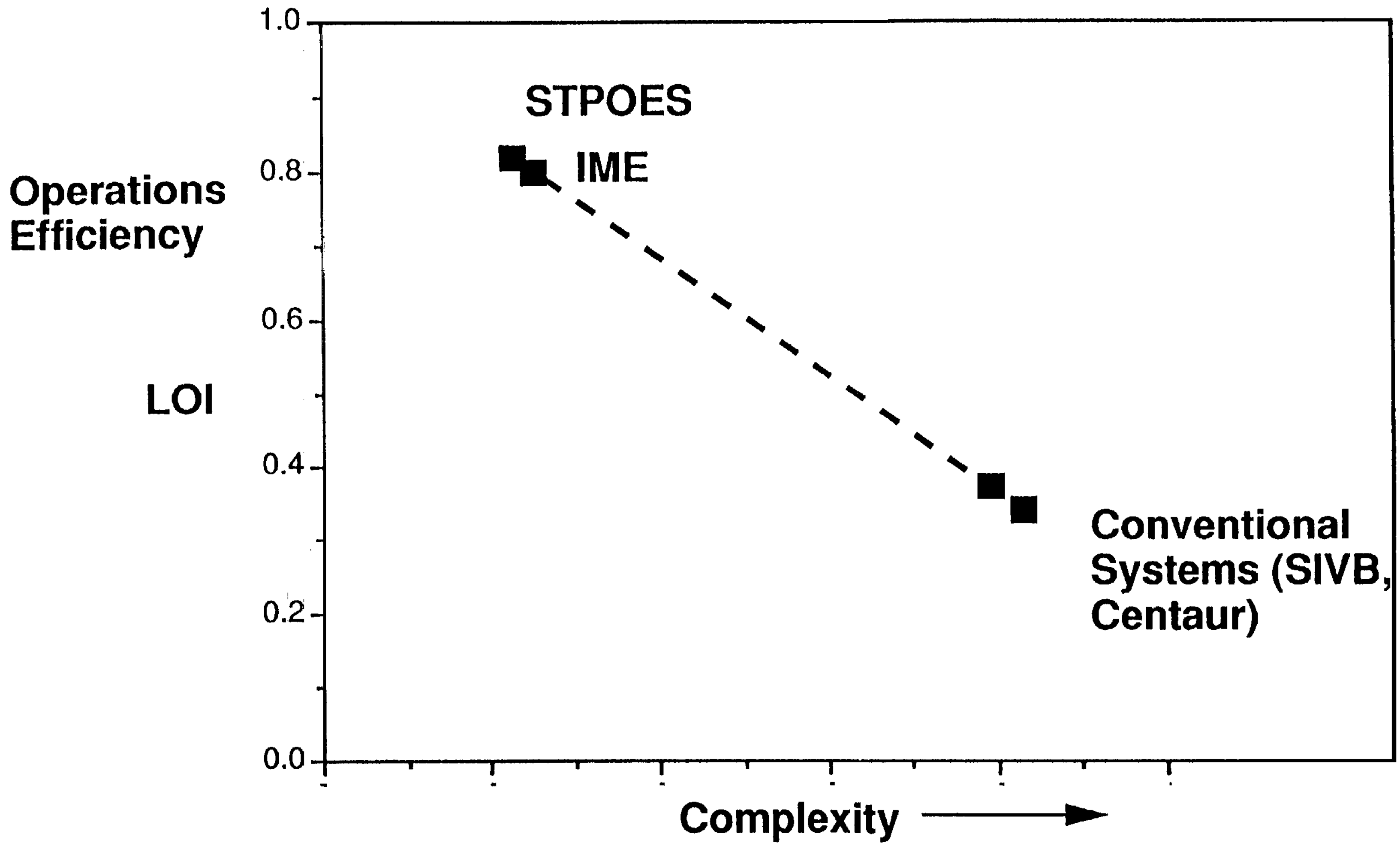


An example of LOI used as an effective "strategic" tool for evaluating operations for space launch systems

Operations Efficiency for Space Propulsion Systems

Another example application of the LOI as a conceptual design tool is illustrated for a conventional space propulsion system and a system that has explicitly addressed and specifically designed to avoid known operations problems. Despite considering only ground operations and support, if the integrated IME and STPOES propulsion systems indeed have successfully addressed 18 to 20 of the 23 OEPSS operations concerns associated with conventional systems, then these systems should truly achieve the high operations efficiency potentials depicted. The development of an in-space operations index will provide another needed parameter for further operational assessment of future space propulsion systems.

Launch Operations-Driven Architecture with CPI Meets Operations Efficiency for Space Propulsion Systems



An example of LOI used as an effective "strategic" tool for evaluating operations for space launch systems

STPOES Identified Need for In-Space Operations Index

A task that was added to the OEPSS study, entitled Space Transfer Operational Efficiency Study (STPOES), extended the investigation of propulsion operations in space. The study pointed out the need for developing an in-space operations index (ISOI) for evaluating future space propulsion systems and the methodology for the LOI could be used for developing this index.

STPOES Identified Need for In-Space Operations Index

- Space Transfer Propulsion Operational Efficiency Study (STPOES) task extended OEPSS to in-space operations
- Comparative analysis of operability of in-space propulsion systems required
- Methodology for in-space index operations based on LOI

In-Space Operations Index (ISOI)

Work on the In-Space Operations Index (ISOI) is focused on those unique concerns and issues associated with propulsion space operations. Methods for liquid and vapor management have special problems in space. Propellant acquisition and gauging are important design considerations. The concern for propellant tank venting, non-propulsively and with minimum loss of propellant mass, is also important.

Since hardware repair and replacement in space is difficult, if not impossible, dependability and fault tolerance of hardware must be considered. The problem of dormant standby monitoring that results from possibly very long mission duration must also be considered. In-space commodities cannot be easily replenished and therefore their conservation is a very important design consideration.

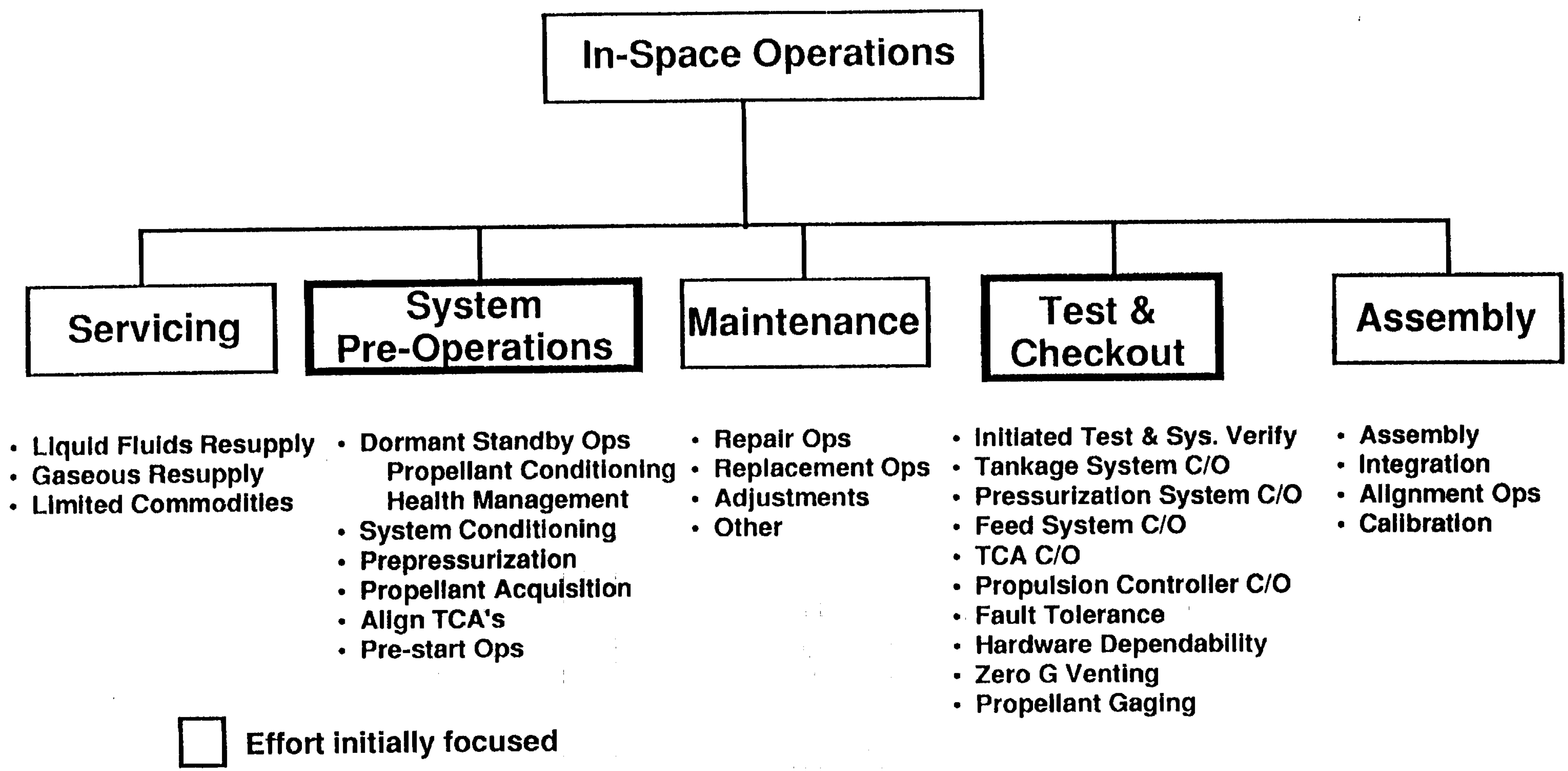
In-Space Operations Index (ISOI)

- ISOI initiated to quantify in-space operability
  - Liquid/vapor concerns
    - Propellant acquisition
    - Propellant gaging
    - Zero-G venting
      - Non propulsive
      - Minimum propellant loss
  - Hardware dependability
  - Fault tolerance
  - Maintenance
  - Dormant standby monitoring
  - Limited commodities

In-Space Propulsion Operations
Major Categories

Shown are the major operations categories that must be used in formulating a methodology for the in-space operations index (ISOI). During the STPOES task, development of the ISOI was initiated and has progressed only through early phases. The methodology for ISOI is discussed in greater detail in the OEPSS Databook Volume VI.

In-Space Propulsion Operations
Major Categories



LOI Methodology Should Be Extended

The ultimate goal of the LOI is to provide a tool that can be used to actually quantify operations. In order for this to be possible, the program must be exercised by many people for a variety of applications. Hard data from as many sources as possible should be used to confirm or to revise the weighing factors, operability ratings, and the defaults.

Then the LOI can become an important tool providing a credible indication of operations costs and an important factor in lowering program costs

LOI Methodology Should Be Extended

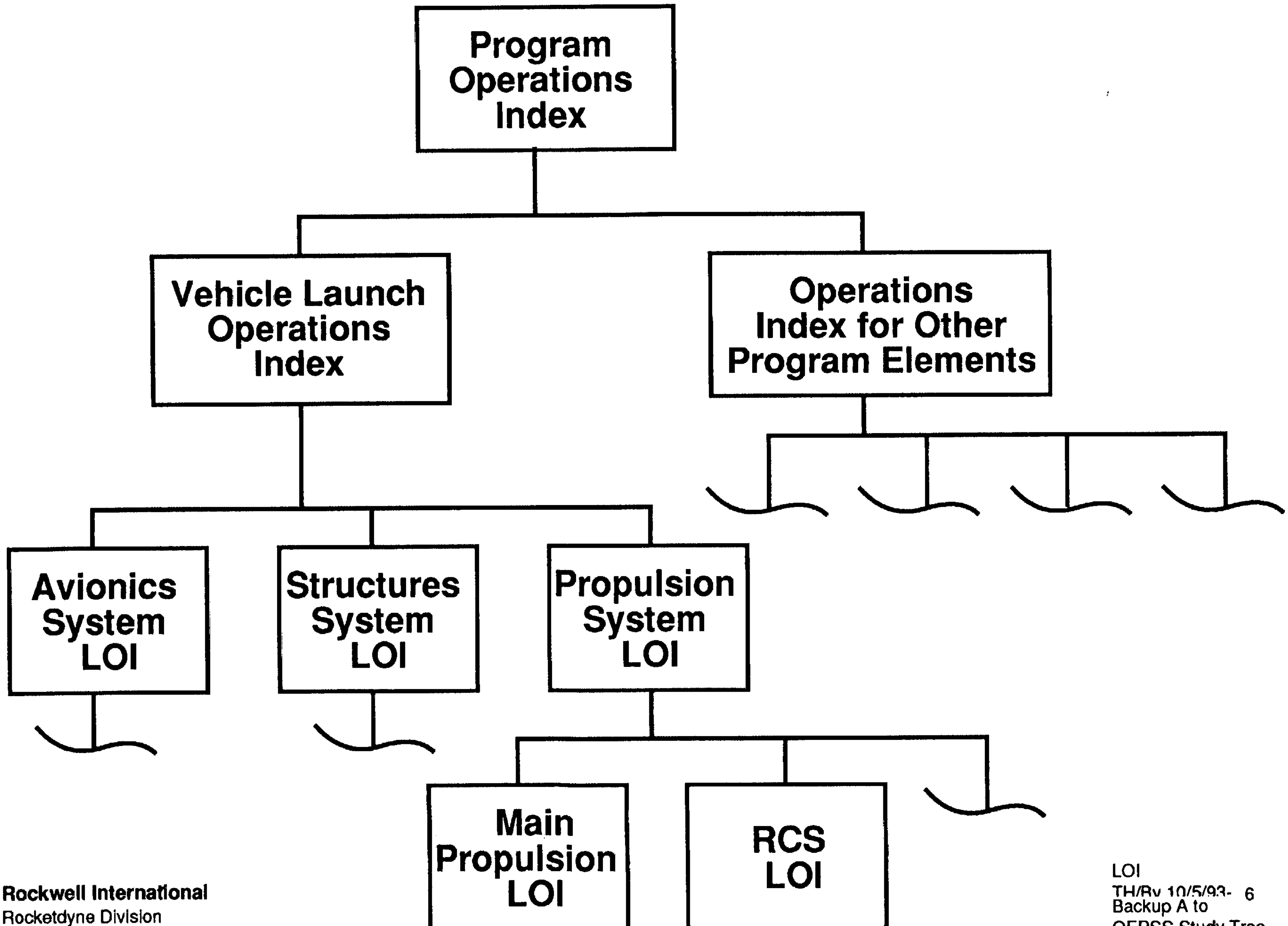
- Goal is to quantify program operations
  - LOI program should be validated
  - Hard data from existing programs should be applied

- Can become a tool useful in focusing on operations costs
  - Fulfills a major factor in lowering program costs

LOI Approach Applies to Various Levels

During OEPSS we have concentrated mainly on the application of LOI to propulsion systems. However, the same methods can be applied to all levels of a complete program. Note that levels lower than the propulsion system can be assessed.

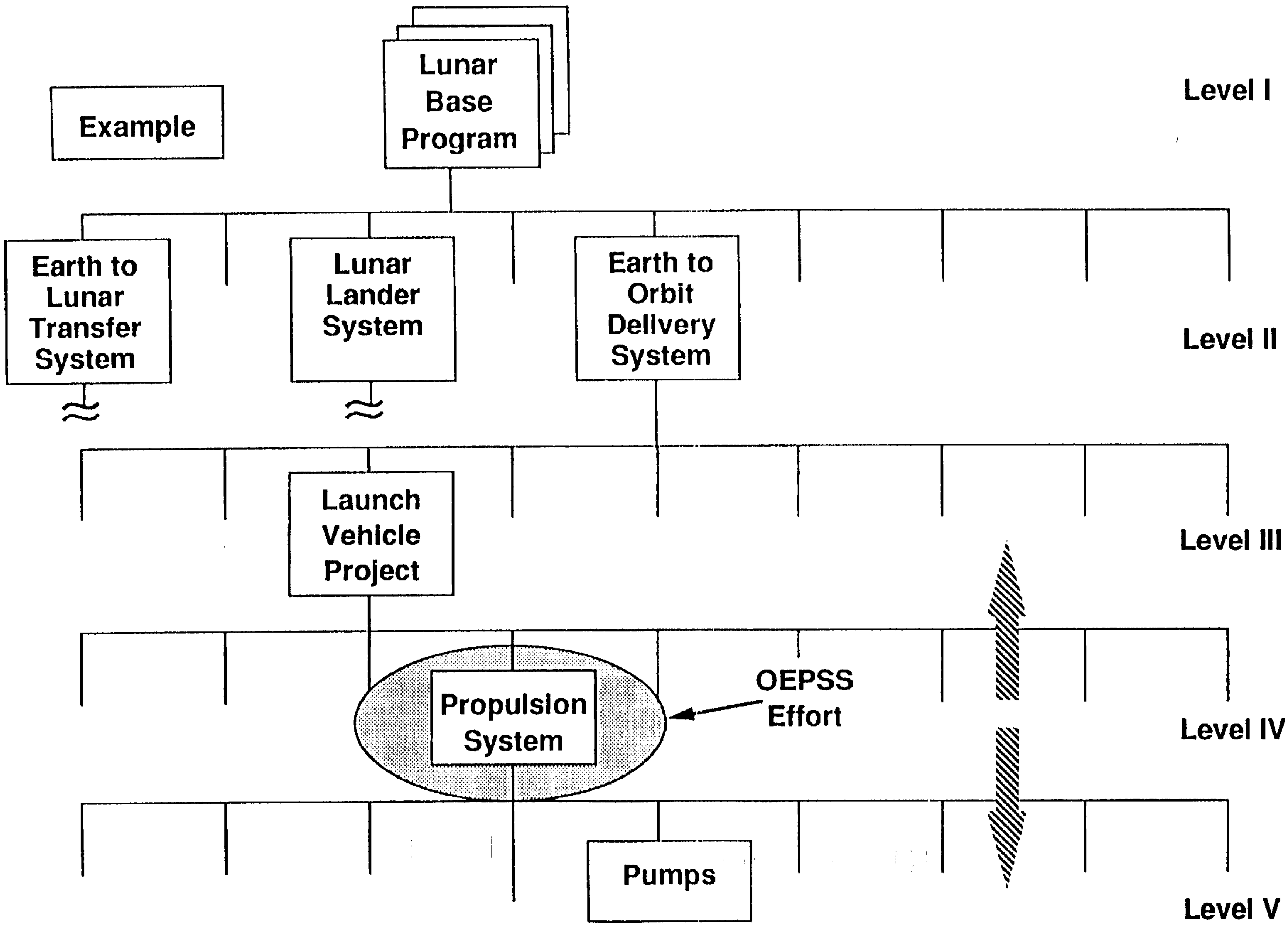
Approach Applies to Various Levels of Operations



Example of Program levels

An example of the various levels of a Lunar Base Program are shown.

Approach Applies to all Levels of Operations



Added Work is Needed Now for LOI to Become an Industry Standard

The work done during the OEPSS study on LOI was only a start. Our industry needs a standard for evaluating the important area of operations. To make this happen, the LOI should be extended to all areas concerned with operations. The individual indexes should then be combined into a program index. The LOI, and eventually the other indexes, should be validated by testing against actual operations data from existing systems. However, obtaining these data from the existing systems can be a difficult and challenging effort.

Added Work is Needed Now for LOI to Become an Industry Standard

- Extend to other subsystems, flight operations, etc.
- Combine into program index
- Validate by testing against existing systems when opportunity permits

Our Industry Must Have Operability Figure of Merit

It is obvious that our goal of achieving easy access to space can only be reached if we can develop systems and programs that our country can afford. It is also obvious that operations are a significant portion of any space program cost and must be monitored and controlled throughout the development program. The LOI does provide a method for monitoring operations costs. We have demonstrated that the LOI is an achievable metric and a usable prototype tool.

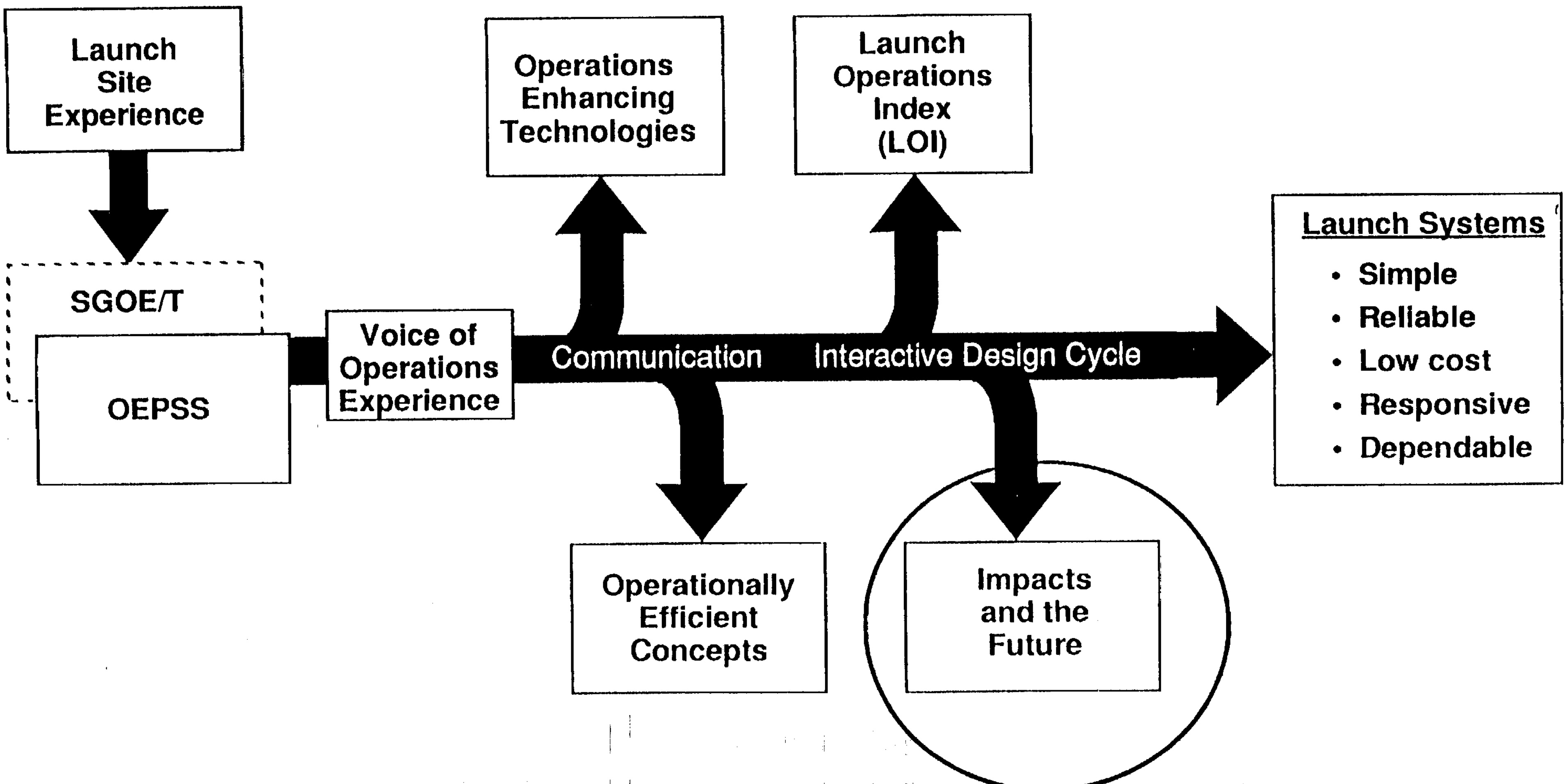
Our Industry Must Have Operability Figure of Merit

- Costs are primary driver to achieve goal of easy access to space
- Operations must be an early and quantifiable consideration
    - LOI provides method
- LOI is an achievable metric
    - Prototype tool is now usable

"OEPSS...one step in the right direction ...many steps must follow"

This completes our discussion of the LOI. Now we will address the impact the OEPSS study has had on the design community and what needs to be accomplished in the future.

"OEPSS...one step in the right direction ...many steps must follow



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OEPSS
Impacts and the Future

Some Programmatic Firsts

The first exercises in a "self examination by KSC" were the Shuttle Ground Operations Efficiencies/ Technologies study (SGOE/T) and the Operationally Efficient Propulsion System Study (OEPSS). The OEPSS was the first attempt ever by the launch site to document and effectively communicate to the aerospace community general propulsion system ground processing activities at the launch site. In performing this self examination and attempting to illustrate for the design centers our past and present problems, several key groups of data were generated: first, a generic operations concerns list documenting major propulsion system cost drivers; second, identification of known and achievable launch operations enhancing technologies; third, provided top level illustrations of propulsion system architectures that were used to explain the effects of considering the concerns and applying enhancing technologies to increase operations efficiency; fourth, generated a prototype tool for a figure of merit to evaluate the operational efficiency of a concept; fifth, aggressively used every opportunity to share the OEPSS message with the aerospace community. And lastly, as a readily available reminder of the important OEPSS message, the entire three-year study has been highlighted and made into an OEPSS video.

OEPSS
Some Programmatic Firsts
From the Launch Site

- Propulsion system focus
- Established launch site concerns list
- Identified operations enhancing technologies
- Presented operations enhancing propulsion architectures
- Generated prototype LOI as FOM for launch operations
- Interactive in the propulsion design cycle
- Documented results of the study in an OEPSS video

Additional OEPSS Tasks

The previous chart highlighted some programmatic firsts as activities of the OEPSS study. There were, however, numerous other tasks performed by the study that were equally important such as: evaluating launch site operations, exploring ways to assist the design centers and pursuing operations information. One of the first tasks of the study was to generate a generic liquid propellant vehicle and to define the "processing operations" related to the propulsion systems as we know it today. The study then began to expand operational efficiency ideas to space systems, such as in the task "Space Transfer Operational Efficiency Study," looking at a next generation lunar descent vehicle. During this task, we investigated the availability and level of effort required to retrieve past systems data that was "archived." The study also put together a presentation as to what would be considered. An investigation was also made to determine how operationally efficient a launch pad can become should the operations technologies identified by OEPSS were to be incorporated into the vehicle design. Along with this, the team scoped out the idea of a launch operations test bed located "offline" to wring out the systems and its operations procedures prior to entering mainstream operations. Many questions were generated by our booster propulsion module architecture; many said it wouldn't work. Extensive digital transient simulation modeling was done to show that it was dynamically stable and sound under all important operating conditions.

Additional OEPSS Tasks From the Launch Site

- Develop ground operations data for generic liquid propellant vehicle
- Expand "operational efficiency" ideas to Space Systems
- Investigate historical data availability
- Scope out concepts
  - Operationally efficient launch pad
  - Launch site--integrated test bed--
- Anchor integrated propulsion system architecture with dynamic transient simulation computer modeling
- Assist in hosting operations workshops and forums

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OEPSS
Intangible Products

- Most importantly...
  - Interacting with the aerospace community
  - Conducting workshops/seminars to exchange information
  - Supporting symposiums with the OEPSS message
  - Sharing years of launch site experience and activities
  - Establishing communication links between design centers and the launch site
  - Being a catalyst in the Penn State summit that resulted in the establishment of the Space Propulsion Synergy Group
  - "Interactive Design Cycle" with ALS PSWIG

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OEPSS
Tangible Products

- Documentation of launch site concerns
- Identification and documentation of operations enhancing technologies
- Investigation of innovative operations enhancing propulsion architecture concepts
- Generation of space transfer propulsion operational efficiency evaluation data
- Development of a prototype Launch Operations Index computer program
- A dynamic video overview emphasizing the important areas covered by the OEPSS study on operations

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The Voice of Operations Experience

OEPSS Identifies Major Operations Concerns and Impacts

Operations Experience Base

No.		No.	
1	Closed aft compartments	13	Gimbal system
2	Fluid system leakage • External • Internal	14	High maintenance hardware
3	Hydraulic system	15	Ordnance Operations
4	Ocean recovery/refurbishment	16	Retractable T-O umbilical carrier plates
5	Multiple propellants	17	Propellant tank pressurization system
6	Hypergolic propellants (safety)	18	Excessive interfaces
7	Accessibility	19	Conditioning/geysering (LOX tank forward)
8	Sophisticated heat shielding	20	Preconditioning system
9	Excessive components/subsystems	21	Expensive commodity usage -- helium
10	Lack of hardware integration	22	Lack hardware commonality
11	Separate OMS/RCS	23	System contamination
12	Pneumatic systems		

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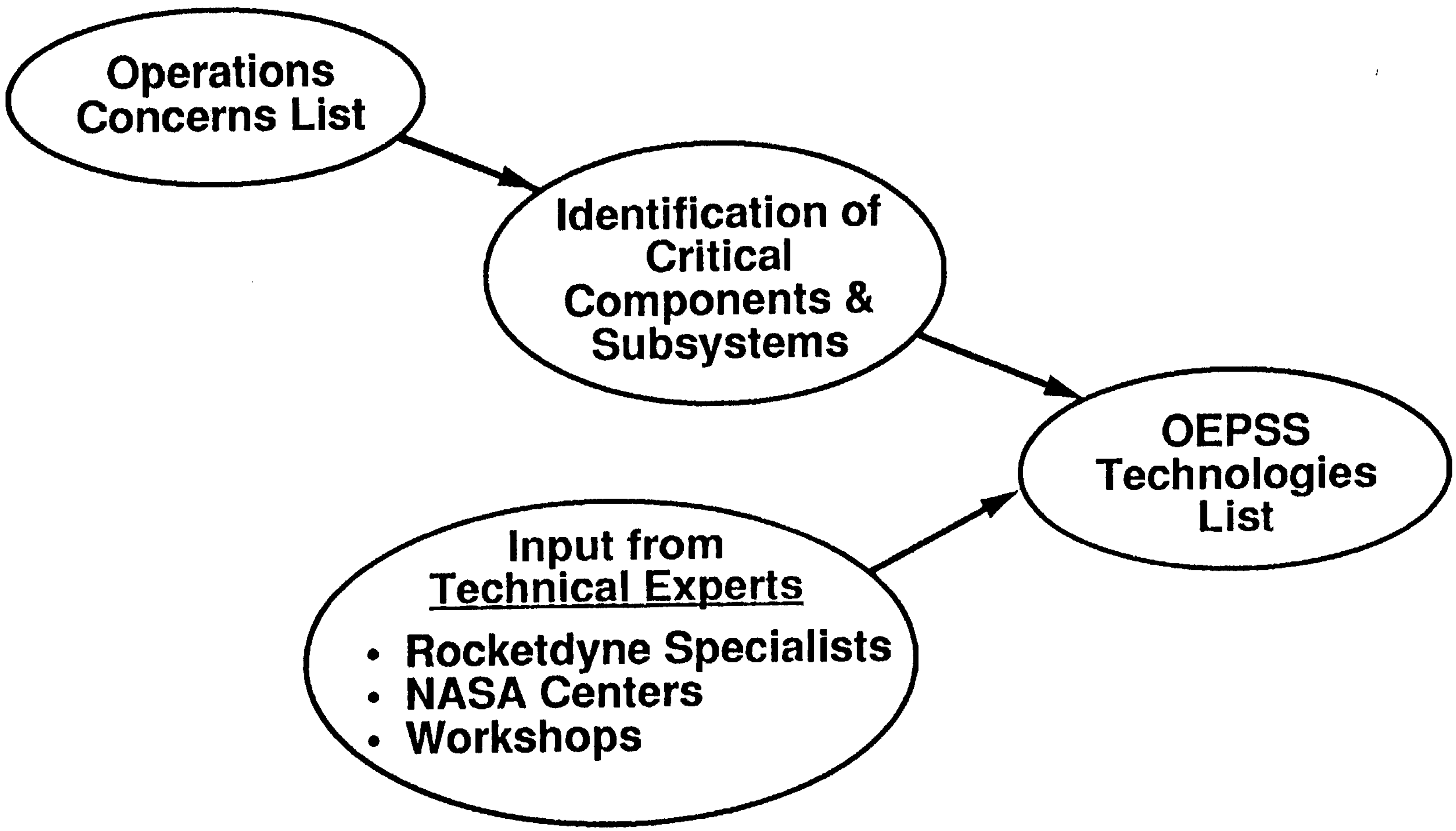
Origin of OEPSS Technologies List



Identified operations technologies that have high payback and are achievable

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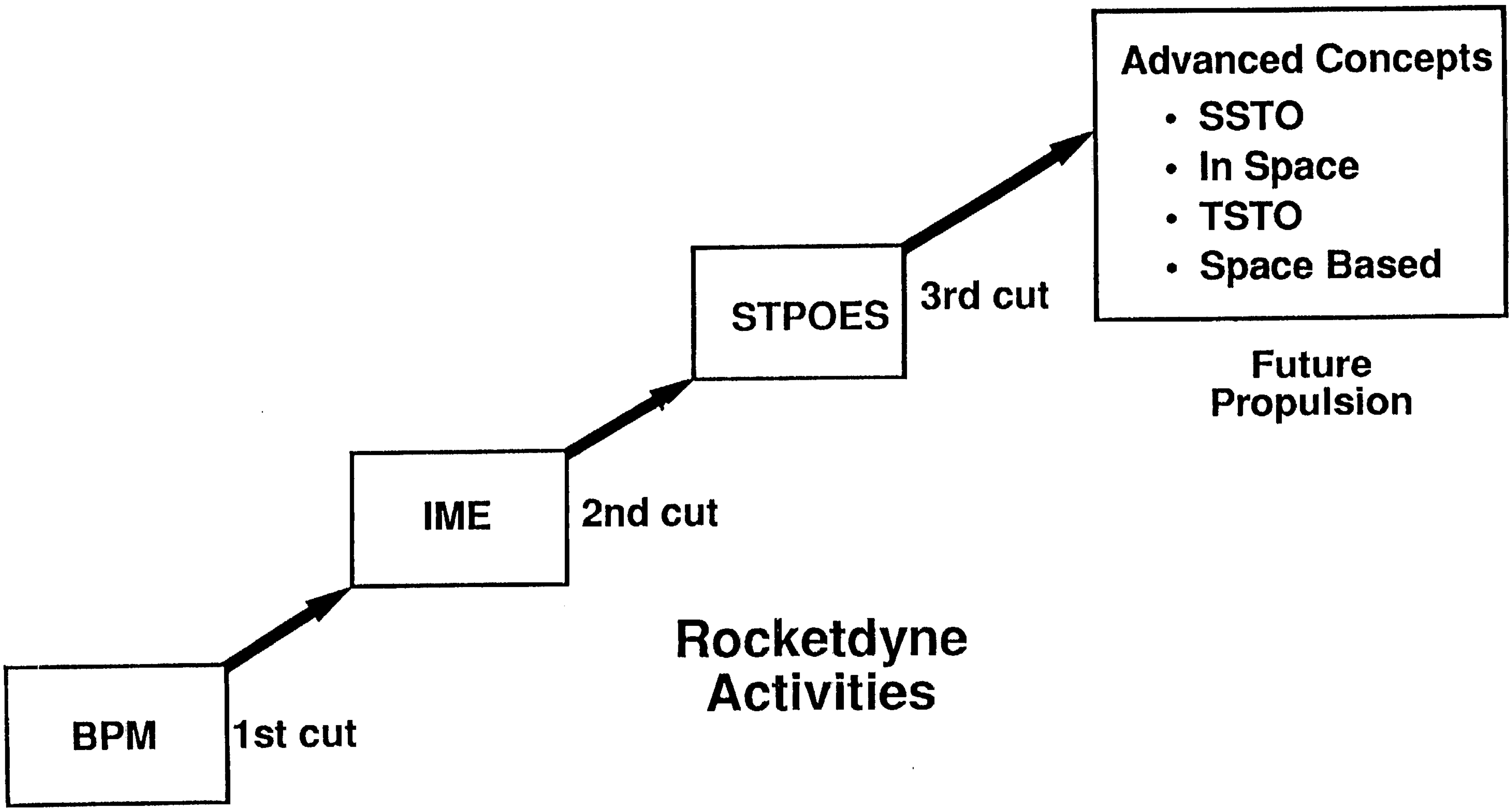
Operations Experience Continuously Applied to all Future Propulsion Concepts

Must be Primary Focus of Conceptual Architectures



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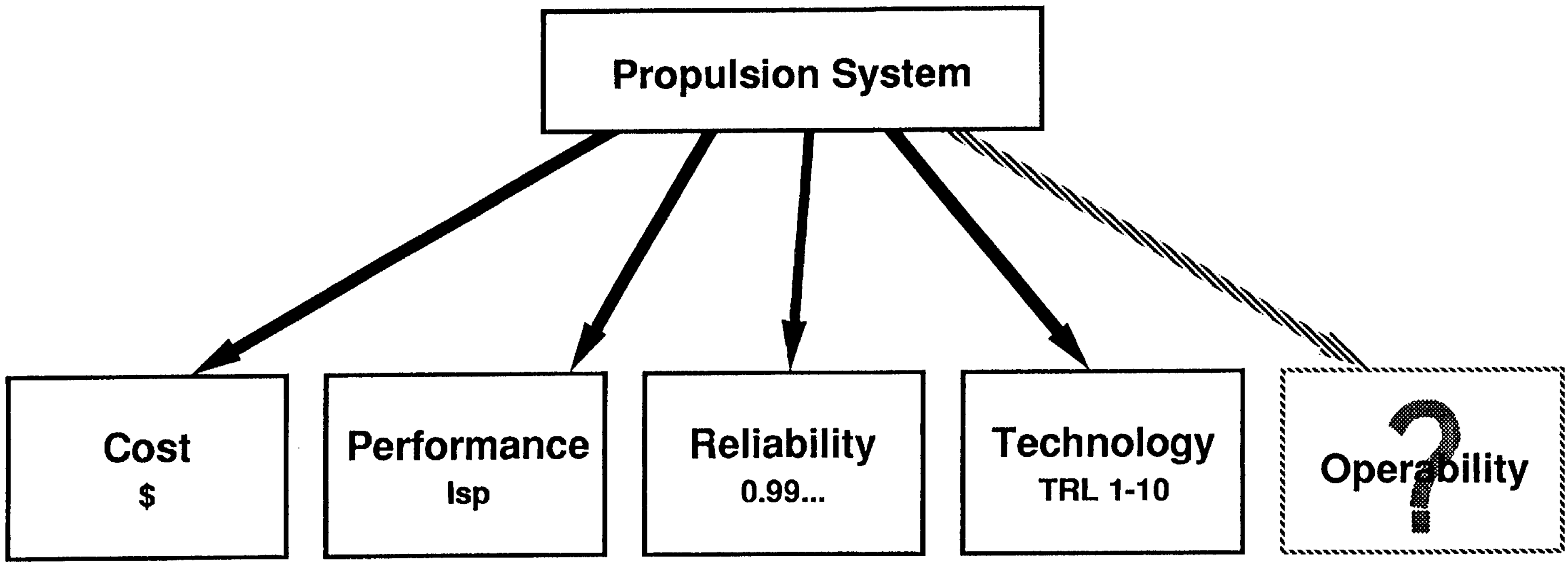
Why is LOI Needed?



Cost, performance, reliability, and technology maturity, are quantified; but the important and critical measurement of operations is missing

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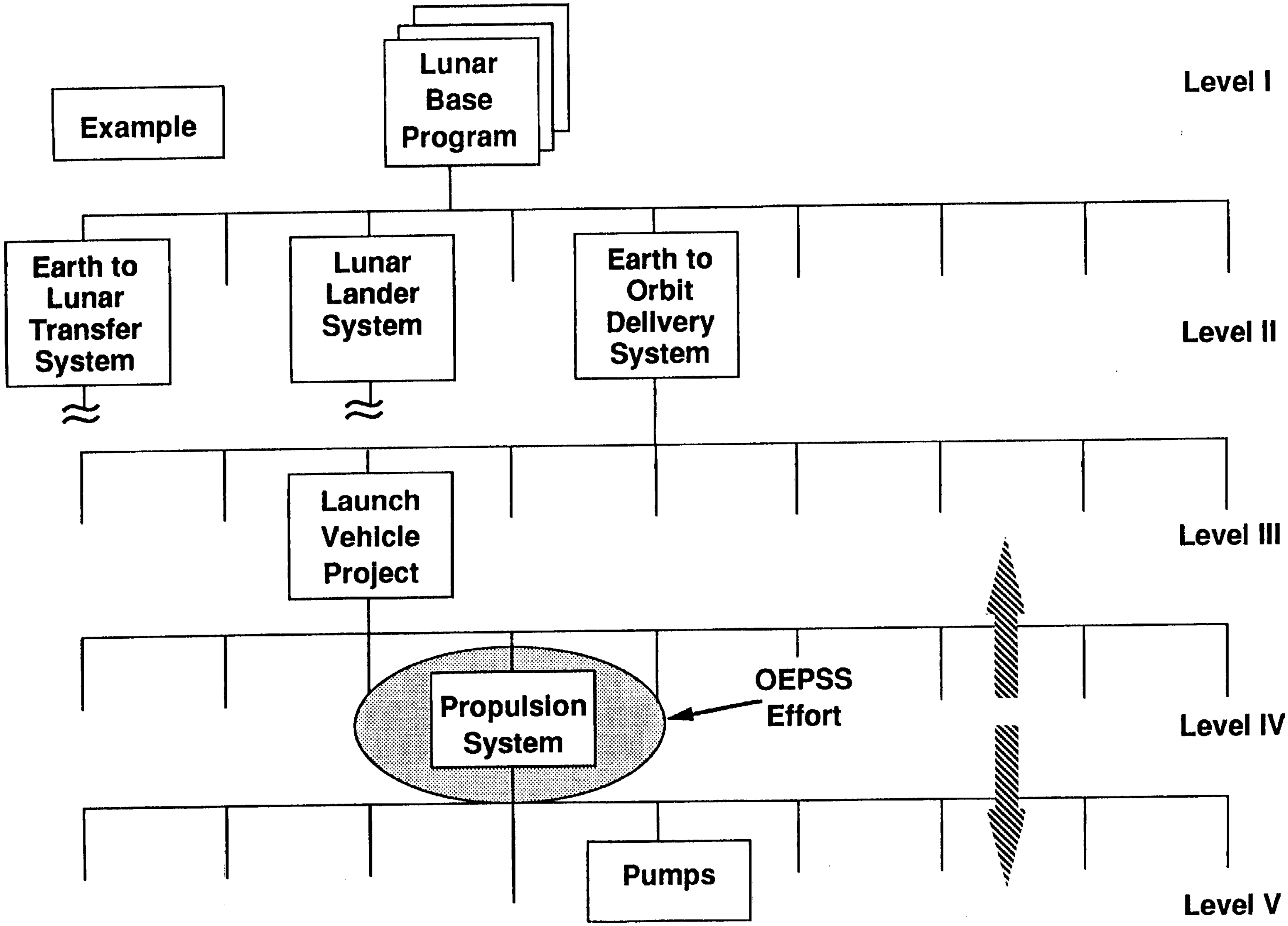
Approach Applies to all Levels of Operations



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OEPSS

Continuing efforts must include--

- Anchor operations concerns with hard data
- Update and expand operations concerns list
- Fully develop the operations indexes
- Continue to identify and promote operations enhancing technologies
- Support operationally efficient propulsion system architectures with operations experience
- Anchor architecture with OEPSS developed dynamic simulation model
- Document operations activities continually through video productions
- Be interactive in the propulsion design cycle

And, most importantly--

Get the message and data out to the aerospace community

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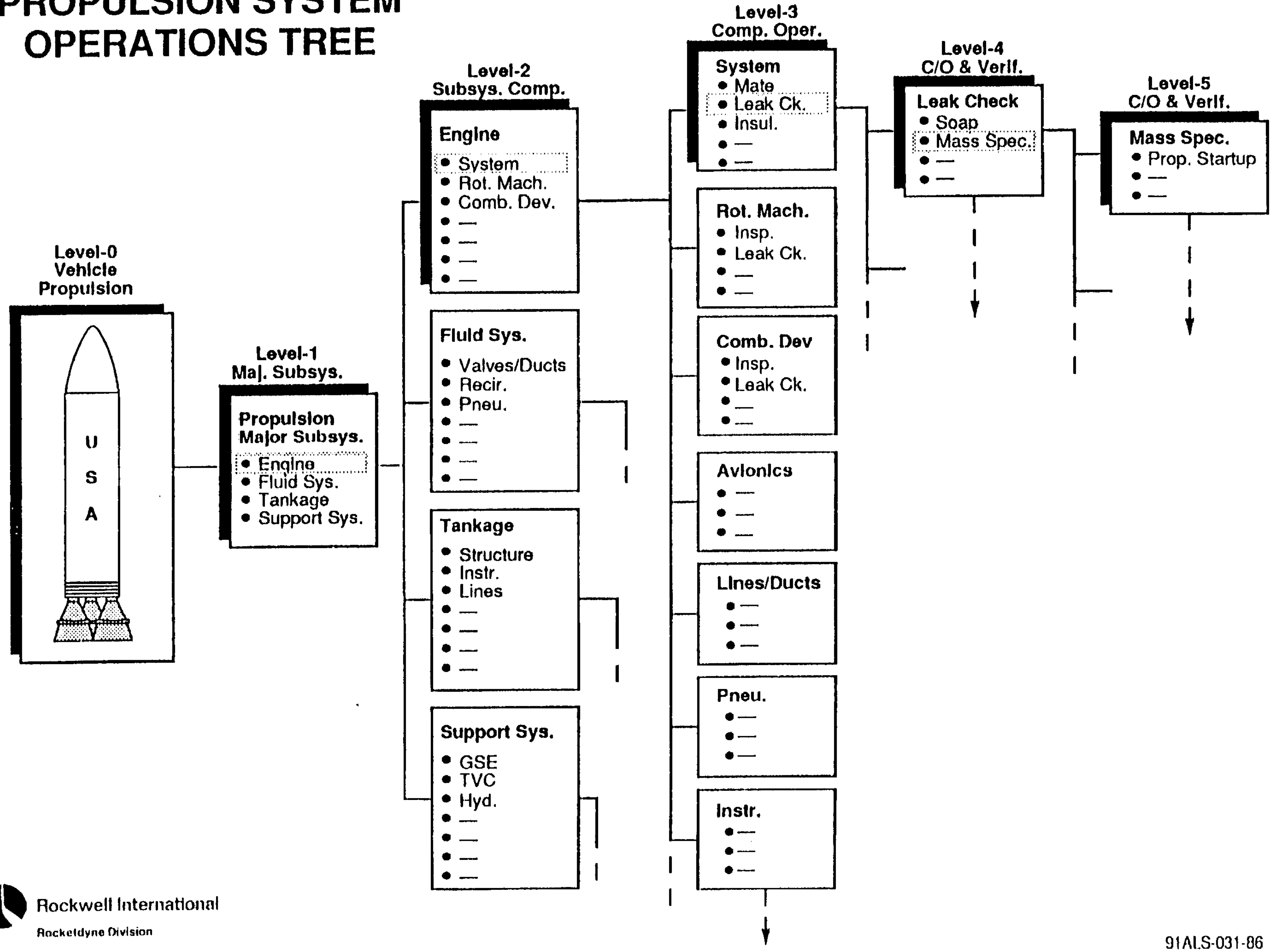
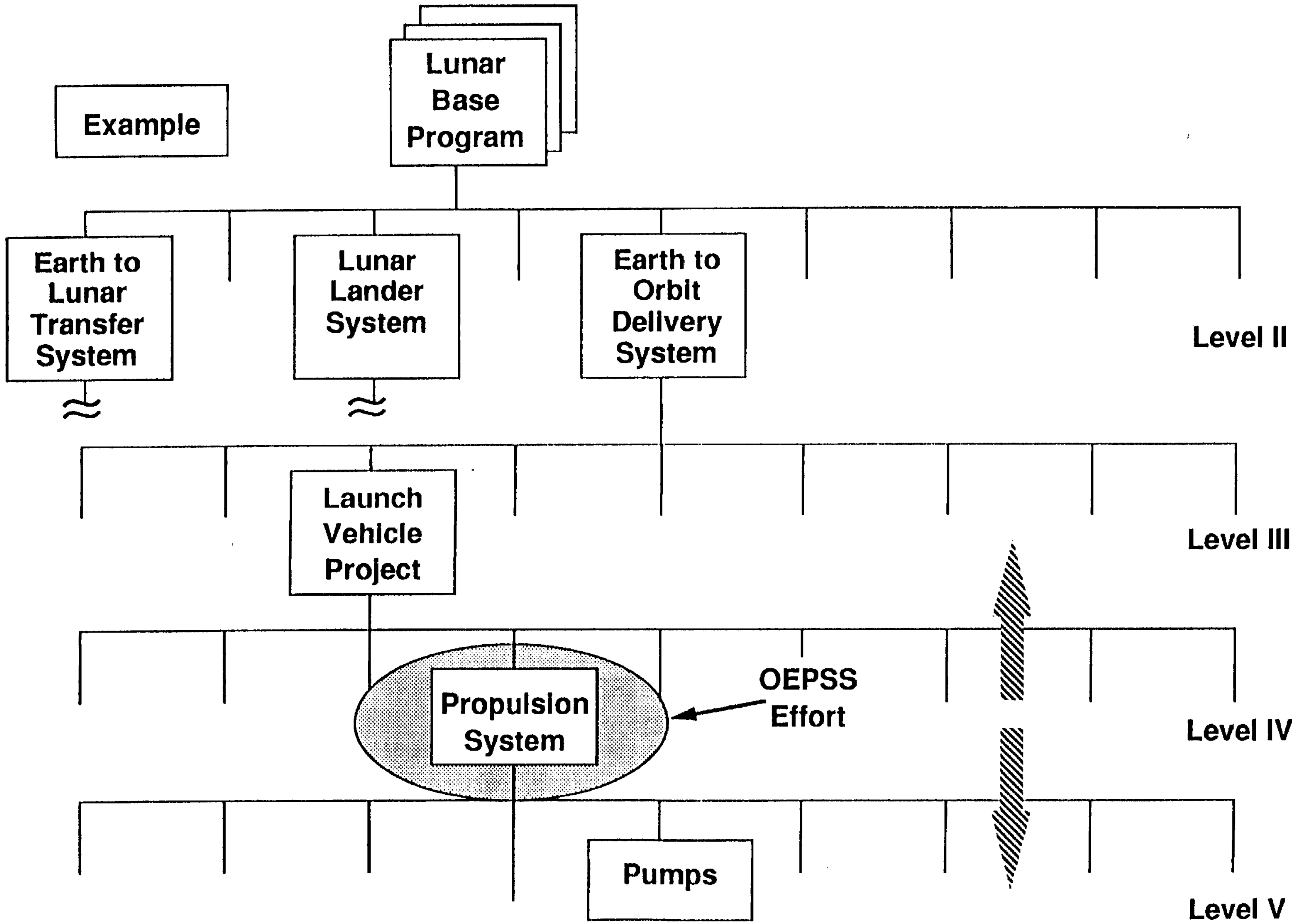
PROPULSION SYSTEM OPERATIONS TREE



Rockwell International
Rocketdyne Division

91ALS-031-86

Approach Applies to all Levels of Operati



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The Foundation of OEPSS

"The launch site operations experience....

...and communicating this experience effectively to the aerospace community"

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Reward of the OEPSS Efforts

Finally, witnessing the gradual acceptance that "Operations" is a key and integral part of the Design-Build-Operate triad and this is the answer to quantum reductions in launch operations costs

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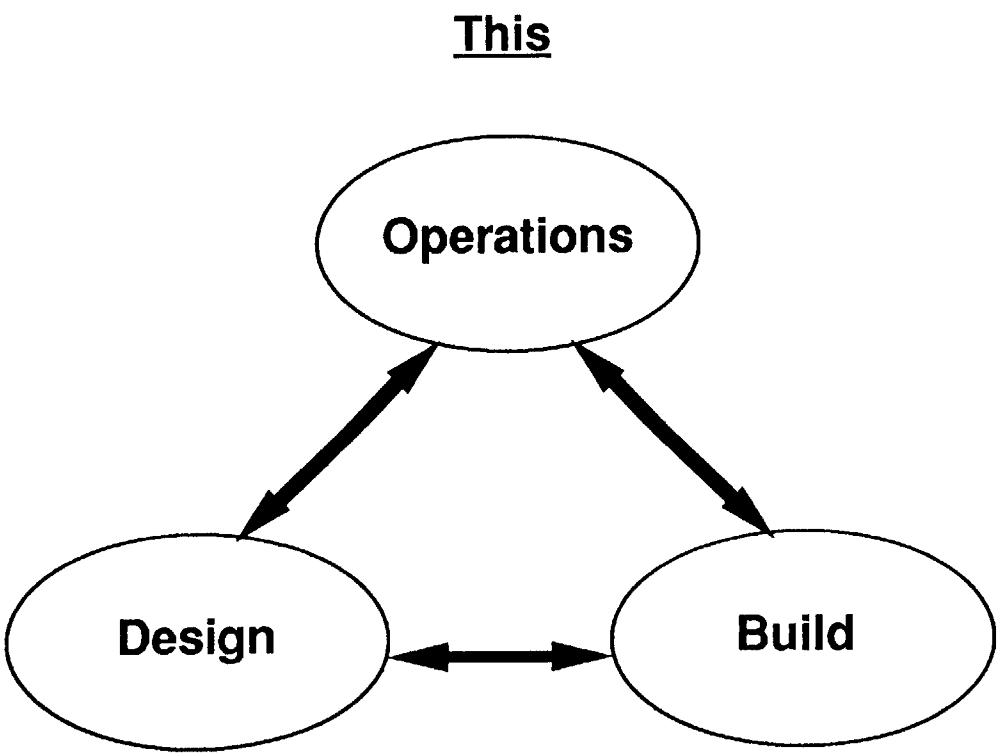
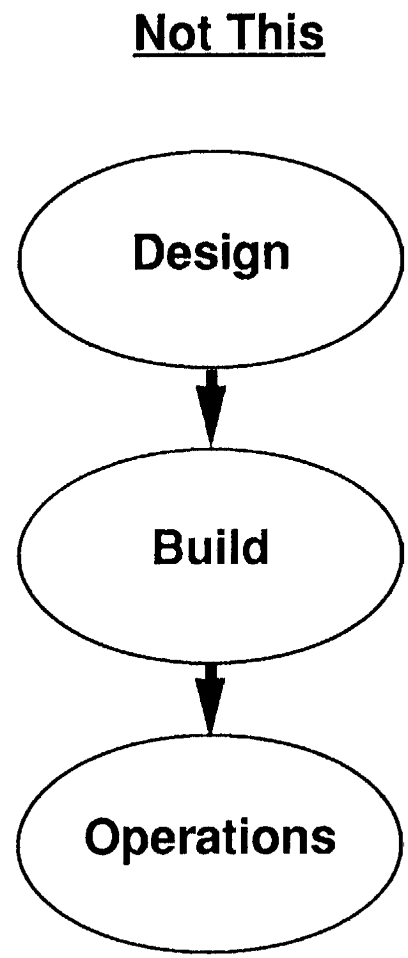
Operations Must Be Interactive



Interactive Design Cycle



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OEPSS Deliverables

- OEPSS Data Books:
  - Executive Summary
    - Vol. 1 Generic Ground Operations Data
    - Vol. 2 Operations Problems
    - Vol. 3 Operations Technology
    - Vol. 4 Design Concepts
    - Vol. 5 Final Briefing (Basic Phase)
    - Vol. 6 Space Transfer Propulsion Operational Efficiency Study
    - Vol. 7 Launch Operations Index Design Features & Options
    - Vol. 8 BPM Engine Start Dynamics and Operation
    - Vol. 9 BPM Preliminary Development Plan
    - Vol. 10 Air Augmented Ejector Rocket

- OEPSS Final Briefing/Report (including viewgraphs)
- LOI Computer Program
- OEPSS Video
- OEPSS Video Script

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OEPSS

The study has made a significant impact...
and
its objectives must continue...

...until operations is a routine and integral part of the design process

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OEPSS
Video Abstract

The OEPSS video film, along with the OEPSS Databooks, provides a data base of current launch experience that will be useful for design of future expendable and reusable launch systems. The focus is on the launch processing of propulsion systems. A brief 15-minute overview of the OEPSS study results is found at the beginning of the film. The remainder of the film discusses in more detail: current ground operations at the Kennedy Space Center; typical operations issues and problems; critical operations technologies; and propulsion architecture concepts that will substantially increase the operational efficiency of booster and space propulsion systems. The impact of system architecture on the launch site and its facility infrastructure is emphasized. Finally, a particularly valuable analytical tool, developed during the OEPSS study, that will provide for the "first time" a quantitative measure of operations efficiency for a propulsion system is described.

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OEPSS in 70 Minutes

A lasting and dynamic overview of the

"Operationally Efficient Propulsion System Study"

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OEPSS Video

The running time and durations of the twelve subject segments covered by the OEPSS video are shown. This will allow any segment (e.g., launch experience, concerns, technology, space operations, etc.) to be quickly located for viewing.

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OEPSS Video

Segment	Title	Time	Total Time	
1	Introduction	3:49	3:49	14:02
2	Overview	10:13	14:02	
3	Launch Experience	3:27	17:29	
4	Operations Problems	10:37	28:06	
5	Operations Technology	5:36	33:42	
6	Design Concepts	14:04	47:46	
7	Launch Site	4:12	51:58	54:45
8	Launch Operations Index	5:33	56:91	
9	Space Operations	3:48	60:39	
10	Workshops	1:44	62:23	
11	Databook	4:14	66:37	
12	Summary (wrap-up)	2:10	68:47	