NASA Contractor Report CR-185289

# Integrated Hydrogen / Oxygen Technology Applied to Auxiliary Propulsion Systems

Final Report

Rockwell International

September, 1990

Prepared for
Lewis Research Center
Under Contract NAS3-25643

National Aeronautics and
Space Administration


(NASA-CR-185289) INTEGRATED HYDROGEN/OXYGEN TECHNOLOGY APPLIED TO AUXILIARY PROPULSION SYSTEMS Final Report, Sep. 1990 (Rockwell International Corp.) 104 p CSCL 21H

N91-10116

Unclas

G3/20 0310082

**NASA** National Aeronautics and Space Administration

# Report Documentation Page

| | | |
|---|---|---|
| 1. Report No. NASA CR-185289 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle Integrated Hydrogen/Oxygen Technology Applied to Auxiliary Propulsion Systems | | 5. Report Date October, 1990 |
| | | 6. Performing Organization Code |
| 7. Author(s) David L. Gerhardt | | 8. Performing Organization Report No. None |
| | | 10. Work Unit No. 506-42-31 |
| 9. Performing Organization Name and Address Rockwell International Space Transportation Systems Division 12214 Lakewood Blvd. Downey, CA 90241 | | 11. Contract or Grant No. NAS3-25643 |
| | | 13. Type of Report and Period Covered Contractor Report Final |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191 | | 14. Sponsoring Agency Code |

15. Supplementary Notes

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16. Abstract The integration of launch and auxiliary propulsion systems (APS s) to provide specific benefits has been a design goal on many past and current launch vehicles. However, past studies of integrated hydrogen/oxygen propulsion systems emphasized the achievement of high performance over low cost and operability. The purpose of the IHOT study was to determine if the vehicle/mission needs and technology of the 1990's support development of an all cryogenic $H_2/O_2$ system. The IHOT study resulted in the definition of three APS concepts; two cryogenic IAPS, and a third concept utilizing hypergolic propellants.

All systems were subject to the same criteria, of minimizing cost and the ground operations necessary for processing. Imposing these criteria on the hypergolic system for AMLS resulted in a system much more competitive with the IAPS concepts than the current Shuttle system. Many of the processing problems associated with the Shuttle result from the pad-clear, serial operations which could be minimized, or designed out of a new hypergolic concept.

One of the key study results was the conclusion that the LCC differences between IAPS and hypergolic systems were not as significant as had been anticipated.

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|---|---|
| 17. Key Words (Suggested by Author(s)) Integrated Hydrogen/Oxygen Systems Auxiliary Propulsion Systems Hydrogen/Oxygen Propulsion Operational Efficiency | 18. Distribution Statement Unclassified-Unlimited |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No of pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 104 | A06 |

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

## 1. FOREWORD

This report constitutes the final documentation of the Integrated Hydrogen / Oxygen Technology contract (NAS3-25643). This final report is submitted by the Space Transportation Systems Division and Rocketdyne Division of Rockwell International to the National Aeronautics and Space Administration, Lewis Research Center, Cleveland Ohio.

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## 3. SUMMARY

### *Objectives and Scope:*

The integration of launch and auxiliary propulsion systems (APS's) to provide specific benefits has been a design goal on many past and current launch vehicles. However, past studies of integrated hydrogen/oxygen propulsion systems emphasized the achievement of high performance over low cost and operability. The purpose of the IHOT study was to determine if the vehicle/mission needs and technology of the 1990's support development of an all cryogenic $H_2/O_2$ system. In order to accomplish this, IHOT adopted the approach of designing integrated auxiliary propulsion systems (IAPS) for a representative manned vehicle; the Advanced Manned Launch System (AMLS). The primary objectives of the study were to develop IAPS concepts which appeared to offer viable alternatives to state-of-the-art (ie, hypergolic, or earth-storable) APS approaches. It was realized early that the scope of the IHOT effort would have to be well-focused to be consistent with program funding constraints. This precluded an assessment of propellant scavenging, or integration of the APS with additional subsystems (such as power systems, and life support).

At the top level, all prospective concepts were to be compared and evaluated based upon their relative cost and operability. This concern resulted from experience with the current Shuttle program, where the design of a majority of the subsystems were driven by peak performance or annual funding constraints. Concern for simplified operations or low life cycle cost (LCC) were not the primary design discriminators.

In addition, IHOT was to establish the viability of IAPS concepts, and quantify their specific benefits compared to an hypergolic alternative. The intent was not to provide a single definitive "answer" for a specific application, but rather to provide information to quantify the features and requirements of integrated concepts. The specific IHOT program objectives were as follows:

- Define operationally efficient APS concepts for two $H_2/O_2$ systems and one hypergolic system.
- Compare the three APS concepts in terms of LCC, operational efficiency, and performance.
- Define the technologies which must be developed in order to assure the viability of the above concepts; and enable or enhance the cost, operational, and performance objectives.

The concepts developed were also to have general applicability to a range of manned spacecraft, and not be limited solely to AMLS.

### *Key Study Results:*

The IHOT study resulted in the definition of three APS concepts; two cryogenic IAPS, and a third concept utilizing hypergolic propellants. The first of the $H_2/O_2$ IAPS concepts incorporates a high-pressure gaseous RCS (filled during ascent from the main propulsion system), operating at a mixture ratio of 16:1. The OMS for this concept is a more conventional pressure-fed liquid system. The second $H_2/O_2$ IAPS utilizes a pressure-fed, liquid RCS with recirculation pumps and a pump-fed liquid $H_2/O_2$ OMS. The hypergolic APS concept utilizes a conventional pressure-fed, MMH/NTO RCS and OMS.

All systems were subject to the same criteria, of minimizing cost and the ground operations necessary for processing. Imposing these criteria on the hypergolic system for AMLS resulted in a system much more competitive with the IAPS concepts than the current Shuttle system. Many of the processing problems associated with the Shuttle result from the pad-clear, serial operations which could be minimized, or designed out of a new hypergolic concept.

One of the key study results was the conclusion that the life cycle cost differences between IAPS and hypergolic systems were not as significant as had been anticipated. This resulted from the same emphasis on operational efficiency for all concepts in the early design process. Significant reductions in the cost of ground operations were achieved for all three concepts by designing around the need for serial APS operations, particularly at the launch pad. The dominant factor in LCC then became the combined development costs of the RCS and OMS engines. The hypergolic concept LCC were comparable with the IAPS concept which incorporated a gaseous $H_2/O_2$ RCS and a pressure-fed liquid OMS. The all-liquid IAPS concept had significantly higher LCC due to the complexity of liquid injection RCS, and pump-fed OMS engines. The loaded weight of the all-liquid IAPS was 8000 lb lower than the hypergolic concept, and nearly 9000 lb less than the other IAPS concept. This should mitigate the subsystem LCC impact in a complete vehicle trade, where lower system weight translates into a payload (and therefore, cost) benefit. The scope of the IHOT study precluded the inclusion of these vehicle-level cost trades.

The specific technology requirements necessary to support the selected APS concepts were also identified. Implicit in all three concepts is the development of BITE (built-in-test-equipment) and the attendant expert systems necessary to allow dramatic reduction in ground operations cost. Without automation of ground operations and a "cultural change" in the attitude toward launch processing, IAPS concepts will not significantly alter the cost and complexity of auxiliary propulsion systems. Other key technology requirements identified include high mixture ratio thrusters for gaseous RCS applications, and liquid injection RCS thrusters for the all-liquid IAPS concept.

However, the need for IAPS is being driven by more than just cost and operability. Future restrictions on the use and transport of hypergolic propellants may force the development of new systems even without the need for large cost/operability benefits. IHOT results indicate that new IAPS systems are possible that are competitive with hypergolics regarding cost, minimize ground operations, and eliminate the toxicity concerns of current hypergolic propellants.

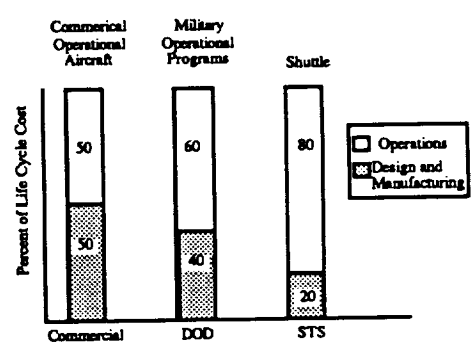
| PROGRAM | DESCRIPTION | OUTCOME | IAPS USED? |
|---|---|---|---|
| Shuttle, Phase A/B (Rockwell studies) | Integrated; Liquid OMS, Gaseous ACPS, $LO_2/LH_2$ propellants | • Potential OPS cost savings<br>• Potential performance gains<br>• Funding & DDT&E forced selection of hypergolic system | No |
| | Integrated; Main Propulsion & OMS System, $LO_2/LH_2$ propellants | • SSME's inefficient for OMS<br>• Poor cryo storage in MPS feed system | No |
| Shuttle Evolution (Rockwell Studies) | Integrated; OMS &RCS tankage, hypergolic propellants | • Work in progress<br>• Projected results<br>• Enhanced turnaround<br>• Improved performance | No |
| Advanced Launch System (Phase 1 Air Force Contract) | Partial Integration; cold gas blowdown APS using core ullage | • Viable for low-impulse attitude applications<br>• ALS APS requirement not well defined | No |
| | Partial Integration; GO2/GH2 bipropellants APS | • Higher impulse (over cold gas)<br>• Cost incompatible with ALS objectives | No |
| | Integrated; OMS & ACS, $LO_2/LH_2$ supplied by core vehicle | • Simplified servicing<br>• Cost incompatible with ALS objectives | No |
| Space Tug | Integrated; common MPS & APS tankage, $LO_2/LH_2$ propellants | • Small (5%) payload increase<br>• Additional abort contingency<br>• Propellant allocations interchangeable | No |
| Peacekeeper, Stage IV | Integrated; axial & attitude control systems, NTO/MMH propellants | • Concept selected and built | Yes |

**Historical Sample of Past Systems Considered for IAPS**

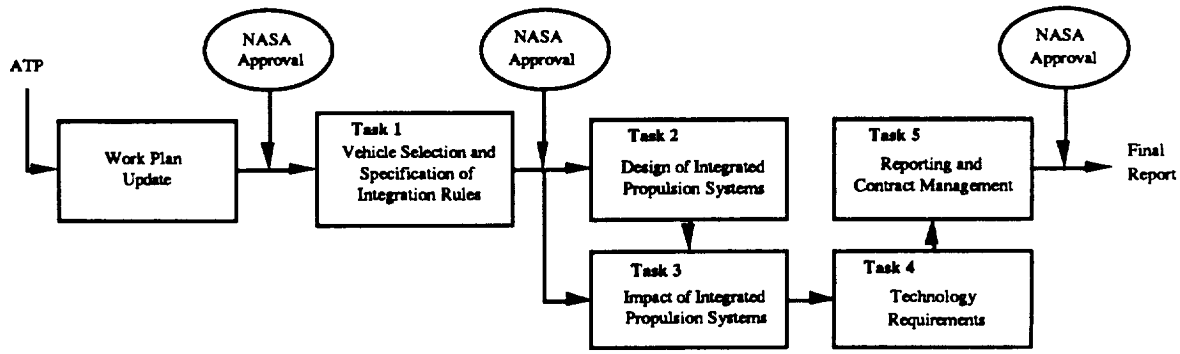
## 4. INTRODUCTION

Integrated propulsion systems, incorporating the functional or physical interconnection of fluid systems at some level to achieve desired systems benefits, has been an objective of many study programs. The table above provides a representative historical sample of systems considered for vehicles ranging from the original Space Shuttle design thru the Peacekeeper (Stage IV).

Typical applications of integrated systems involved the main propulsion system (MPS), auxiliary propulsion system (APS), environmental control & life support system (ECLSS), fuel cells, power systems, and payloads. However, the primary objectives of past attempts at integration have focused on three areas; performance, packaging, and mass fraction. Life cycle cost, and efficient ground operations were typically secondary considerations. As indicated in the following figure, an emphasis on operability will be required in future vehicles to reverse trends towards increased costs for maintenance and operations.




**Operations Cost Reduction Is a Major Element in New Design Efforts**




**IHOT Contract Study Plan**

In-house studies at the NASA/Lewis Research Center[1,2] led to the formulation of the IHOT contract. The study was not intended to provide definitive answers to all possible aspects of IAPS design. Rather, the scope of the IHOT effort was to be sufficient to drive out the viability of specific concepts, and to establish a quantitative comparison of their cost and operational benefits. The approach adopted to accomplish this objective is summarized in the figure above. The top-level approach was to first select a vehicle/mission combination which offered the potential for significant benefits through utilization of integrated systems. Representative APS concepts would be developed for several integrated, and conventional (or "state-of-the-art", hypergolic) concepts. These concepts would be compared based upon their LCC, ground operations, performance, and mass properties.

As indicated, one of the important aspects of the IHOT contract is the definition of the enabling technology requirements necessary to support the development of IHOT systems. This particular task is intended to establish the paths for future research, and indicate the time-phased milestones which must be met.

The IHOT contract has built upon the experience of Shuttle and other applicable studies to assess the feasibility of integrated hydrogen/oxygen propulsion systems. In doing so, the emphasis has been placed on cost and operability, rather than simply performance. This assures that the results will be pertinent to the next generation of manned launch systems.

[1]Weight Savings in Aerospace Vehicles Through Propellant Scavenging, Steven J. Schneider and Brian D. Reed, NASA Technical Memorandum 100900, May 23, 1988

[2]Advanced APS Impacts on Vehicle Payloads, Steven J. Schneider and Brian D. Reed, NASA Technical Memorandum 102086, May 23, 1989

# 5. IHOT STUDY RESULTS

This section of the IHOT Final Report provides a detailed discussion of the contract study results. The first topic concerns a description of how a reference vehicle and mission were selected. In conjunction with the definition of the study groundrules, this established the context for all subsequent work.

The second part of the study described below contains a description of how the initial down-select process was performed on potential IAPS concepts. The criteria used, alternatives considered, and results of this initial screening are discussed.

Following the selection of two IAPS and one hypergolic concept, a detailed evaluation was performed. The groundrules and assumptions of the evaluation are discussed, each concept is described in detail (including mass properties, volurme, etc.), and the relative sensitivity of each is indicated regarding changes in mission requirements.

The absolute, and relative benefits of the selected IAPS configurations are described in the fourth section. Specifically, the operational impacts of each of the concepts are compared, and then included in an evaluation of the life-cycle-costs associated with each system.

Finally, technology requirements are identified which must be addressed to prepare for the next generation of manned spacecraft. Requirements are broken out as either enabling, or enhancing. For technologies identified as enabling (or required) for IAPS, a timeline is identified to provide a clear overview of the necessary development process.

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## 5.1. Vehicle and Mission Selection

### 5.1.1. Study Groundrules

In order to assure a consistent approach to the IHOT study effort, a significant effort was undertaken in the early phases to establish a set of study groundrules. This codification of guidelines accomplished several important objectives:

- Assured emphasis on cost and ground operations
- Brought in representatives of these functions at the formative stages of the design process
- Provided a comprehensive systems approach to the vehicle, mission, and concept selection process

The groundrules (listed in tabular form on the following page) result in large part from the "Lessons Learned"[3] in the Shuttle and Apollo programs. The Phase 1 Advanced Launch System contract also was responsible for the development of a significant body of work regarding design practice to minimize cost and operations on new launch vehicles. In addition, the work and recommendations of the Operationally Efficient Propulsion System (OEPS) contract[4] were reviewed and considered in establishing the IHOT guidelines.

### 5.1.2. Reference Vehicle

The IHOT contract was to investigate the viability of integrated hydrogen/oxygen auxiliary propulsion systems as applied to manned, reusable vehicles. It was also desired to allow the potential of applicability to other emerging programs, such as Lunar/Mars. Reference vehicle selection criteria are summarized as follows:

- $LO_2/LH_2$ main propulsion system
- Reusable - recover added system cost
- Require specific performance, operations, & mission requirements data (data availability)
- Vehicle must allow incorporation of IAPS without major redesign
- Must employ sufficient $LO_2/LH_2$ systems to benefit from integration
- Vehicle IOC must allow time for sufficient DDT&E

[3]Space Shuttle Directions, Advanced Programs Office, June 1986, NASA, Lyndon B. Johnson Space Center

[4]Operationally Efficient Propulsion System Study, NASA, J.F, Kennedy Space Center, contract NAS 10-11568, May 1989

| | RULES | DISCUSSION |
|---|---|---|
| CONCEPT DESIGN | • Make best use of prior studies. Leverage emerging technologies to achieve practical concepts.<br><br>• All concepts shall provide for safe vehicle return and abort | Innovations/technologies which could mitigate problems with cryo IAPS include:<br>• Advanced conditioning techniques<br>• Elimination of propellant acquisition<br>• Active controls (smart sensors)<br>• Materials (high temperature thrusters, advanced tankage,..)<br>Designs must consider:<br>• Tank capacities and margins<br>• Redundancy/ failure criteria<br>• Responsiveness |
| MISSION/ FLIGHT OPER'NS | • Propellant margins assigned to a system cannot be used as primary source for other propulsion elements<br><br>• IAPS configurations shall not add mission operational complexity, criticality, or compromise mission integrity | Margins are calculated against uncertainties. If they are reduced because of reduced uncertainties, this is unrelated to system integration.<br>• Combining margins within integrated systems might increase usable reserves (requires use for mutually exclusive contingencies).<br>Concepts must be noncritical with respect to:<br>• Restarts • Maneuvers needed<br>• Thermal control • Mission Duration<br>• Mission flexibility • Req'd crew/ground involvem'nt |
| GROUND OPER'NS | • Concepts shall reflect modern operations technologies<br>• Wherever possible, concepts shall minimize/eliminate blocks of operations, particularly sequential<br><br>• Alternative designs shall be assessed for operability and maintainability | Design of systems will include early consideration of built-in test & health monitoring, automated leak check, etc.<br><br>Features which make integrated systems pay off in operations include:<br>• Reduce umbilical connections (ideally, one pair for propellant)<br>• Eliminate toxic, corrosive, carcinogenic hypergolics<br>• Combine hazardous operations into concurrent blocks<br>Inherently operable, maintainable design features include:<br>• Modularity<br>• Forgiving, noncritical designs<br>• Ease, or elimination of, onboard purge, cleaning, drying, and/or inspection |
| COST ESTN | • IAPS concepts & integ'd hydrogen/oxygen tech's shall be assessed against their relative effects on cost<br>• Costs in various categories shall be estimated in a manner which expedites trades & comparisons | Other study rules will ensure that the concepts studied will meet the mission needs. Cost provides the means to assess relative concept benefits<br><br>Cost categories used will cut across the entire AMLS life cycle:<br>• DDT&E<br>• Production<br>• Recurring operations<br>Cost elements used will be common to currently accepted work breakdown structures:<br>• Research and Technology<br>• Development and test<br>• Hardware and software<br>• Mission and ground operations |

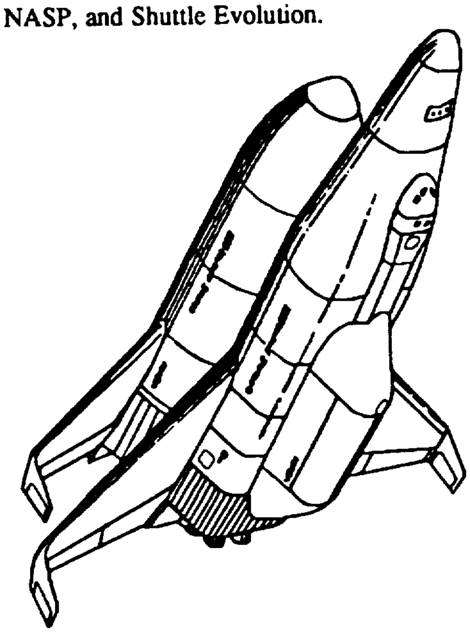
**Top Level Study Rules and Guidelines**

Vehicles considered for selection as the IHOT baseline included the Advanced Manned Launch System (AMLS), Space Transportation System "Evolution" vehicle, Shuttle C, the Advanced Launch System (ALS), National AeroSpace Plane (NASP), NASP Derived Vehicle (NDV), and the Personnel Launch System (PLS). The following table summarizes the lack of compliance of various vehicles with the study requirements:

| Criteria | Vehicles *Not* Applicable |
|---|---|
| Earth-to-Orbit | PLS(depending on ELV) |
| Maneuver Reqt's | Shuttle-C, ALS |
| IOC/Need Date | STS Evolution, Shuttle-C |
| $LH_2/LO_2$ MPS | PLS |
| Reusable | Shuttle-C (?), ALS(?), PLS(?) |
| Data availability? | NASP, NDV, PLS |
| Config. adaptable? | STS Evolution, PLS (depending on ELV) |
| Integrable systems? | PLS |

**Vehicles Not Meeting IHOT Criteria**

The AMLS was selected as the reference vehicle for the study, based upon the fact that it met the vehicle criteria summarized above, had adequate system/mission definition, and was consistent with the IHOT study resources. It is also felt that many of the conclusions drawn from the AMLS selection will also have applicability to NASP, and Shuttle Evolution.



**Advanced Manned Launch System**

5.1.3. Reference Mission

Several factors shaped the selection of the IHOT reference mission. The primary mission objective was to be earth-to-orbit applications. In addition, substantial on-orbit maneuvering was desired in order to assure justification of the need for an IAPS. The mission duration should also be long enough to require substantial APS usage, while still being short enough to allow "practical" application of cryo storage. Finally, the mission need date must be compatible with the technology maturation requirements and the vehicle IOC. Two primary missions are currently identified for the AMLS vehicle:

| Mission | Characteristics |
|---|---|
| Space Station Resupply | • 20KLb payload<br>• 262 NMi<br>• 28.5 Degrees |
| Polar Platform Servicing | • 12KLb payload<br>• 150 NMi<br>• 98 Degrees |

**AMLS Mission Definition**

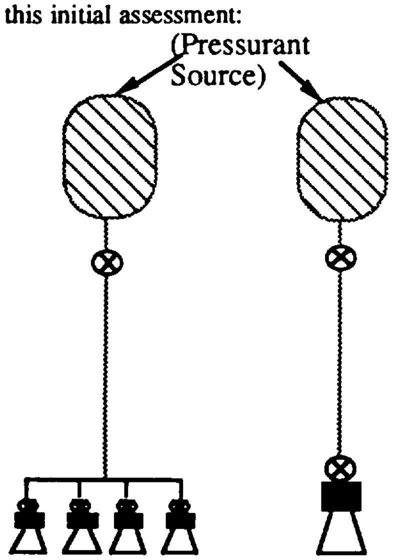
The Space Station Resupply was selected, based upon meeting the mission criteria, and the availability of the data[5]. Mission $\Delta V$ requirements were established based upon the referenced NASA mass properties/mission data, combined with a Rockwell assessment of APS requirements. This included nominal mission requirements, as well as allowance for abort and failure criteria.

[5] Shuttle II Status, Del Freeman, NASA Langley Research Center, August 24, 1988; Shuttle II Desired System and Operational Characteristics, Theodore A. Talay, NASA Langley Research Center, September 22, 1987; Shuttle II, The Langley Research Center Study, Vehicle Analysis Branch

## 5.2. Initial Concept Selection

### 5.2.1. Selection Criteria Definition

The scope, and objectives of the IHOT contract made it necessary to survey a large number of potential IAPS concepts with widely varying characteristics. In order to accomplish this within the study resources, the initial down-select of concepts for the AMLS vehicle was performed in a manner so as to assess the relative cost, operational, and performance characteristics for a simplified representation of each system. Based upon the results of this ranking, three systems (two cryo IAPS, one SOA) were selected for subsequent detailed evaluation. The following figure illustrates the simplified "APS model" used for this initial assessment:




**Functional Model for Initial Evaluation**

The following sections describe how the initial down-select process was accomplished.

#### *5.2.1.1. Cost*

The costs for the initial down-selection were evaluated based upon three specific contributors.

- Development of Components
- Production Costs
- Operations & Support

For each component in the representative functional model, an evaluation was made which resulted in a ranking of 1 - 5 (5 best) for each element of cost. These rankings were weighted equally, and summed for the overall cost evaluation. The result was a representative cost assessment which included the effects of increased cost for development of pumps, sophisticated engines, and other components. Production costs were assessed based on the number of components required, size, type, and complexity. Operations support was assessed based upon the number of man-hours necessary for the specific functional activities required of each concept.

#### *5.2.1.2. Ground Operations*

Evaluation of ground operations for each prospective IHOT concept included four specific areas:

- Runway operations
- Turnaround processing
- Launch pad servicing
- Return-to-flight

The manpower estimates for runway operations include non-productive time waiting for orbiter landing, safety checks prior to vehicle access, crew removal and transport of the orbiter to the processing facility. It is assumed that only the aft RCS will remain active through the landing approach phase of the mission. All other hydrogen/oxygen systems will be inerted on orbit/transition (OMS, FRCS, MPS, interconnect lines...).

Turnaround testing will test/evaluate only those components not used in flight. BITE (built-in-test-equipment) will provide flight test data analysis for anomaly identification. It will also acquire and evaluate the ground turnaround test data, accounting for approximately 70% of the test support required. Included in this would be most internal/external leakage checks, instrumentation checks, wiring validation, heater checks, moisture sampling of gas systems, and evaluation of valve signatures & timing. Helium tanks have factors of safety (4X) that allow pressurization to flight loads at the orbiter processing facility (OPF) *prior* to transfer to the pad. SOA hypergolic propellants will not be loaded at the pad, but rather will require the removal of forward and aft modules which will be transported to a dedicated facility for all servicing operations and return-to-flight testing.

Launch pad servicing will be restricted to fill, vent, and draining of cryo (liquid) hydrogen and oxygen only; for all concepts. This allows elimination of dedicated access and GSE structures at the pad.

If a vehicle is withdrawn from normal flight operations and must be processed for return-to-flight from standdown, it is assumed that all components will be tested and evaluated. All electrical equipment and most instrumentation will be evaluated by BITE. GSE will be required for some component testing, and will be mimimized by utilization of BITE.

With the above functional requirements in mind, each of the four major segments of ground operations were evaluated for each concept. The evaluation of each segment included a weighted assessment of the relative GSE impact, labor impact, indirect costs, and base & range support. The sum of all of these contributors allowed a comparative analysis of the ground operations impacts of the different IHOT concepts

##### 5.2.1.3. *Other Criteria*

In addition to criteria for evaluating cost and operational effectiveness, each concept was evaluated to identify any performance characteristics or technical risk concerns which might disqualify it from further consideration. These criteria included system complexity, power requirements, propellant/pressurant volume or mass constraints, and a range of technology issues which might be discriminators.

#### 5.2.2. Viable Alternatives

The following table presents the key variables which contributed to the definition of prospective IHOT IAPS concepts:

| Storage/ Transfer Fluid Phase | Transfer Mechanism | Conditioning Requirements |
|---|---|---|
| Gas<br>Liquid<br>Supercritical | Pump<br>Pressure<br>Compressor | None<br>Heat Exch'ger<br>Liquid Cond'g<br>Recirculation |

**Alternative Elements in IAPS Concepts**

Consideration of the AMLS vehicle constraints, the cost and operational criteria led to the development of thirteen concepts for evaluation. These concepts are summarized in Appendix A.

| **Functional Group** | *Gaseous Storage, Primary & Vernier RCS* | *Liquid Storage, Primary & Vernier RCS* | *Liquid Storage, Gaseous Primary & Vernier RCS* | *Liquid Storage, Supercritical Transfer Primary & Vernier RCS* | *Supercritical Storage & Transfer to Primary & Vernier RCS* |
|---|---|---|---|---|---|
| **Optional Config'ns** | (1) Recharge from OMS/MPS, blowdown | (2) 2-phase engines, no thermal cond'g, potential large MR/thrust excursions<br>(3) No two phase flow, but requires overboard bleed<br>(4) No two phase flow, propellant recirc with electric pumps | (5) Hi-pressure storage & pressure fed liquid transfer to HX<br>(6) Low-press. storage, elec. pump fed liquid transfer to HX<br>(7) Low-press. storage, gas-turbine pump fed to HX | (8) Potential large MR/thrust variations, no thermal cond'g<br>(9) Feed system recirculation, with bleed to tank<br>(10) Electrically driven feed system recirc pumps | (11) Potential large MR/thrust variations, no thermal cond'g<br>(12) Electrically driven recirc pumps |
| **Potential OMS/RCS Impacts** | *Requires separate OMS tankage* | *Good candidates for common OMS/RCS tankage* | *(5) probably separate.*<br>*(6),(7) possibly common* | *Good candidates for common OMS/RCS tankage* | *Requires separate OMS tankage* |

**Summary of Initial IAPS System Characteristics**

### 5.2.3. Results of Initial Screening

The results of the initial screening of IHOT concepts are shown in the table below. Concepts were selected based upon their LCC, simplicity, and minimization of technical risk concerns such as two-phase flow at thruster inlets. The selected IAPS concepts were Options 1 (gaseous RCS, liquid OMS) and 4 (liquid OMS/RCS, with recirculation). The only competing systems were the supercritical systems (11, 12), but the enormous power requirements to supply primary RCS propellant flowrates led to their disqualification.

A description of the ground operations contributors and assumptions is included in Appendix B.

| | CONCEPT OPTIONS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **NORMALIZED LCC SENS'Y** | | | | | | | | | | | | |
| Development | 35 | 86 | 64 | 71 | 74 | 90 | 100 | 88 | 88 | 91 | 68 | 75 |
| Production | 86 | 85 | 86 | 86 | 100 | 98 | 99 | 90 | 90 | 91 | 84 | 85 |
| Ground Operations | 31 | 60 | 65 | 62 | 85 | 78 | 100 | 92 | 92 | 92 | 54 | 54 |
| *Weighted $\Sigma$; Equal Wt.* | *51* | *77* | *72* | *73* | *86* | *89* | *100* | *90* | *90* | *91* | *69* | *71* |
| *Weighted $\Sigma$; 25/25/50 %* | *46* | *73* | *70* | *70* | *86* | *86* | *100* | *91* | *91* | *92* | *65* | *67* |
| **NORMALIZED PERF. CHAR'S** | | | | | | | | | | | | |
| System Complexity | 43 | 40 | 43 | 57 | 73 | 97 | 100 | 68 | 71 | 86 | 60 | 78 |
| Power Requirements | 0 | 0 | 0 | 1 | 0 | 8 | 1 | 8 | 8 | 8 | 100 | 100 |
| Propellant/Press't Volume | 57 | 52 | 100 | 52 | 73 | 55 | 57 | 46 | 46 | 46 | 36 | 36 |
| Propellant/Press't Mass | 65 | 59 | 100 | 59 | 63 | 58 | 59 | 55 | 55 | 55 | 55 | 55 |
| *Weighted $\Sigma$; 40/40/10/10%* | *29* | *27* | *37* | *34* | *43* | *53* | *52* | *41* | *42* | *48* | *73* | *80* |
| **TECHNICAL RISK CONCERNS** | | | | | | | | | | | | |
| Two Phase Flow Thrusters | | • | | | | | | | | | | |
| Zero-G Liquid Acquisition | | • | • | • | • | • | • | • | • | • | | |
| Zero-G Gaging | | • | • | • | • | • | • | • | • | • | | |
| Integrated SSME (press'n syst.) | • | | | | | | | | | | | |
| Liquid Thrusters | | | • | • | | | | • | • | • | • | • |
| Gaseous Thrusters/Gas Gen'r | • | | | | • | • | • | | | | | |
| Supercritical Bellows | | | | | | | | • | • | • | | |
| In-Tank Heater/Mixer | | | | | | | | | | | • | • |
| High Pressure Pump | | | | | | • | • | • | • | • | | |
| Heat Exchanger | | | | | • | • | • | | | | | |
| Fuel Cell/Radiator Limits | | | | | | • | • | • | • | • | • | • |

**Results of Initial IAPS Concept Screening**

## 5.3. Detailed Concept Evaluation

### 5.3.1. Groundrules and Key Assumptions

The following three sections describe the groundrules and key assumptions in the areas of cost, ground operations, and vehicle requirements which shaped the selected IHOT concepts.

#### *5.3.1.1. Cost*

One of the primary differences between IHOT and previous APS studies is it's emphasis on cost as a measure of merit at a very early phase of the design cycle. Previous work typically involved a heavy emphasis on high performance, and low weight. IHOT acknowledges the key drivers of future space systems to be low cost and enhanced operational effectiveness. This is reflected in the IHOT groundrule that an estimate of the life cycle cost must be made for each of the selected concepts. Cost may then be used as a figure of merit for evaluating the relative effectiveness of different approaches to IAPS.

In addition, generation of LCC for each concept assists in the generation and prioritization of lists of technology requirements necessary to support future IAPS systems. Increased development costs may be traded against higher operational expenditures.

One key area of concern which could not be addressed regarding cost was a complete vehicle level trade. The absence of detailed cost and configurational data for the AMLS vehicle meant that the LCC benefits of (for example) a low-cost, "heavy" IAPS could not be traded against the cost of carrying that inert weight to orbit. Detailed cost analysis of integrated vehicle characteristics will have to await further AMLS definition.

### *5.3.1.2. Ground Operations*

Ground operations, if not included at the earliest phases of design definition, can be a major cost driver for future IAPS configurations. Conversely, early concern for ease of servicing and operations can result in the sharing of GSE, interfaces, and functions with other vehicle systems as well as a dramatic reduction in serial operations. This approach results in substantial reductions in ground operations even for conventional hypergolic APS. For cryo IAPS it may result in the elimination of all, or most of the operations specifically concerning servicing of the IAPS at the pad; where all possible interfaces/operations would be shared with other subsystems. The groundrules and assumptions described in this section have been imposed on all IAPS and hypergolic designs. This not only resulted in proper concern with operations and servicing at the earliest phases of the design process, but also assured a fair assessment of the potential for new SOA designs which would be specifically geared towards more efficient servicing.

The groundrules and assumptions regarding ground operations described in this section involve several specific areas of emphasis:

- Use of the "clean pad" concept
- Definition of specific operations design guidelines
- Alteration of the current philosophy towards testing
- Definition of additional instrumentation to support required testing and data acquisition
- Assumptions involving new types of component functional and leak tests

The "clean pad" concept utilized in the IHOT study applies to all three IHOT configurations which were carried forward for detailed evaluation. The term "clean pad" refers to an absolute minimum of structure exposed to launch blast effects, resulting in greatly reduced pad maintenance. The cryogenic IAPS concepts (1 & 4) load OMS and RCS propellant through the main propulsion interfaces, while the SOA concept is loaded and serviced completely off-line during turnaround processing, and would go to the pad ready for launch. Note that RCS propellants for Concept 1 are supplied by the main propulsion system during ascent, and are not loaded on the ground. On the ground the Concept 1 RCS tanks are at ambient conditions, with an inert pressurant back-fill.

The designs for all three concepts were constrained to accommodate the ground ops design guidelines shown in the following table.

| |
|---|
| 1. Built-in test equipment (BITE) utilization on the vehicle allows diagnostic routines both in flight and on the ground without putting all data to be evaluated on the downlink. Self-test enhances confidence in results. |
| 2. Expert system leak monitor allows accurate evaluation at any ambient temperature - even unstabilized. |
| 3. Replacement of 2-stage regulators with redundant regulators eliminates a second reference pressure source set-up. |
| 4.Use of only electrically operated isolation valves simplifies diagnostic and checkout routines that eliminate external GSE in many cases. |
| 5. Minimum use of check valves, using isolation valves instead (where possible) to reduce vehicle-to-GSE interface requirements and test time. |
| 6. Replacement of relief valves by pressure transducer activated isolation valves may be an item to reduce checkout time and vehicle GSE interface complexity |
| 7. Component number reduction saves manhours, BITE complexity, and vehicle interfaces. |
| 8. Elimination of complex components reduces need for complex diagnostic sensors, and lowers checkout time. |
| 9. Component type standardization reduces types of GSE, procedural direction, spares, training, BITE-routines, etc. |
| 10. Elimination of launch pad operations above pad level avoids between launch maintenance, blast damage repair, and minimize interface cleaning. Only cryo propellant servicing is provided at the pad. |
| 11. Increased pressurant tank safety factor will allow personnel access to vehicle at operating pressures. Avoids servicing at the pad & blowdown post-flight. |
| 12. Accept factory or bench test data for LRU's to eliminate test lines to veh. I/F |

**Ground Operations Time/Cost Savings Through Design**

The test philosophy which guided the assessment and definition of all three concepts specifically addressed the reduction of ground test efforts, and enhancements to current practices for real-time monitoring of system operation. This philosophy towards testing is summarized below:

| |
|---|
| 1. All possible or practical testing that can safely be performed on-orbit or during other mission phases will be implemented.<br>2. Propellant and helium tank relief will attempt to use solenoid valves instead of pneumatically/ mechanically actuated valves, with trigger signal provided by pressure transducers to simplify procedures for periodic testing.<br>3. Do not repeat successful on-orbit tests during ground checkout.<br>4. Utilize normally open solenoid valves, rather than manual valves.<br>5. Eliminate the dual regulator concept used on Shuttle, due to the difficulty of testing (two regulated reference pressures required). The preferred method is to use three parallel regulators with isolation valves, where any one leg may be selected for use.<br>6. Eliminate multiple level check valves where possible, to simplify on-orbit evaluation or anomaly investigations.<br>7. Test environment - temperature controlled environment is not required for leak testing if an expert system is employed for both on-board and ground BITE.<br>8. Propellant sevicing lines will be bled/vented at the pad during fill or hold-for-launch. OMS lines will be evacuated on orbit after the re-entry transition burn. Concept 1 RCS lines will be evacuated during ascent, and then pressurized from the MPS for proper fill.<br>9. Both the Ground System and BITE must have adequate resolution to do leak checks, and a sampling rate that will support millisecond range valve timing, crack and reseat checks for fast response valves.<br>10.On the pad, use approach of BITE monitor of go/no go status for engines and other elements of IAPS. |

**IHOT Test Philosopy**

The sensing, monitor, and control of the OMS/RCS functions, both in the mission and during turnaround processing will be performed by BITE. The ground system will also incorporate BITE which will supplement that on the vehicle, acting as a repository for accumulated flight data and furnishing additional test routines, monitor and recording capability for all vehicles of the fleet as they pass through the turn-around facility.

The types of test equipment required to support in-flight data recording or test routines will include instrumentation of the following types:

| |
|---|
| Redundant pressure and temperature transducers in the lines upstream and downstream of each active component and tank |
| Flow measurement systems in selected fill, drain and vent lines |
| Hazardous (hydrogen) gas monitors in vehicle compartments |
| Leak detectors for both propellants at all non-welded mechanical fittings |
| Accelerometers near each engine |
| Engine valve currents |
| Position and limit event measurements |
| Voltage measurements at selected valves |
| Command events, both switch and software issue |
| Software anomaly flags |
| Engine erosion evaluation |

**Instrumentation to Support In-flight Recording and Test**

These sensors will provide information to an on board expert system that can evaluate, for example, leakage by PVT relationships between any two closed sections of the system by using inputs of pressure and temperature data, the gas tables and system volumes in its memory, and other knowledge data about measurement tolerances, acceptable limits, etc. Another application of the expert concept would be the evaluation of system sensor data during each operational flight sequence, where trend analysis would flag deviations from nominal measurement characteristics or tolerances.

BITE routines presently identified for this concept include those listed below:

- Valve cycling of isolation valves to test individual segments of redundant valves, such as:
  - (a) 3 x 3
  - (b) 2 x 3
  - (c) 1 x 3
  - (d) 2 x 2

- Valve operational timing, with tables listing performance parameters for each type, including engines.
- PVT parameters such as gas law tables, pressure and temperature sensor coefficients, system volume data versus pressure, etc.
- Pressure decay monitor versus temperature (mass loss) of closed fluid lines.
- Engine igniter system performance evaluation
- Engine performance characteristics versus design
- Combustion stability monitor and cut-off system
- Nozzle burn-through instrumentation monitor and cut-off system

| |
|---|
| RCS |
| • Fuel regulator flow, lockup, & creep |
| • Oxidizer regulator flow, lockup, & creep |
| • Isolation valve thermal relief, cracking, & reseat pressures (fuel, oxidizer) |
| • Isolation valve operating times, open/close |
| • Relief valve system operating time, open |
| • Thruster chamber pressure calibration |
| • Thruster leak detection sensor (temperature) checkout |
| OMS |
| • Helium regulator flow, lockup, &creep |
| • Fuel check valve cracking pressure, flow |
| • Oxidizer check valve cracking pressure, flow |
| • Isolation valve thermal relief, cracking & reseat pressures (fuel, oxidizer) |
| • Isolation valve operating times, open and close |
| • Relief system valve operating times, open |
| • Check valve individual cracking pressure |
| • Engine instrumentation checks |

**Shuttle-Derived OMS/RCS Functional Test Summary**

The functional series of tests required to support turnaround processing were developed from Shuttle-derived processing techniques summarized in the functional and leak test summary tables on this page, and modified as indicated by recent studies to improve ground operations[6]. IHOT Concept 1 (gaseous RCS, liquid OMS) was studied in detail as a representative example for identifying functional tests, and leak tests which must be performed for a cryo-based $H_2/O_2$ system. This assessment indicated that component functional tests may include all, or subsets of the accompanying list shown on this page.

Similarly, leak tests which may be required could include any or all of the following Shuttle-derived tests:

| |
|---|
| RCS |
| • Fuel manifolds, fwd intern.(comp.-to-comp.) |
| • Oxidizer manifolds, fwd internal |
| • Tank outlet, fuel fwd internal |
| • Tank outlet, oxidizer fwd internal |
| • Tank isolation, MPS $GO_2$ fwd & reverse internal (thermal relief) |
| • Tank isol'n, MPS $GH_2$ fwd & reverse internal |
| • Thruster fwd and reverse leakage, fuel |
| • Thruster fwd and reverse leakage, oxidizer |
| OMS |
| • Fuel manifold, fwd leakage |
| • Oxidizer manifold, fwd leakage |
| • Fuel inerting, fwd leakage |
| • Oxidizer inerting, fwd leakage |
| • Fuel tank isolation, fwd leakage |
| • Oxidizer tank isolation, fwd leakage |
| • Fuel fill/drain, fwd leakage |
| • Oxidizer fill/drain, fwd leakage |
| • Fuel vent & relief, fwd leakage |
| • Oxidizer vent & relief, fwd leakage |
| • Fuel check valve isolation, fwd leakage (check valves in Concept 4) |
| • Fuel check valve isolation, cracking press. |
| • Fuel check valve isolation, reverse leakage |
| • Oxidizer check valve isolation, fwd leakage |
| • Oxidizer check valve isol'n, cracking press. |
| • Oxidizer check valve isol'n, reverse leakage |
| • Helium isolation, fwd leakage @ reg. out |
| • Helium fill, reverse leakage |
| • Engine valve leakage, fuel fwd & reverse (for degradation of propellant valve seals) |
| • Engine valve leakage, oxidizer fwd & reverse |

**Shuttle-Derived Leak Test Summary**

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[6] Circa 2000 System, Shuttle Ground Operations Efficiencies Study, Vol. 6, Boeing, July, 1988; Operationally Efficient Propulsion System Study (OEPSS), Rockwell - Rocketdyne, ALS90-36, 13 Feb. 1990.

From the ground operations side of the AMLS (again, utilizing Concept 1 for reference), leak rate GSE is required for the evaluation of the following components which cannot be evaluated in flight by BITE:

1. System vent and relief valves
2. System inerting valves (OMS)
3. Fill and drain valves (OMS)
4. Gaseous propellant fill valves

A "PVT" expert system is suitable for the following tests:

1. Tank outlet isolation valve up-to-down leakage
2. Engine isolation valve (OMS) up-to-down leakage
3. Manifold isolation valve (RCS) up-to-down leakage
4. Thruster propellant valve forward leakage

A detailed assessment of the tasks required for evaluation of sub-system performance prior to launch was performed and tabulated in a series of tables for Concept 1, to serve as a model for evaluation of the other concepts. The tabulation defines by component the types of tests that might be performed (from those Shuttle-based requirements listed previously), the interval at which these tests must be performed, ie: each turnaround cycle (T/A), following replacement (LRU), or at a major maintenance interval (each 5th, 10th,... flight). The supporting tasks to perform the test, the estimated manhours (MH), and ground support equipment (GSE) are also presented for each test type. The circled GSE numbers refer to those in the subsequent tabulation (see: Concept 1,4 Turnaround Processing Station GSE) for the turnaround processing station. Note that discussions with design engineering after these tables were presented resulted in the use of the component acceptance test data, rather than performance of thermal relief (reverse flow) testing. Thus, this item was not included in the final turn-around timeline data.

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| ISOLATION VALVE | LEAKAGE: | | | | | | | |
| | FORWARD | X | | | OVERALL | (PRESSURANT LOAD, LEAK RATE MONITOR) | 1.7 | 1 3 4 7 - 12 |
| | FORWARD | | X | X | INDIVIDUAL (2) | | 0.1 | |
| (1) | REVERSE | X | | | OVERALL | | 1.7 | |
| | REVERSE | | X | X | INDIVIDUAL (2) | | 0.1 | |
| (1) | THERMAL RELIEF: | | | | | | | |
| | CRACK | | X | | OVERALL | (PRESSURANT LOAD, PRESS MONITOR, FLOW RATE MONITOR) | 1.8 | 2 3 4 7 - 12 |
| | FLOW | | X | | OVERALL | | | |
| | RESEAT | | X | | OVERALL | | | |
| | CRACK | | | X | INDIVIDUAL (2) | | 0.5 | |
| | FLOW | | | X | INDIVIDUAL (2) | | | |
| | RESEAT | | | X | INDIVIDUAL (2) | | | |
| | OPERATING TIMES | | | | | | | |
| | OPEN | | X | | OVERALL | (SAMPLE RATE TO MONITOR MILLISEC INTERVALS) | 1.3 | 1 - 12 |
| | OPEN | | | X | INDIVIDUAL (2) | | 0.4 | |
| | CLOSE | | X | | OVERALL | | 1.3 | |
| | CLOSE | | | X | INDIVIDUAL (2) | | 0.4 | |

(1) DOES NOT APPLY TO PRESSURANT OR VENT SYSTEM VALVES

(2) ASSUMES ALL PREPARATIONS HAVE BEEN ACCOMPLISHED DURING AN OVERALL TEST, AND REFLECTS OPERATIONS OR DELAY MONITOR TIME FOR ONLY ONE ELEMENT. MULTIPLY THIS TIME BY THE NUMBER OF ELEMENTS FOR TOTAL TIME (MH)

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Detail Task Description, Isolation Valve

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| REGULATOR | RCS PROP | | | | | | | |
| | $LH_2$ UNIT | | | | | | | 2 7 8 - 12 |
| | • FLOW-HIGH | | X | X | REPEAT FOR EACH OF THE THREE LEGS | CONNECT FLOW METER TO TEST POINT. PRESSURIZE $LH_2$ TANK TO TBD PSIA | 2.2 | |
| | • FLOW-LOW | | | X | | | | |
| | • LOCKUP | | X | X | | | | |
| | • CREEP | | | X | | | | |
| | • FWD LEAKAGE | (1) | X | X | | | | |
| | $LO_2$ UNIT | | | | | | | |
| | • FLOW-HIGH | | X | X | AS ABOVE | AS ABOVE BUT PRESS $LO_2$ TANK | 2.2 | 2 7 8 - 12 |
| | • FLOW-LOW | | | X | | | | |
| | • LOCKUP | | X | X | | | | |
| | • CREEP | | | X | | | | |
| | • FWD LEAKAGE | (1) | X | X | | | | |
| | OMS PRESSURANT | | | | | | | |
| | • FLOW-HIGH | | X | X | AS ABOVE | AS ABOVE BUT PRESS HELIUM TANK | 2.2 | 2 4 8 - 12 |
| | • FLOW-LOW | | | X | | | | |
| | • LOCKUP | | X | X | | | | |
| | • CREEP | | | X | | | | |
| | • FWD LEAKAGE | (1) | X | X | | | | |

(1) UNLESS TESTED DURING PRIOR FLIGHT, AND TURNAROUND INTERVAL IS NORMAL, ie: NOT GREATOR THAN (TBD) DAYS

**Detail Task Description, Regulator**

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| CHECK VALVE | • FLOW RATE AND CRACKING PRESSURE (OVERALL) | (1) | X | X | TEST IN CONJUNC. WITH REG., OR SUPPLY FROM GSE | CONNECT FLOW METER & PRESS SOURCE GSE TO TEST POINTS | 1.8 | 2 7 8 .. 12 |
| | • INDIVIDUAL: CRACKING PRESS | | | X | SEPARATE GSE PRESSURE SOURCE AND MONITOR FOR EACH VALVE | CONNECT PRESS SOURCE & MONITOR TO TEST POINTS & GSE | 0.4 (2) | 2 7 8 .. 12 |
| | • REVERSE LEAK: OVERALL INDIVIDUAL | (1) | X | X | NEED TEST POINT FOR EACH VALVE | CONNECT GSE LEAK DETECTOR @ UPSTREAM TEST POINT | 1.8<br>0.4 (2) | 1 7 8 .. 12 |

(1) UNLESS TESTED DURING THE PRECEDING FLIGHT, AND TURNAROUND INTERVAL DOES NOT EXCEED (TBD) DAYS
(2) MULTIPLY MH BY NUMBER OF ELEMENTS FOR TOTAL TIME (MH)

**Detail Task Description, Check Valve**

(Note: no check valves in Concept 1, data used in other concept timelines)

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| RELIEF VALVE | • FORWARD LEAKAGE | (1) | X | X | PRESSURIZE SYST UPSTREAM | • CONNECT LEAK GSE TO T.P. | 1.0 | 1 7 8 - 12 |
| | • SENSOR CALIB | (2) | | X | | • CONNECT GSE PRESS SOURCE & GAGE | 2.0 | 3 5 7 8 - 12 |
| | • OPERATING TIME | | | X | VERIFY COMMAND TO RESPONSE TIME | • CONNECT GSE PRESS SOURCE & MONITOR | 0.5 | 7 8 - 12 |

(1) UNLESS TESTED DURING THE PRECEDING FLIGHT, AND TURNAROUND INTERVAL DOES NOT EXCEED (TBD) DAYS
(2) WHEN TREND DATA FROM FLIGHTS INDICATES A CHANGE OF GREATER THAN ± (TBD) % OF FULL SCALE

Detail Task Description, Relief Valve

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| TANK | PROPELLANT (GASEOUS): | | | | | | | |
| | • LEAKAGE | | | | | | | |
| | - INTERNAL | | X | X | | ON-BOARD EXPERT & HELIUM MASS SPEC | 1.6 | 4 6 7 8 - 12 |
| | - EXTERNAL | | X | X | SNIFF MECH FITTINGS | | | |
| | • INSTRUMENTATION | | | | | | | |
| | - PRESSURE | (1) | X | X | | REMOVE FOR CALIBRATION, REINSTALL, LEAK CHECK, VERIFY AMBIENT DATA | | |
| | - TEMP | (1) | X | X | | | | |
| | - MOISTURE | | | X | | | 2.3 | |
| | PROPELLANT (CRYO): | | | | | | | |
| | • EVALUATE INSULATION | X | X | X | | | | |
| | • LEAKAGE | | | | | | | |
| | - INTERNAL | | | X | | | | |
| | - EXTERNAL | (1) | X | X | | | | |

(1) WHEN TREND DATA FROM PRIOR FLIGHTS INDICATES A CHANGE OF GREATER THAN ± (TBD) % OF FULL SCALE

Detail Task Description, Tank

## Concept 1
## Detail Task Description

| Component | Test Type | T/A | LRU | Major Interval | Remarks | Support Task | Est MH | GSE Req'd |
|---|---|---|---|---|---|---|---|---|
| THRUSTER | <u>VERNIER</u> | | | | | | | |
| | • VALVE SIGN. | | X | X | | | | |
| | • REVERSE LEAKAGE | | | X | | THROAT PLUG | | 5 13 |
| | • FWD LEAKAGE | (1) | X | X | | | 2.8 | 8 - 12 |
| | • Pc XDUCER CAL | | | X | | | | |
| | • LEAK DETECTOR | | X | X | | | | |
| | <u>MAIN RCS</u> | | | | | | | |
| | • VALVE SIGN. | | X | X | | | | |
| | • REVERSE LEAKAGE | | | X | | THROAT PLUG | | |
| | • FWD LEAKAGE | (1) | X | X | | | 2.7 | |
| | • Pc XDUCER CAL | | | X | | | | |
| | • LEAK DETECTOR | | X | X | | | | |
| | <u>OMS</u> | | | | | | | |
| | • VALVE SIGN. | | X | X | | | | |
| | • REVERSE LEAKAGE | | | X | | THROAT PLUG | | |
| | • FWD LEAKAGE | (1) | X | X | | | 2.7 | |
| | • Pc XDUCER CAL | | | X | | | | |
| | • LEAK DETECTOR | | X | X | | | | |

(1) IF THRUSTER WAS NOT SELECTED FOR USE DURING PREVIOUS MISSION, OR TURNAROUND INTERVAL EXCEEDS (TBD) DAYS

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**Detail Task Description, Thruster**

The use of on-orbit test, utilizing BITE, and staff-reductions thru the use of robotics was factored into the task flow, equipment, and man-hour estimates. Thus, the total support staff may only consist of a console operator to control robotics, BITE, and on-board systems which support the test sequence. The robotics application in this case would be employed to connect or disconnect any ground system interface. Maintenance interval testing and LRU (line-replaceable unit) efforts were also considered in the equipment requirements listed for each component, and cross referenced to an overall GSE list.

**Concept 1**
**OMS/RCS GSE Configuration Data Sheet**
**Turnaround Processing Station**

**REQUIREMENTS**

**Functional Requirements**

- Provide Receiving & Handling
- Provide Access
- Provide Inspection
- Provide Pressurization & Purge
- Provide Component Testing
- Provide Health Monitoring
- Provide Repairs as Required

| ID NO. | NAME | QTY. | $K COST |
|---|---|---|---|
| 1 | LEAK DETECTOR | 2 | 40 |
| 2 | FLOW RATE MONITOR UNIT | 2 | 40 |
| 4 | INTERFACE DISCONNECTS | 4 | 100 |
| 4 | HELIUM SUPPLY | 1 | 45 |
| 4 | HELIUM; TANK PRESS'N UNITS | 3 | 30 |
| 5 | NITROGEN SUPPLY | 1 | 45 |
| 5 | APS AREA PURGE UNIT | 1 | 10 |
| 7 | INTERFACE DISCONNECTS | 6 | 150 |
| 8 | POWER SUPPLY/GROUND | 1 | 15 |
| 9 | BITE INTERFACE UNIT | 1 | 10 |
| 10 | BITE INTERFACE UNIT | 1 | 10 |
| 11 | CONTROL CENTER INTERFACE UNIT | 1 | 10 |
| 11 | WORK STATION (consoles) | 3 | 30 |
| 12 | WORK STATION (software) | 1 | 30 |
| 13 | THROAT PLUG SET OMS | 1 | 10 |
| 13 | THROAT PLUG SET RCS MAIN | 1 | 40 |
| 13 | THROAT PLUG SET RCS VERNIER | 1 | 5 |
| 13 | THROAT PRESSURIZATION SET OMS | 1 | 15 |
| 13 | THROAT PRESSURIZATION SET MRCS | 1 | 10 |
| 13 | THROAT PRESSURIZATION SET VRCS | 1 | 5 |
| 14 | APS ACCESS PLATFORM | 1 | 40 |
| 14 | APS ACCESS & LIGHTING | 1 | 5 |
| 14 | APS EXTERIOR PLATFORM | 1 | 20 |
| 15 | LRU REMOVE/REPLACE TOOL SET | 1 | 20 |
| 16 | APS DOLLY | 1 | 40 |
| 16 | OMS ENGINE HANDLING FIXTURE | 1 | 15 |
| 16 | OMS ENGINE ALIGNMENT FIXTURE | 1 | 15 |
| 16 | OMS ENGINE DOLLY | 1 | 15 |
| | | | $820 |

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Concept 1, 4 Turnaround Processing Station GSE

A delta estimate to the above GSE was prepared for Concept 13 (SOA). The following table provides a detailed listing of the additional hardware, components, and associated costs which would be involved for systems utilizing hypergolic propellants. The product of this, and the tables listed above, was the set of assumptions and groundrules which allowed the generation of a manhour estimate for testing of each component (for the respective Concepts), and a definition of the amount of GSE required to support these tests.

| | | | |
|---|---|---|---|
| GSE - Handling | | | Concept 1; $0.81M |
| H70-0511 | Lift Beam | $0.2M | |
| -0580 | Aft sling | 0.05 | |
| -0598 | Fwd sling | 0.12 | |
| -0661 | Fwd handling frame | 0.20 | |
| -0679 | APS handling frame | 0.49 | |
| -0713 | APS cradle | 0.40 | |
| -0715 | Fwd cradle | 0.02 | |
| | | $1.480M | $1.480M |
| GSE - Transport | | | |
| | Tractor | 0.06 | |
| | Trailer | 0.05 | |
| | | $0.11M | $0.11M |
| GSE - Servicing | | | |
| | Work station consoles | 0.02 | |
| | Nitrogen pressurization | 0.096 | |
| | Helium pressurization | 0.10 | |
| | Fuel servicing | 1.25 | |
| | Oxidizer servicing | 1.75 | |
| | Fuel vapor scrubber | 0.18 | |
| | Oxidizer vapor scrubber | 0.30 | |
| | SCAPE suites (10) | 1.00 | |
| | SCAPE maintenance | 1.00 | |
| | SCAPE air system | 1.00 | |
| | | $6.696M | $6.696M |
| GSE - Maintenance | | | |
| | Engine items, RCS | 1.00 | |
| | Engine items, OME | 1.00 | |
| | Welding, brazing | 1.00 | |
| | | $3.00 | $3.00 |
| Facility | | | |
| | Includes overhead cranes, HVAC, fluid distribution, electrical power... | 9.00 | |
| | | $9.00M | $9.00M |
| Total | | | $21.096M |

**Concept 13 (SOA) Additions to GSE Requirements**

### *5.3.1.3. Vehicle Requirements*

**Reliability**

The reliability and failure requirements for the IHOT concepts were based upon the groundrules established for the AMLS and PLS vehicles. Specifically, all elements of the selected designs were to be man-rated per JSC23211[7], with spacecraft systems designed for fail operational/ fail safe operation. This is reflected in the number of components in each concept, and the topology of the respective APS systems.

**Margin/ Reserves**

Tanks used for storage of two-phase propellants incorporated a 5% factor in establishing the size to allow for ullage. Due to the lack of definition of the AMLS vehicle, no other allowance for propellant margin or reserves was included. This same groundrule was applied uniformly to all three concepts.

**Mission Constraints**

Selection of the reference mission for AMLS (Space Station resupply) was covered previously in Section 5.1.3. The primary impact on the IHOT study of AMLS mission constraints was to establish the quantity, size, and location of the IAPS engines (primary/vernier RCS, OMS). The following table summarizes the issues considered.

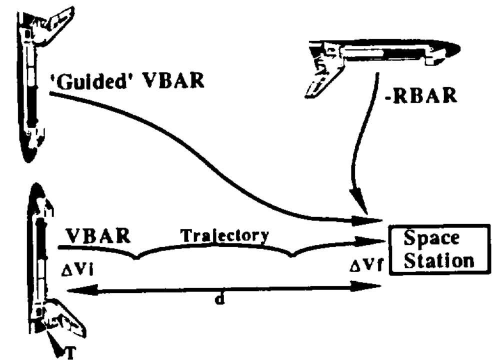
| |
|---|
| • Location, and quantity of engines must satisfy fail op/fail safe criterion |
| • Must be consistent with Shuttle desire for increased vernier control |
| • No "fast-separation" maneuver requiring primary thrusters forward (AMLS sep'n maneuver under MPS power) |
| • Impingement/contamination of Space Station by AMLS thrusters |
| • Thruster concerns of aero-heating, moment arms, etc. |
| • Adequate control during initial aerodynamic descent envelope |

**Mission Constraint Issues**

In addition, the potential impact on the specific IAPS concept of a number of abort scenarios were considered, including return-to-launch site, abort-to-orbit, propellant dump requirements, and RCS for safe return. To the depth possible in the IHOT study, the needs of these concerns were provided for in the detailed system definition and schematics.

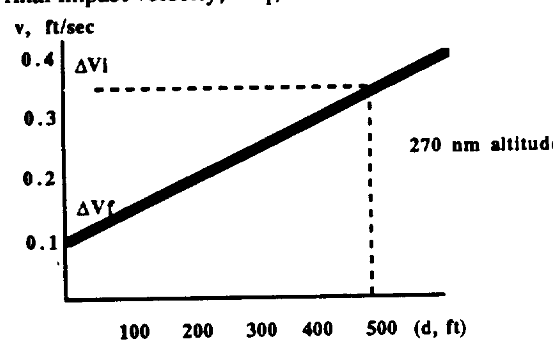
[7]Guidelines for Man Rating Space Systems, Advanced Programs Office, Lyndon B. Johnson Space Center, September, 1988 (preliminary draft)

As indicated in the following figure, several nominal trajectories are possible for rendezvous with the Space Station.




**Nominal Docking Approaches to Space Station**

The parallel VBAR approach was investigated for the size/quantity/location verification of the IHOT AMLS concepts. In this instance, the approaching vehicle docking mechanism is aligned with the target vehicle (Space Station) docking mechanism at a distance 'd' as shown in the figure above. The approaching vehicle initiates an incremental velocity, $\Delta V_i$, in the direction of the target vehicle. The value of $\Delta V_i$ can be calculated from the following figure, based upon the final impact velocity, $\Delta V_f$, and the distance, 'd'.




**Parallel VBAR Approach Rate**

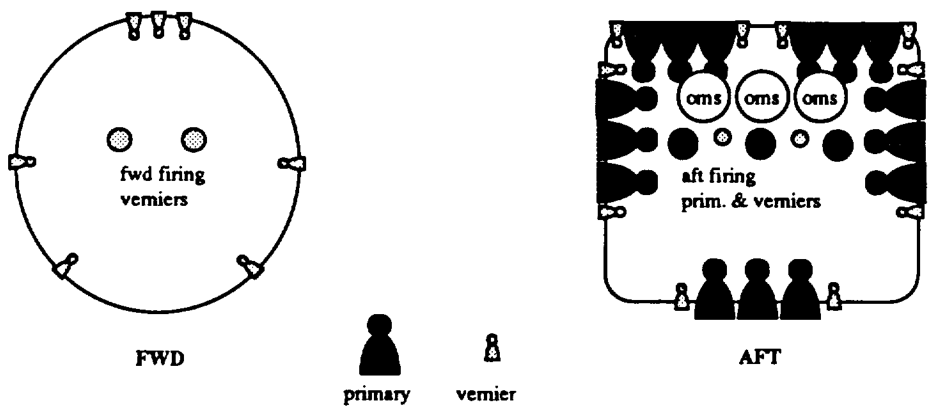
As the vehicle approaches the Space Station, the approaching vehicle CG drops below the docking point, towards the earth[8]. A force, 'T', can be applied at an inclination (~10 deg) up and away

[8]A Parallel V-bar with Engine Canting, JSC Memo FM2-85-89, Sept 24, 1985.
IL FSD&P/IGN&C 90-760-002, G.D. Carden, Jan. 5, 1990.
Space Station Program Orbiter Mating Interim Assessment Report, NASA JSC-32030, Feb. 1987.

from the Space Station which will result in bringing the approaching vehicle to the docking line and in reducing its forward approach velocity. This process is repeated several times depending on the distance, 'd', the intervals between force, 'T', application, and the duration of the force.

As indicated by the two previous figures, the only translational force required after the initial velocity $\Delta Vi$ is the 'T' force, which is sufficient to keep the vehicle z-axis roughly parallel with the Space Station docking axis (or velocity vector). The thrust 'T' may be provided by the aft primary thrusters on AMLS. While performing the parallel VBAR docking approach, the vehicle's attitude may be maintained by the vernier thrusters. Initial IHOT investigations indicated no need for forward primary thrusters under the VBAR approach. No other mission phases were identified which would mandate the need for forward primary thrusters. Separation from the Space Station may be accomplished by unlatching the interfaces and using a small (mechanical) pushoff. The vehicle will drift down and forward relative to the Space Station. During the separation maneuver, the attitude control is maintained by the vernier thrusters. In this case (as with docking), no forward primary thrusters are needed to perform the separation maneuver.

The location and type of IHOT thrusters for all three concepts are shown in the figure below. This was the configuration which was evaluated for VBAR feasibility. The size of the thrusters which resulted are summarized in the following section, and were determined based upon providing adequate control for Space Station docking, and a preliminary orbital mechanics assessment of the thrust and impulse requirements for an AMLS-size vehicle.




Notes:

1. Options 1 and 4 require 3 OMS engines, for adequate redundancy (no OMS/RCS interconnect).
2. Up fwd verniers triple redundant, to separate from Station. Not req'd for down firing (safe return possible with 2 failures).
3. Engines not to scale.

**AMLS Thruster Locations**

### 5.3.2. Definition of Selected Concepts

The following four sections define the specific characteristics of the IHOT concepts developed for AMLS. The first section summarizes the component sizing, characteristics, and mass properties for ease of comparison of the three selected concepts. The next three sections describe the specific functional and operational characteristics of the concepts, including schematics, assumptions, and unique features.

#### *5.3.2.1. Engine and Component Definition*

The top-level performance, size, and mass-property characteristics are summarized in this section. The table below summarizes the engine characteristics for the three IHOT APS concepts. Performance characteristics for Option 13 were derived from Shuttle performance. The techniques for determining the engine performance for Options 1 and 4 are described in Appendix E. The next table summarizes the line sizes for the three IHOT concepts.

| Option 1 | Exp'n Ratio | Pc | Isp, delivered | Thrust | Mixt.Ratio |
|---|---|---|---|---|---|
| Primary | 22 | 100 | 310.5 | 870 | 16 |
| Vernier | 22 | 100 | 305.9 | 50 | 16 |
| OMS | 55 | 100 | 425.7 | 4000 | 6 |

| Option 4 | Exp'n Ratio | Pc | Isp, delivered | Thrust | Mixt.Ratio |
|---|---|---|---|---|---|
| Primary | 22 | 150 | 423.8 | 870 | 4 |
| Vernier | 22 | 150 | 419.5 | 50 | 4 |
| OMS | 100 | 800 | 462.2 | 4000 | 6 |

| Option 13 (SOA) | Exp'n Ratio | Pc | Isp, delivered | Thrust | Mixt.Ratio |
|---|---|---|---|---|---|
| Primary | 22 | 150 | 280 | 870 | 1.6 |
| Vernier | 22 | 110 | 265 | 50 | 1.6 |
| OMS | 55 | 125 | 313 | 6000 | 1.6 |

**IHOT Engine Performance Parameters**

| | Option 1; Line Sizes(in.)... est'd, for gaseous | | | |
|---|---|---|---|---|
| | Engine (O2) | Engine(H2) | Manifold(O2) | Manifold(H2) |
| Primary | 2 | 1 | 4 | 2 |
| Vernier | 0.5 | 0.25 | 1 | 0.5 |
| OMS | 1.5 | 1.5 | 1.5 | 1.5 |

| | Option 4; Line Sizes(in.) | | | |
|---|---|---|---|---|
| | Engine (O2) | Engine(H2) | Manifold(O2) | Manifold(H2) |
| Primary | 0.75 | 1.25 | 1.5 | 1.25 |
| Vernier | 0.25 | 0.25 | 0.5 | 0.5 |
| OMS | 1.5 | 1.5 | 1.5 | 1.5 |

| | Option 13; Line Sizes(in.) | | | |
|---|---|---|---|---|
| | Engine (N2O4) | Engine(MMH) | Manifold(N2O4) | Manifold(MMH) |
| Primary | 0.75 | 0.625 | 1.5 | 1.5 |
| Vernier | 0.25 | 0.25 | 0.5 | 0.5 |
| OMS | 1.5 | 1.5 | 1.5 | 1.5 |

**IHOT Engine Line Sizes**

The propellant and pressurant requirements for the IAPS concepts were determined based upon the vehicle mission requirements discussed in section 5.3.1.3. Option 1 requires no helium pressurant, and provides gaseous hydrogen and oxygen (from the RCS tanks) as pressurant for the OMS system. Option 4 has a single helium tank for each cryogen, which provides pressurant to the RCS system and part of the OMS net positive suction head (NPSH) requirements. The expander cycle OMS engine provides autogenous pressurant during operation. Option 13 requires separate helium bottles for the forward and aft RCS modules, since there is no interconnection between these systems.

**Option 1**

| | O2 Mass (lb) | H2 Mass (lb) | O2 Volume (ft^3) | H2 Volume (ft^3) |
|---|---|---|---|---|
| **Primary** | 1822 | 114 | 756 | 517 |
| **Vernier** | 455 | 29 | (included) | (included) |
| **Pressurant** | 750 | 205 | (included) | (included) |
| **OMS** | 17677 | 2946 | 261 | 700 |
| | (Volumes include 5% ullage) | | | |
| **Totals** | 20704 lb | 3294 lb | 1017 $ft^3$ | 1217 $ft^3$ |

**Option 4**

| | O2 Mass (lb) | H2 Mass (lb) | He Mass (lb) | O2 Volume (ft^3) | H2 Volume (ft^3) | He Vol (ft^3) |
|---|---|---|---|---|---|---|
| **Primary** * | 1249 | 312 | 47.2 | 23 | 97.5 | (incl., OMS) |
| **Vernier** * | 310 | 78 | (included) | (included) | (included) | (incl., OMS) |
| **OMS** | 16281 | 2714 | 112.3 | 240 | 678.4 | 56.7 |
| | *(Note: RCS propellant qty includes 10% for venting losses, Volumes include 5% ullage) | | | | | |
| **Totals** | 17840 lb | 3104 lb | 159.5 lb | 263 $ft^3$ | 775.9 $ft^3$ | 56.7 $ft^3$ |

**Option 13 (SOA)**

| | N2O4 Mass (lb) | MMH Mass (lb) | He Mass (lb) | N2O4 Vol. (ft^3) | MMH Vol. (ft^3) | He Vol (ft^3) |
|---|---|---|---|---|---|---|
| **FWD RCS** | 560 | 350 | 1.1 | 6.2 | 6.3 | 0.4 |
| **Aft RCS** | 1120 | 700 | 2.3 | 12.4 | 12.8 | 0.9 |
| **OMS** | 17300 | 10800 | 35 | 192 | 197 | 12.5 |
| **Totals** | 18980 lb | 11850 lb | 38.4 lb | 210.6 $ft^3$ | 216.1 $ft^3$ | 13.8 $ft^3$ |

**IHOT Propellant and Pressurant Requirements**

The comparative mass properties of the three IHOT concepts are defined in the following table. The assumptions and analyses responsible for definition of specific engine weights are defined in Appendix F. The derivation of mass properties for the small flow control components (valves, etc.) are detailed in Appendix G, and summarized below. Tank weights for storage of cryogens are based upon the use of a dewar similar in design to Shuttle PRSD tanks, but adjusted for the appropriate operating conditions. The high-pressure gaseous RCS propellant storage tanks of Option 1 are composite wrapped, with an aluminum liner for the hydrogen, and an inconel liner for the oxygen. The mass properties of Helium tanks reflect a 4:1 safety factor, to allow safe access to the vehicle after the tanks have been pressurized in the processing facility (eliminates helium at the pad).

**Option 1**

| Comp. | Qty /Veh | Unit Wgt | Tot. Wt. |
|---|---|---|---|
| *Tankage* | | | |
| RCS | | | |
| Helium | 0 | | 0 |
| Hydrogen | 1 | 2647.4 | 2647 |
| Oxygen | 1 | 2662.2 | 2662 |
| OMS | | | |
| Helium | 0 | 0.0 | 0 |
| Hydrogen | 1 | 2821.8 | 2822 |
| Oxygen | 1 | 614.6 | 615 |
| *Distribution* | | | |
| Lines, Manifolds | 8 | 68.9 | 551 |
| Regulators | 6 | 15.7 | 94 |
| Disconnects | | | 0 |
| Orifice | 0 | | 0 |
| *Valves* | | | |
| Isolation | 90 | 4.8 | 430 |
| Check | 0 | | 0 |
| Quad check | 0 | | 0 |
| Relief | 0 | | 0 |
| Fill/Drain | 4 | 5.1 | 20 |
| Manual | 0 | | 0 |
| *Elec. Comp's* | | | |
| Recirc. Pump | 0 | | 0 |
| Elec. Motor | 0 | | 0 |
| Tank Heater | | | 0 |
| *Engines* | | | |
| RCS | | | |
| Primary | 18 | 34.6 | 623 |
| Vernier | 21 | 9.3 | 195 |
| OMS | 3 | 225.8 | 677 |
| TOTAL | 154 | | 11338 |

**Option 4**

| Comp. | Qty /Veh | Unit Wgt | Tot Wt. |
|---|---|---|---|
| *Tankage* | | | |
| RCS | | | |
| Helium | 0 | 0.0 | 0 |
| Hydrogen | 1 | 582.6 | 583 |
| Oxygen | 1 | 88.7 | 89 |
| OMS | | | |
| Helium(H2) | 1 | 954.6 | 955 |
| Helium(O2) | 1 | 75.6 | 76 |
| Hydrogen | 1 | 572.2 | 572 |
| Oxygen | 1 | 130.5 | 131 |
| *Distribution* | | | |
| Lines, Manifolds | 8 | | 1216 |
| Regulators | 12 | 7.3 | 88 |
| Disconnects | | | 0 |
| Orifice | 2 | | 0 |
| *Valves* | | | |
| Isolation | 124 | 3.5 | 434 |
| Check | 1 | 1.4 | 1 |
| Relief | 0 | 1.5 | 0 |
| Fill/Drain | 4 | 5.0 | 20 |
| Manifold | 36 | 3.2 | 114 |
| *Elec.Comps* | | | |
| Recirc. Pump | 4 | 0.9 | 3 |
| Elec. Motor | 4 | 0.5 | 2 |
| Tank Heater | | | 0 |
| | | | 0 |
| *Engines* | | | |
| RCS | | | |
| Primary | 18 | 22.0 | 396 |
| Vernier | 21 | 5.3 | 111 |
| OMS | 3 | 181.8 | 545 |
| TOTAL | 243 | | 5336 |

**Option 13**

| Comp. | Qty /Veh | Unit Wgt | Tot Wt |
|---|---|---|---|
| *Tankage* | | | |
| Helium - Fw | 2 | 3.0 | 6 |
| Helium - Aft | 2 | 106.0 | 212 |
| mmh - Fw | 1 | 29.0 | 29 |
| nto - Fw | 1 | 29.0 | 29 |
| mmh - Aft | 1 | 755.0 | 755 |
| nto - Aft | 1 | 755.0 | 755 |
| *Distribution* | | | |
| Lines, Manifolds | 14 | | 166 |
| Regulators | 12 | 1.9 | 23 |
| Disconnects | | | |
| Orifice | | | |
| *Valves* | | | |
| Isol(hi press) | 24 | 1.2 | 28 |
| Isol (lo press) | 12 | 4.4 | 52 |
| 3x3 check | 4 | 3.3 | 13 |
| Relief | 4 | 2.3 | 9 |
| Fill/Drain | | | 0 |
| He | 4 | 0.7 | 3 |
| mmh | 2 | 1.1 | 2 |
| nto | 2 | 2.0 | 4 |
| Manifold Vlv | 48 | 4.4 | 209 |
| *Elec. Motor* | *0* | | *0* |
| Tank Heater | 4 | --- | |
| *Engines* | | | |
| RCS | | | 0 |
| Primary | 18 | 33.2 | 598 |
| Vernier | 21 | 9.4 | 197 |
| OMS | 2 | 302.0 | 604 |
| TOTAL | 179 | | 3693 |

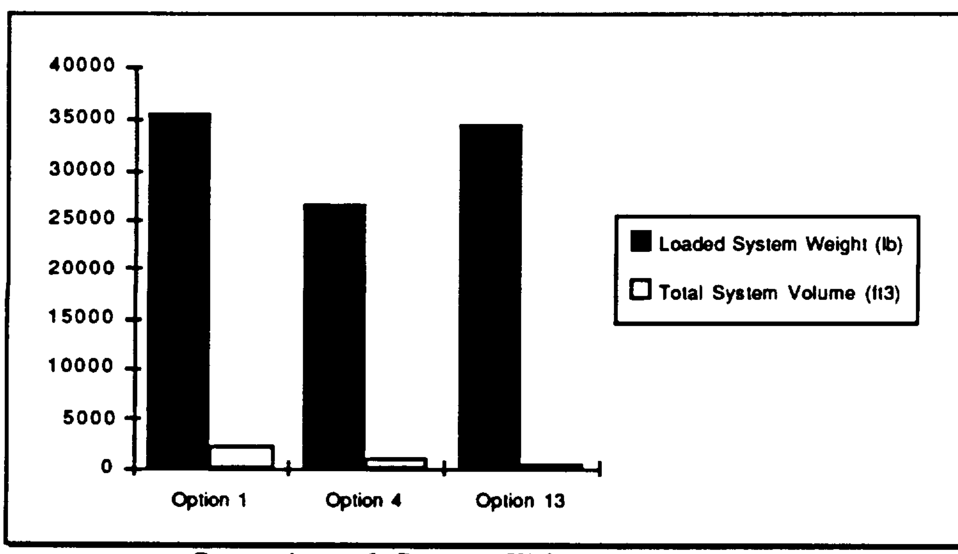
**IHOT IAPS Mass Properties Summary**

It should be noted in the previous table that no allowance is made for the structural weight of the actual forward and aft modules for Option 13. This would shift the inert weight comparison strongly towards the IAPS options.

The final table of engine and component definition describes the volumetric packaging efficiency of the IAPS tankage. From this, and the previous table it is clear that the operational benefits of $H_2/O_2$ IAPS systems exact a price in weight and packaging. It must be remembered, however, that the drivers of this study were cost and operations - not high performance. Traditionally, one considers hydrogen/oxygen systems for their inherent high performance due to the energy of the propellants. One of the primary objectives of IHOT, however, was to determine the performance penalty (if any) that a hydrogen/oxygen IAPS might impose on the next generation of manned launch vehicles, compared to a well-designed hypergolic (SOA) APS. The tables of this section indicate that the cryo IAPS concepts are less efficient from a packaging viewpoint, but very competitive in terms of loaded system weight (Concept 1: 775 lb penalty; Concept 4: 8121 lb benefit, compared to Concept 13), as illustrated in the final figure.

| Option 1 | | | | Option 4 | | | | Option 13 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | Qty /Veh | Vol. (ft^3) | Press. (psia) | Comp. | Qty /Veh | Vol. (ft^3) | Press. (psia) | Comp. | Qty /Veh | Vol. (ft^3) | Press. (psia) |
| *Tankage* | | | | *Tankage* | | | | *Tankage* | | | |
| RCS | | | | RCS | | | | Helium,Fw | 2 | 0.4 | 4000 |
| Helium | 0 | - | - | Helium | 0 | - | - | Helium,Aft | 2 | 13.4 | 4000 |
| Hydrogen | 1 | 517 | 2470 | Hydrogen | 1 | 98 | 195 | mmh - Fw | 1 | 6.3 | 250 |
| Oxygen | 1 | 756 | 1200 | Oxygen | 1 | 23 | 195 | nto - Fw | 1 | 6.2 | 250 |
| OMS | | | | OMS | | | | mmh - Aft | 1 | 209.8 | 250 |
| Helium | 0 | - | - | Helium (H2) | 1 | 54 | 4000 | nto - Aft | 1 | 204.4 | 250 |
| Hydrogen | 1 | 700 | 132 | Helium (O2) | 1 | 3 | 4000 | | | | |
| Oxygen | 1 | 261 | 132 | Hydrogen | 1 | 678 | 25 | | | | |
| | | | | Oxygen | 1 | 240 | 25 | | | | |
| Total Vol. | | 2234 | | | | 1096 | | | | 440.5 | |

**IHOT Volumetric Packaging Comparison**




**Comparison of Concept Weights and Volumes**

### *5.3.2.2. Gaseous RCS, Liquid OMS IAPS*

The Option 1 IAPS concept resulted from an attempt to create the simplest possible configuration which would meet the AMLS mission requirements. Minimal ground operations are key objectives of all IHOT concepts. As illustrated in the system schematic, Option 1 imposes no additional ground interfaces on the AMLS design, utilizing the Main Propulsion System interfaces for all fluid fill, vent , and drain. None of the cost, man-power or schedule impacts from these activities are charged to the Option 1, as they are routine activities which must be performed for the MPS. Only those test, and servicing activities specifically related to the IAPS show up as Option 1 cost and schedule items.

On the launch pad, prior to cryogen loading, this concept is "safe" from a vehicle viewpoint. There are no high pressure bottles, and all tanks (OMS, and RCS) have been back-filled with an inert gas to a few psi above ambient pressure (at the processing facility). During MPS fill, the OMS tanks are filled with liquid hydrogen and oxygen. The RCS tanks remain inert thru loading, and the entire launch sequence. During ascent, the RCS tanks are vented thru the thrusters, and then pressurized with high pressure gaseous propellants (2470 psi, hydrogen; 1200 psi, oxygen) supplied by the MPS system. This process would operate functionally very similar to the existing Shuttle external tank pressurization system, which utilizes $GO_2$ heated by the SSME engine turbine exhaust, and $GH_2$ tapped off of the engine cooling jacket. As these propellants are near ambient temperature, the RCS system requires little or no insulation. The OMS tankage requires a vacuum-jacketed dewar design to provide thermal protection for the cryogens.

As previously indicated (section 5.3.2.1), the RCS primary and vernier thrusters operate at a mixture ratio of 16:1 (see Appendix H). This was done to provide hydrogen storage tanks of "reasonable" size. At this mixture ratio the gaseous storage tanks for the hydrogen and oxygen propellants are much more nearly the same size (756 $ft^3$, oxygen; 517 $ft^3$, hydrogen) than they would be if a more "typical" mixture ratio were used. Specific engine and component characteristics / performance parameters are summarized in the previous section (5.3.2.1). The RCS operating conditions (initial temperature and pressure) were determined to assure desired operation during blowdown of the propellants (see Appendix I, Appendix J).

*Assumptions:*
All IHOT concepts must meet the redundancy and failure tolerance requirements which apply to a manned, reusable vehicle such as AMLS. These requirements are summarized in the following table:

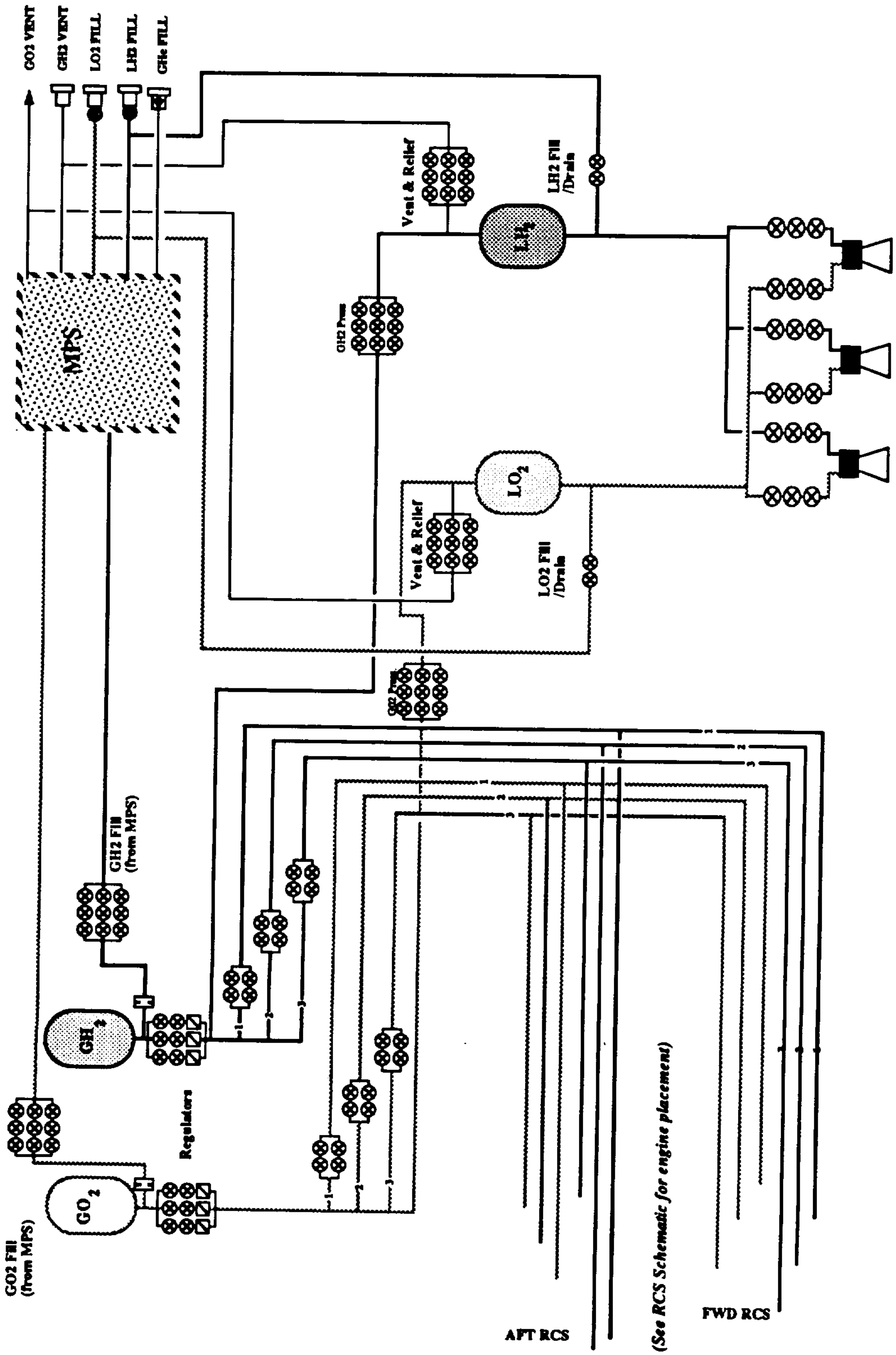
| |
|---|
| ***Overall* OMS/RCS Subsystem Must Satisfy Fail Operational / Fail Safe (FOFS) Criteria** <br> • Subsystem can sustain one failure and not degrade the performance of the mission <br> • Any second failure within the subsystem shall not preclude safe crew return |
| **Exceptions to FOFS** <br> • Pressure vessels shall be designed to adequate margins, and are therefore exempt <br> • Combustion chambers and thrust chambers shall be considered single failure tolerant (fail safe) <br> • Components used only for ground servicing shall be single failure tolerant |
| **Safe Crew Return Requirements** <br> • Two of three OMS engines plus sufficient RCS for minimal entry control, *or* <br> • Sufficient aft RCS for de-orbit plus entry control |

**Redundancy/ Failure Assumptions**

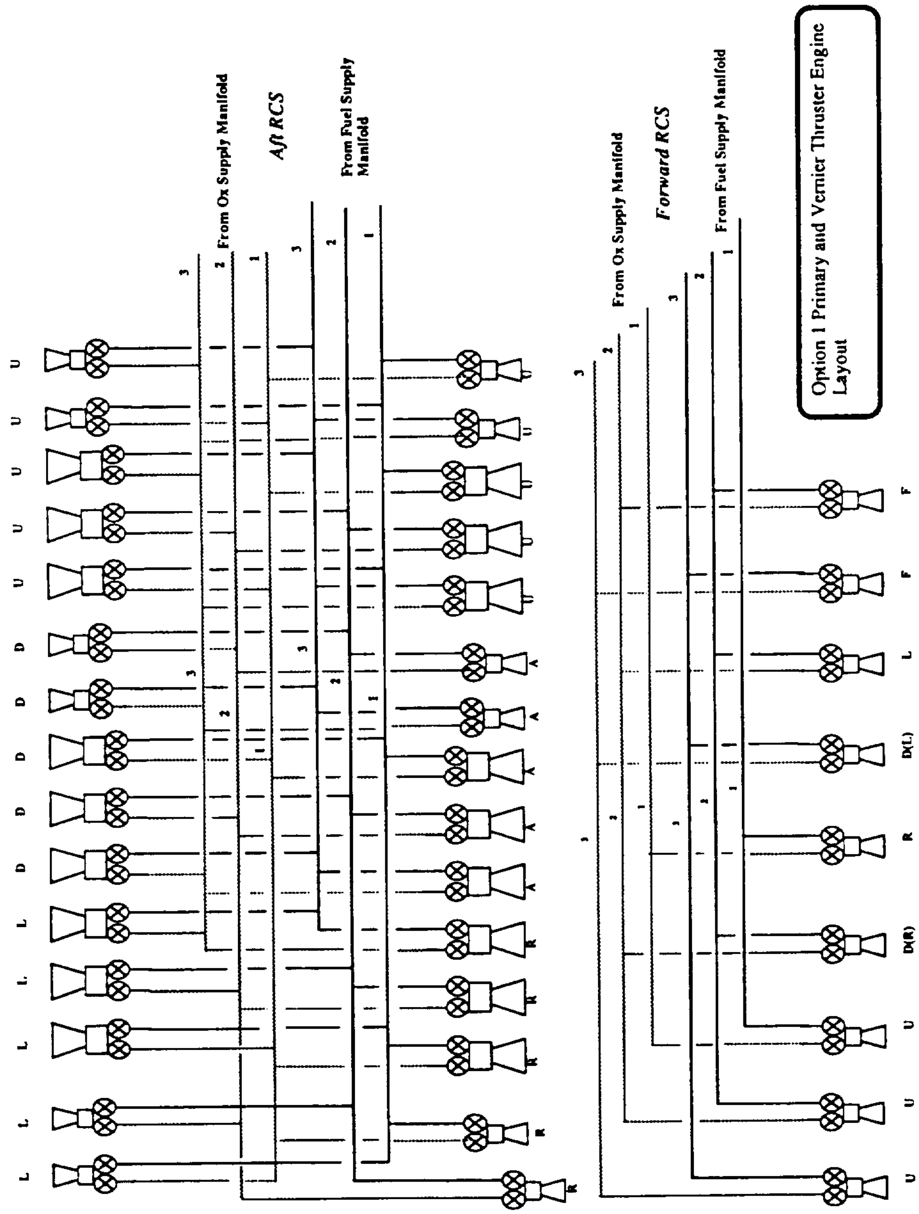
In addition to the above general assumptions, there are a number of system assumptions which are specific to Option 1. These assumptions are summarized as follows:

| |
|---|
| • OMS ullage volume at lift-off, 5% <br> • OMS propellant feed system frictional losses, tank to injector face, 30% <br> • Tank regulator control band is +/- 5% of nominal OMS tank pressure of 130 psi <br> • Pressurant flowrate is 5X the liquid flowrate to the OMS engines <br> • OMS heat transfer estimates increased by 20% <br> • OMS ullage pressure drops to 15 psi between burns <br> • Final OMS tank pressure to be at 50% above regulated pressure <br> • RCS propellant loading time of 200 seconds used to size ascent transfer lines <br> • $LO_2$ temperature @ 160 deg-R, $LH_2$ @ 37 deg-R |

**Option 1 System Modeling Assumptions**




**System Schematic, Gaseous RCS, Liquid OMS IAPS Concept**




**System Schematic, Gaseous RCS, Liquid OMS - RCS Detail**

*Option 1 Features and Characteristics*

In order to assure that the systems evaluated under IHOT adequately represented actual IAPS concepts from a cost and operational viewpoint, significant effort was applied towards system and schematic definition. In Option 1 three OMS engine control valves are used in series, as opposed to two tank isolation valves in parallel with a set of quad engine control valves. This simplifies the system configuration and reduces check-out, while still providing a design which is two failure tolerant (valves may fail in either position).

Cryogen fill and drain valves for Option 1 use two solenoid valves in series instead of quad valves. Since these valves are for ground operations they may be verified on the ground, and still provide two fault tolerance for in-flight valve leakage. These valves are not required for flight operations.

Three OMS engines are required for Option 1, to provide FOFS operation. Unlike Option 13, the primary RCS may not be used as a de-orbit backup. The OMS engines are, however, of a simple pressure-fed design. This decreases the number of components to check out and results in fewer requirements for inerting purges.

The RCS meets the same system failure criteria as the OMS. This is met by a combination of redundant valves, regulators, engines, and the use of three separate manifolds (both forward and aft), to assure that pitch, roll, and yaw control is available with a single manifold. The most innovative aspect of the Option 1 design is the use of MPS-supplied propellants to pressurize the RCS tanks during ascent. Option 1 requires $GH_2$ at 2470 psi, 400 deg-R; and $GO_2$ at 1200 psi and 400 deg-R. This not only decreases checkout and loading time prior to launch, but significantly reduces the RCS tank weight. Due to the IHOT criteria that only *liquid hydrogen and oxygen* would be available at the pad, the Option 1 concept would require RCS tanks to be filled at the AMLS processing facility (as the helium tanks for Option 4). This, however, would require the safety factor for the tanks to be increased from 1.4 to 4.0 in order to allow access to the AMLS during transit and launch operations. The Option 4 and Option 13 helium tanks utilize a safety factor of 4. Filling of the Option 1 RCS tanks during ascent allows a lower safety factor, and is an enabling element in making the concept feasible (from a safety and weight viewpoint). This also maintains consistency with the groundrule of future launch vehicles requiring only liquid hydrogen and oxygen propellants at the launch pad.

### *5.3.2.3. All-Liquid IAPS*

Option 4 is a concept which attempts to achieve simplified operations and low cost with a more "conventional" configuration than Option 1. The primary technology challenges for this configuration are assuring liquid cryogens at the RCS inlet, and stable operation of the thrusters.

Proof of the Option 4 concept would result in the elimination of the heat exchangers, accumulators, and most of the pumps of past IAPS concepts (see Appendix A). It also provides the best combination of weight and performance (of the three IHOT concepts studied).

*Option 4 Features and Characteristics*
The entire integrated OMS/RCS system is triple redundant.

Two high pressure helium tanks supply ullage independently to each propellant tank to avoid vapor migration through componentry between the fuel and oxidizer sides.

Downstream of the He tank, regulators supply 195 psi pressurant to the RCS tanks. The parallel configuration provides the fail-closed redundancy while two isolation valves in series upstream of each regulator provide the required fail-open criteria.

The second set of regulators lower the pressure further to supply the OMS tanks with 25 psi. These regulators require three isolation valves, normally closed, to maintain two fault tolerance in preventing over-pressurization of the low pressure OMS tanks while pressurizing the high pressure RCS tanks.

Both OMS and RCS tank weights are based on STS Power Reactant Storage tanks. The $LO_2$ tanks are 718 Inconel, and the $LH_2$ tanks are 2219 Aluminum. All tanks are assumed to be vacuum jacketed. This is similar (with the exception of design pressure) to the design utilized for the Option 1 OMS.

Triple redundant vent valves accommodate tank overpressurization.

The propellant to each OME is supplied through three electrically operated valves for oxidizer and three for fuel, as per Option 1. This configuration provides for the necessary fail open redundancy since no tank isolation valves are used. For fail closed conditions, the other engine can continue with RCS back-up. Three engines are baselined for adequate redundancy to meet abort criteria.

The pump-fed expander cycle OME's are based on Rocketdyne's Advanced Space Engine. High pressure gas is tapped off to supplement pressurization of the large OMS tanks.

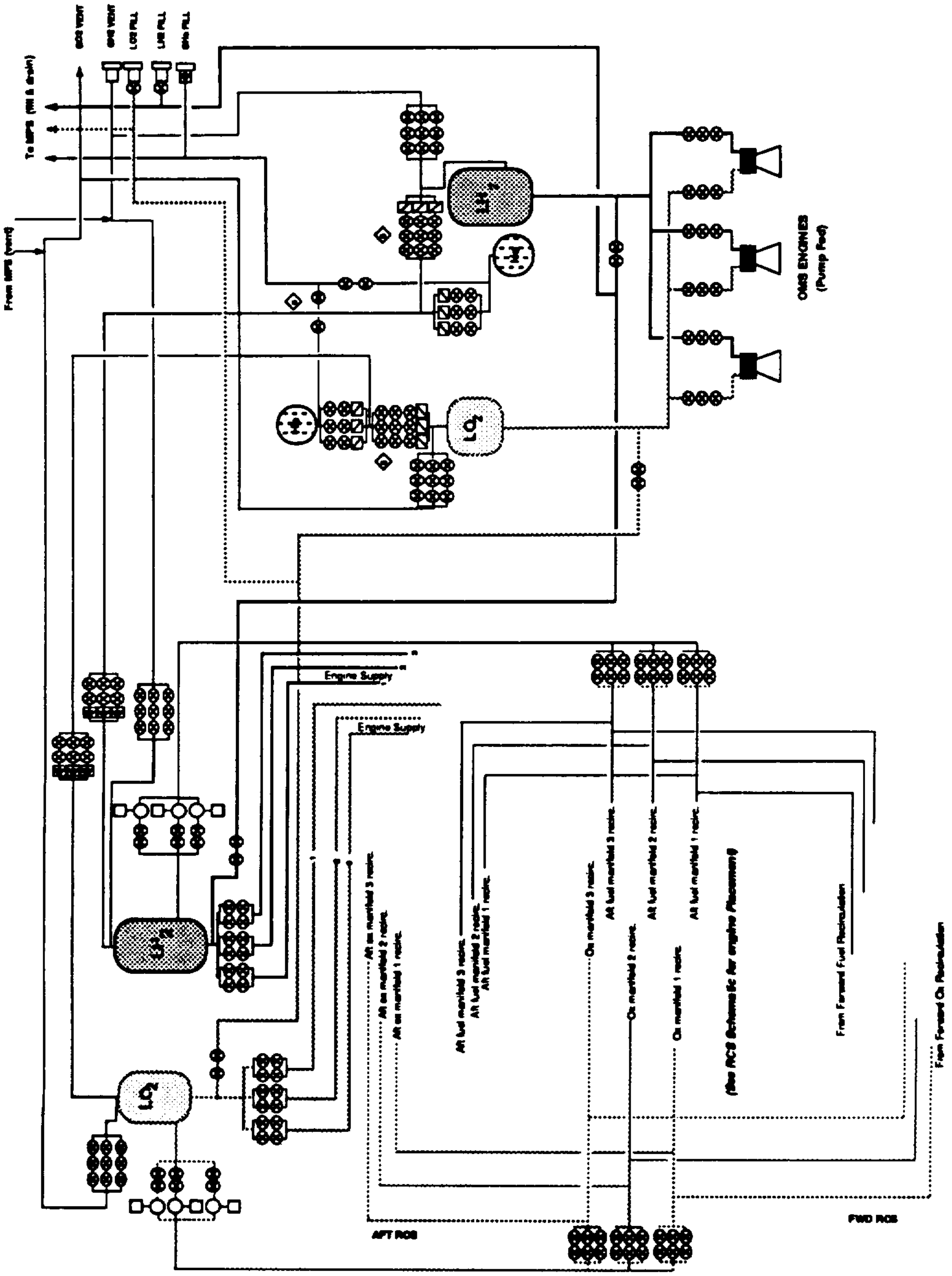
Both the OMS and RCS are serviced with common lines. Valves in series prevent propellant loss from inadvertent opening.

The fill and drain valves consist of a valve which is only open when the ground coupling is inserted into it. A cap is screwed onto the disconnect. Redundancy is not considered necessary for these components.

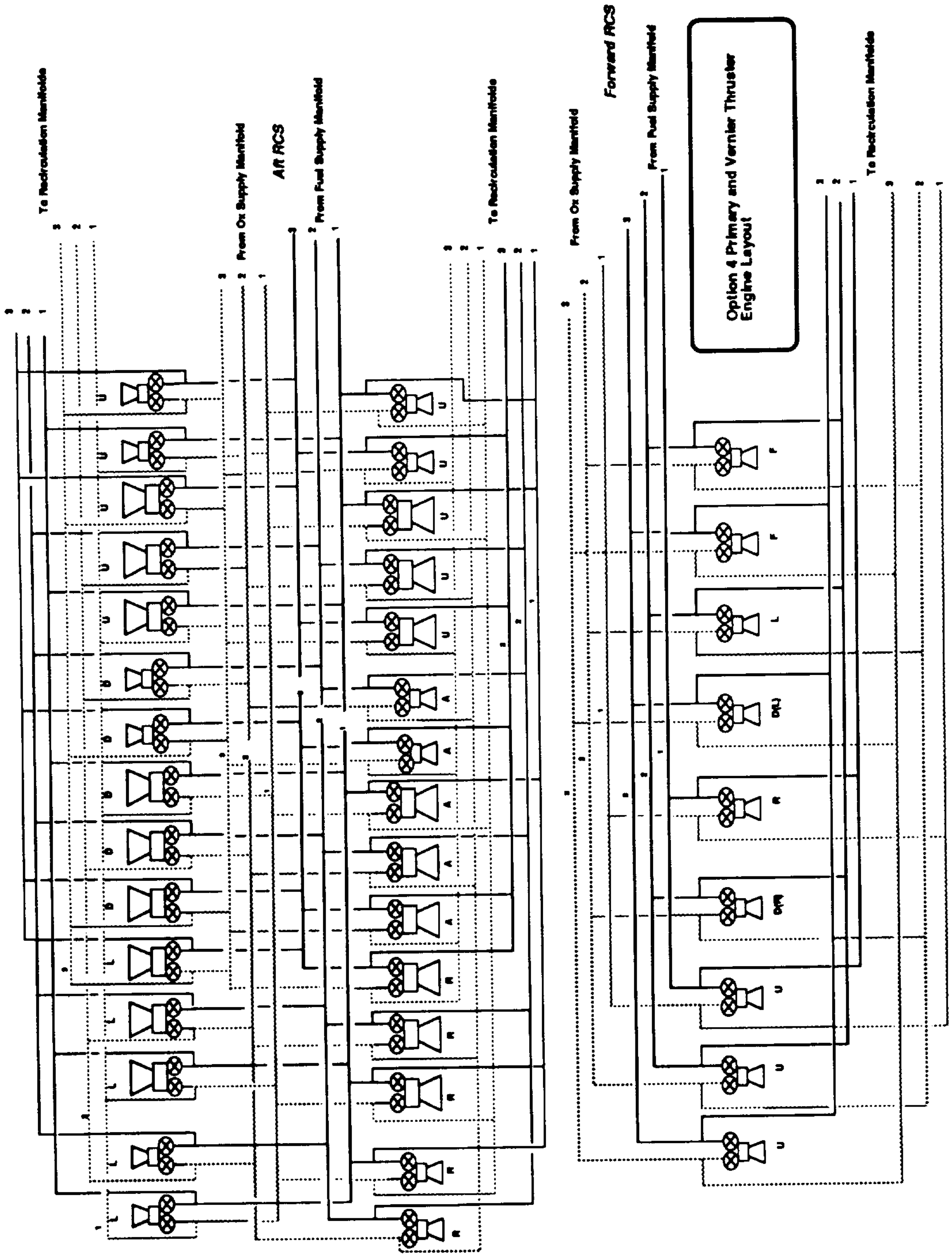
Check and isolation valves upstream of the RCS tanks prevent propellant and/or vapor migration into the RCS regulators, the normally opened isolation valves and into the Helium tanks.

Small recirculation pumps eliminate propellant gasification in localy heated regions by maintaining a constant circulation loop from upstream of the thrusters to the tanks. Three pumps in parallel, with two isolation valves in series each provide the necessary fail open/fail closed redundancy.

The propellant to the RCS is distributed through three manifold arrangements. Each arrangement consists of quad-redundant valve sets. The three manifolds provide upstream isolation for each group of redundant thrusters in case of thruster valve leakage or failure to close.




**System Schematic, Liquid RCS & OMS IAPS Concept**




**System Schematic, Liquid RCS & OMS - RCS Detail**

*5.3.2.4. State-of-the-Art Hypergolic OMS/RCS*

Option 13 is to be used as a basis of comparison for evaluating the relative cost, operations, and performance benefits of $H_2/O_2$ IAPS systems. As such, this option is not simply a Shuttle OMS/RCS implementation for the AMLS vehicle. Rather, it represents a reasonable "next-generation" hypergolic APS. As with Options 1 and 4, the primary criteria for Option 13 were low cost and minimal operational complexity. This is reflected in the pressure-fed design, using forward and aft "modules" which can be processed, loaded, and serviced off-line. Helium bottles have a safety factor of 4x, to allow filling in the processing facility and transport to the pad at flight pressure with minimal risk to personnel.

The following section describes the functional operation of Option 13, and illustrates the system schematic for both the forward and aft modules.

Forward RCS Module

The entire Option 13 RCS system is triply redundant (excluding tanks, pressure vessels, lines). The forward module is easily removable and serviced independently from the aft in the Hypergolic Maintenance Facility. It is understood that this was also the intent of the Shuttle APS design. If an operationally efficient vehicle is to be possible, however, design compromises imposed on Shuttle must be avoided on AMLS. The IHOT study attempts to quantify LCC and operational issues so that the true program impacts of future funding and design changes may be evaluated.

In Option 13, two high pressure (4000 psi) helium tanks supply pressurant independently to each propellant tank to avoid vapor migration through componentry (i.e. check valves) between the fuel and oxidizer sides.

Three parallel regulators provide the required fail-closed redundancy while two isolation valves in series upstream of each regulator provide the required fail-open criteria. Eliminating the dual regulators presently used on the STS will enable in-flight checkout of each regulator as well as the isolation valves.

Triply redundant check-valves in series and parallel provide the necessary failure criteria since only one set of tanks exist (i.e., there is no crossfeed). The check valves are required to prevent propellant vapor migration upstream into the regulators, causing corrosion and/or sticking.

The burst disk and relief valve accommodate tank overpressurization due to thermal effects. The assembly is normally inert. The burst disk provides a leak free barrier between propellant vapors and the relief valve, eliminating the potential for valve degradation. Since the relief valve is a spring loaded poppet valve, the chance that it will stick closed is minimal and a parallel configuration was not deemed necessary. To accommodate occasional burst disk failures during checkout procedures, an independently removable burst disk will enable simple replacement.

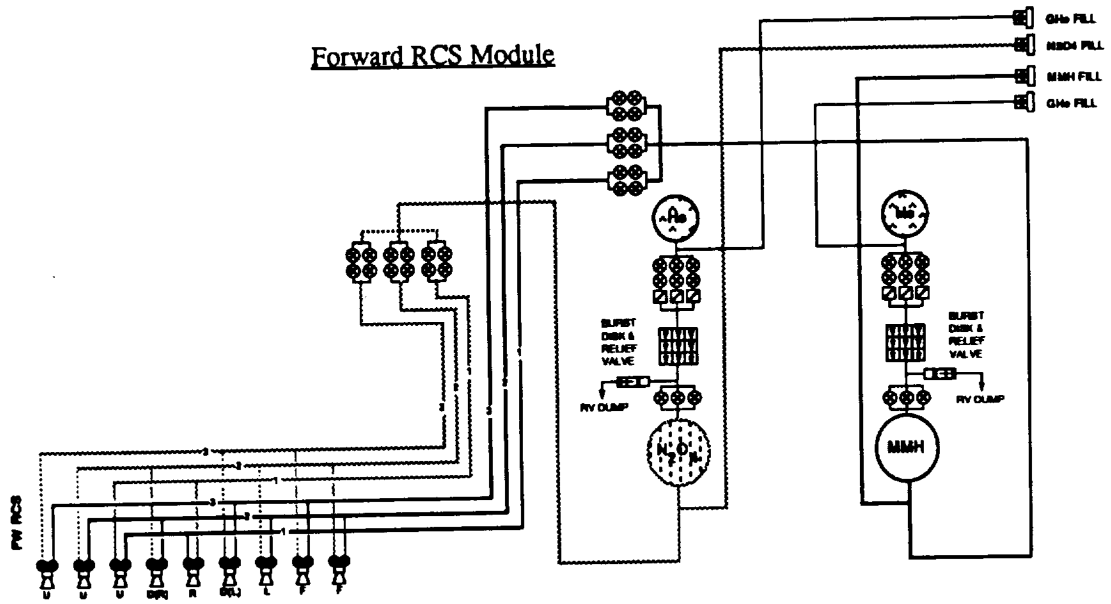
The manual valve presently on the STS is replaced by three parallel electrically operated isolation valves. These valves, used only for ground checkout, would be in an open position during flight. The valve permits isolation from the tank when testing a regulator after replacement.

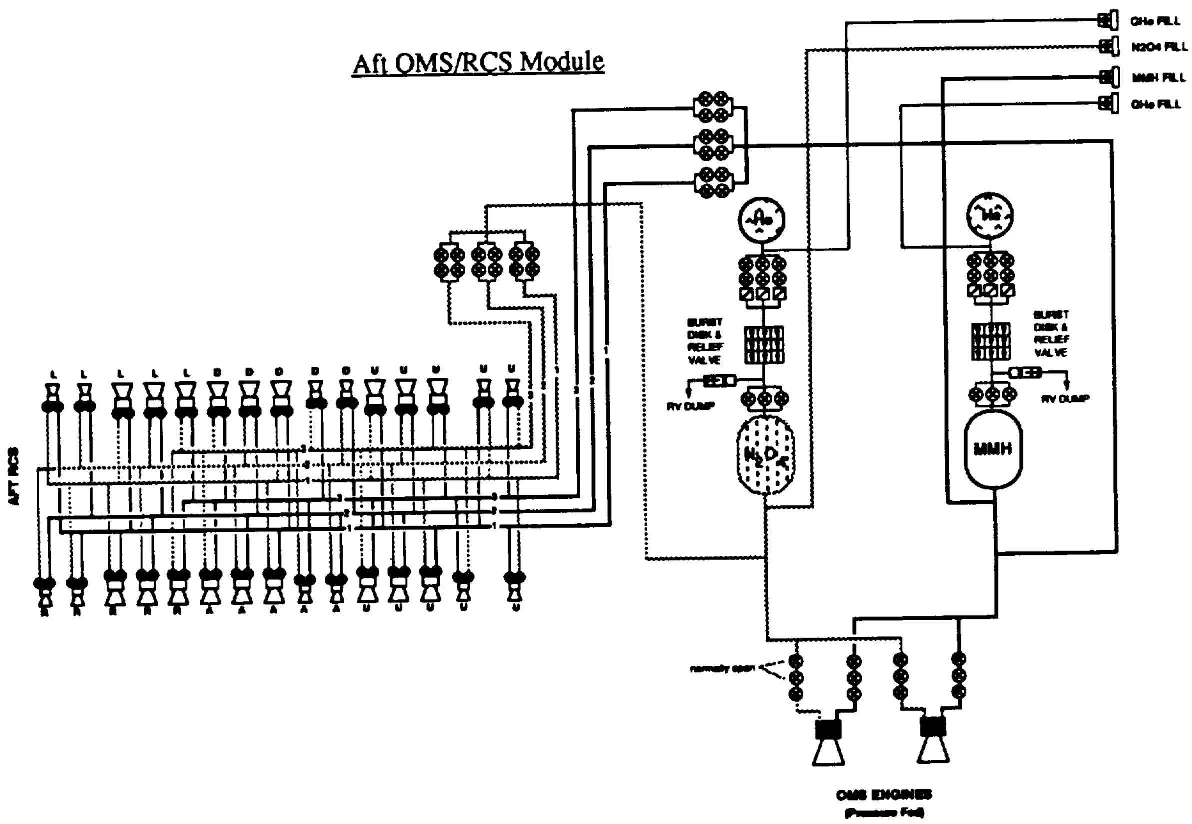
The propellant tanks will be similar to the present STS 0-g titanium tanks to accommodate on-orbit attitude control maneuvers. Each tank contains approximately 7 cubic feet of propellant.

The propellant is distributed through three manifold arrangements. Each arrangement consists of quad-redundant valve sets. The three manifolds provide upstream isolation for each group of redundant thrusters incase of thruster valve leakage or failure to close.

The vernier thrust level has been increased from the Shuttle value of 25 lbf to 50 lbf. This is true for all IHOT options, and results both from the increased size of the AMLS vehicle as well as the elimination of primary forward thrusters.

The fill and drain valves consist of a valve which is only open when the ground coupling is inserted into it. A cap is screwed onto the disconnect. Redundancy is not considered necessary for these components.




**System Schematic, Hypergolic SOA Concept**

Aft RCS/OMS Module

The entire integrated OMS/RCS system of Option 13 is triply redundant. The RCS provides back-up for OMS. The aft OMS/RCS module is easily removable and is completely serviced off line, in the Hypergolic Maintenance Facility.

Two high pressure (4000 psi) helium tanks supply pressurant independently to each propellant tank to avoid vapor migration through componentry (i.e. check valves) between the fuel and oxidizer sides. Each tank is built with a safety factor of four to accommodate transport while fully filled.

Three parallel regulators provide the required fail-closed redundancy while two isolation valves in series upstream of each regulator provides the required fail-open criteria. Eliminating the dual regulators presently used on the STS will enable in-flight checkout of each regulator as well as the isolation valves.

Triply redundant check-valves in series and parallel provide the necessary failure criteria since only one set of tanks exist (i.e., there is no crossfeed). The check valves are required to prevent propellant vapor migration upstream into the regulators causing corrosion and/or sticking.

The burst disk and relief valve accommodate tank overpressurization due to thermal effects. The assembly is normally inert. The burst disk provides a leak free barrier between propellant vapors and the relief valve, eliminating the potential for valve degradation. Since the relief valve is a spring loaded poppet valve, the chance that it will stick closed is minimal and a parallel configuration was not deemed necessary. To accommodate occasional burst disk failures during checkout procedures, an independently removable burst disk will enable simple replacement.

The manual valve presently on the STS is replaced by three parallel electrically operated isolation valves. These valves, used only for ground checkout, would be in an open position during flight. The valve permits isolation from the tank when testing a regulator after replacement.

The propellant tanks baselined are up-scaled OMS tanks with a modified propellant acquisition system to accommodate 0-g and low-g RCS use. Presently, to satisfy delta-v and maneuvering requirements, approximately 210 cubic feet of propellant will need to be stored in each tank (note residuals and contingency propellant margin is not included). This quantity is two and one third larger than the present STS OMS tank.

The propellant to the RCS is distributed through three manifold arrangements. Each arrangement consists of quad-redundant valve sets. The three manifolds provide upstream isolation for each group of redundant thrusters in case of thruster valve leakage or failure to close.

The primary thrusters will be comparable to the STS while the vernier thrust level will increase from the 25 lbf STS to 50 lbf.

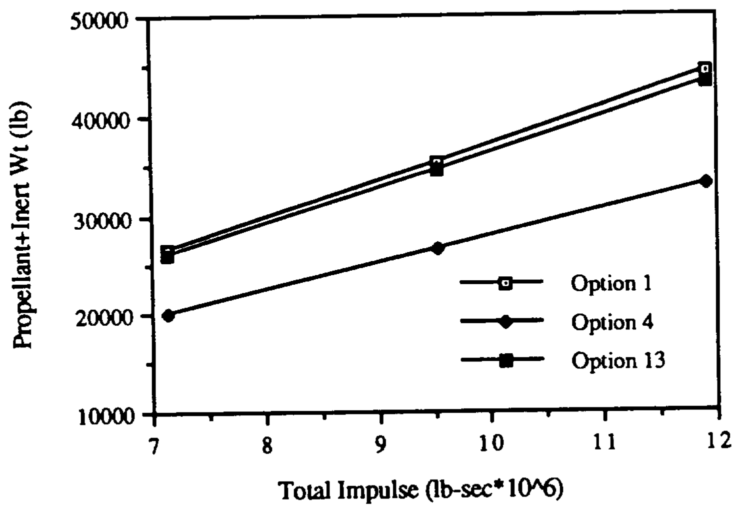
The propellant to each OME will be supplied through three electrically operated valves for oxidizer and three for fuel. This configuration provides for the necessary fail open redundancy since no tank isolation valves are used. For fail closed conditions, the other engine can continue with RCS back-up. For complete OMS loss, the RCS will perform the de-orbit burn with some performance losses.

The fill and drain valves consist of a valve which is only open when the ground coupling is inserted into it. A cap is screwed onto the disconnect. Redundancy is not considered necessary for these components.

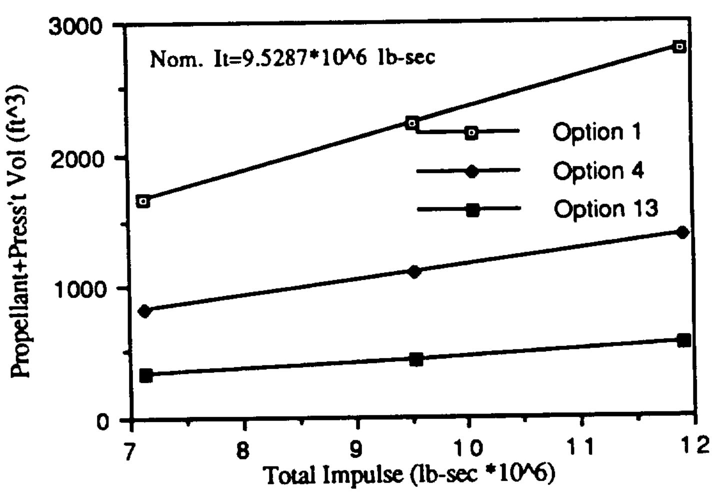
### 5.3.3. Sensitivity to Changes in Mission Requirements

In addition to definition of the three point designs for the IHOT selected concepts, the sensitivity of each design to changes in mission requirements was determined. The impact of changes in vehicle payload, inert weight, and flight performance is reflected directly in the need for increased auxiliary propulsion system total impulse. These revised total impulse requirements then impact the APS total weight and volume requirements. The following two figures illustrate the sensitivity of each IHOT concept to variations in total required impulse. In addition to the final system sensitivity results illustrated, a number of supporting trades were performed which provided insight into various aspects of IAPS design. Some of these studies (such as monopropellant gaseous verniers for Option 1) proved to be unacceptable for inclusion in the final system design. However, the data for several of these trades is included in the appendices to this report.

Appendix K defines the RCS weight and volume trades for Option 1 considering either hydrogen or oxygen as a vernier monopropellant gas, and bipropellant gaseous primary thrusters at various mixture ratios. Appendix L illustrates the effects on delivered vacuum performance of RCS and OMS engines of changes in propellant mixture ratio, and chamber pressure.




**Impact of Impulse Requirement on Total System Weight**




**Impact of Impulse Requirement on APS Volume**

## 5.4. Evaluation of IAPS Benefits

### 5.4.1. Simplified Ground Operations and Processing

**Statement of Problem**

The problem addressed in this phase of the IHOT study was to provide a quantitative assessment of the relative merits of the various concepts developed, from the viewpoint of ground operations. These data would be provided to the LCC estimate for each concept to assure accurate representation of the operational aspects of each concept developed. A final objective of this portion of the study was to demonstrate that the respective concepts could support the mission model requirements as specified for AMLS.

**Proposed Approach**

The approach used to resolve the above problems was to first define the types of data which would be needed to create a timeline for each concept, and to accumulate the cost of GSE for each of these concepts. The task flow developed was modeled after the present Shuttle, enhanced by the results of the various improved operations studies[9]. The component testing estimates and final schematics formed the basis for establishing the length of turnaround operations, where the number of components that cannot be verified on orbit, the disposal of residual propellants, and LRU operations were combined into a process flow.

**Assumptions**

The requirements for health monitoring, BITE, and expert system involvement were also factored into the amount of GSE required for processing support. The primary assumption is that BITE technology will continue to advance rapidly and in the near term can be expected to be routinely produced as a part of each mechanical component - as is current practice with avionics. The management of this BITE, either by an Expert,or Neural network system is currently in work by Rockwell, for support of the Shuttle extended duration Orbiter (EDO), for classified military systems, and on various Shuttle ground monitor systems[10]. Thus, it is reasonable that design, verification, and validation of these systems will no longer be a barrier to implementation of these tools, and current cost estimates show that the development of these systems will not exceed that of the current generation of manual GSE.

The other key assumption which must be verified prior to detailed operational comparisons was that the processing time required for each concept would meet the AMLS mission model (flight rate) requirements. The work proving out the validity of this assumption is included as Appendix C.

**Summary of Results**

The timelines developed using the approach defined have accommodated the mission model's maximum launch rate. The OMS/RCS operations fall well within the time available in the turnaround facility, and the clean pad concept assures that payload operations have been completed and only cryo connections/servicing are required at the launch pad.

The manloading of the timelines was built from sub-task scheduling extracted from the following figures, which were developed from the Shuttle-based data previously discussed in section 5.3.1.2. Note again that the schedules assume the implementation of robotics for interface connections, built-in test (BITE), and expert/neural net systems to reduce the hands-on staff to a minimum; eg, a console operator and one or two test area technicians. Note again that these typical functional and leak test timelines may include tasks not required for the final concept schematics, but were needed in some instances to present the impact of not implementing an improved ground operations task flow.

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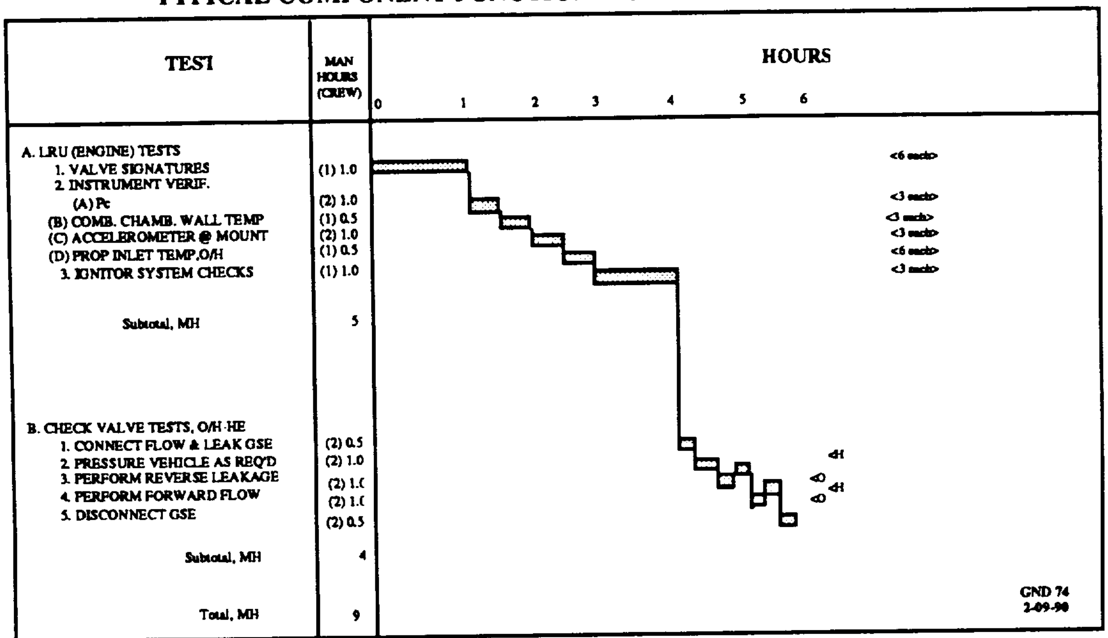
[9] Space Shuttle Directions, NASA-JSC Advanced Programs Office, June 1986.
Propulsion Considerations Required to Support Future "More Operational" Vehicles, NASA-KSC, 1988.

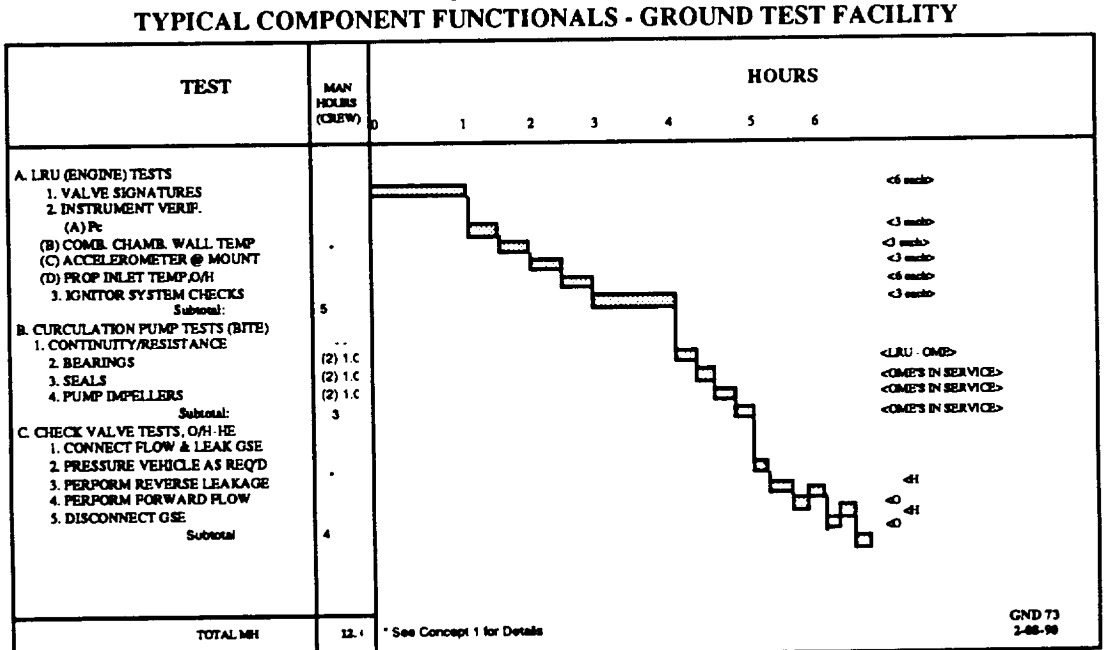
[10] Final IR&D Report FY89, In-Flight Expert Systems (89 268/26803), Software Engineering, Rockwell STSD, 1989.

## CONCEPT 1
### TYPICAL COMPONENT FUNCTIONALS - GROUND TEST FACILITY

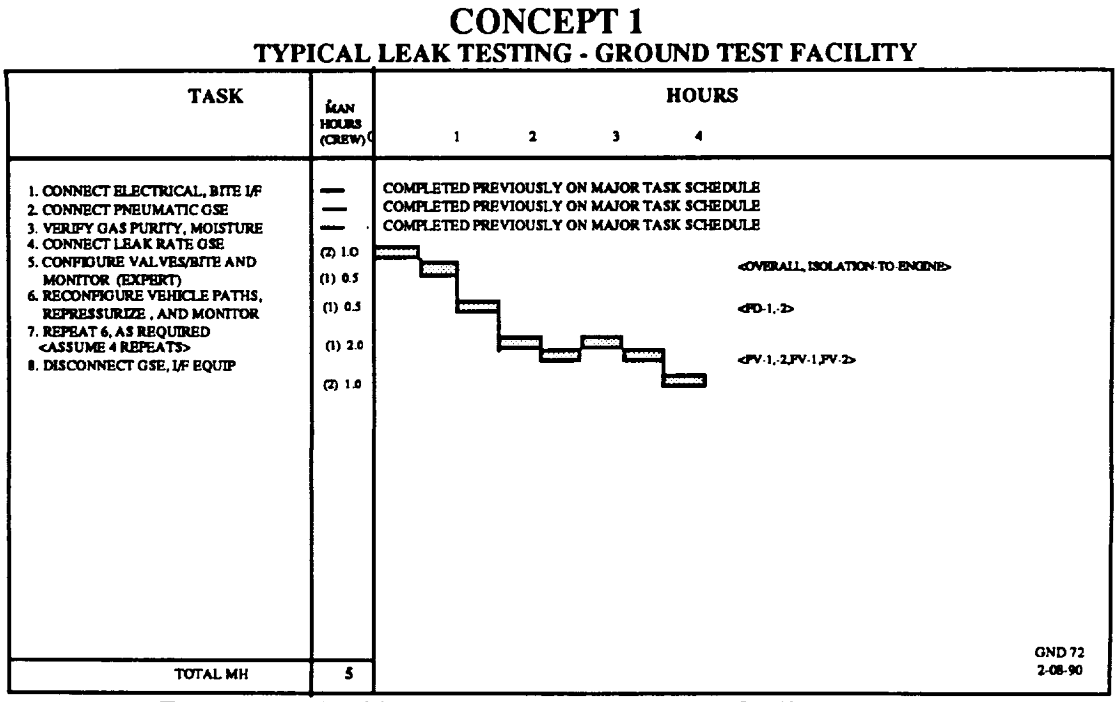



Typical Functional Test Times and Manloading at the Turnaround Facility

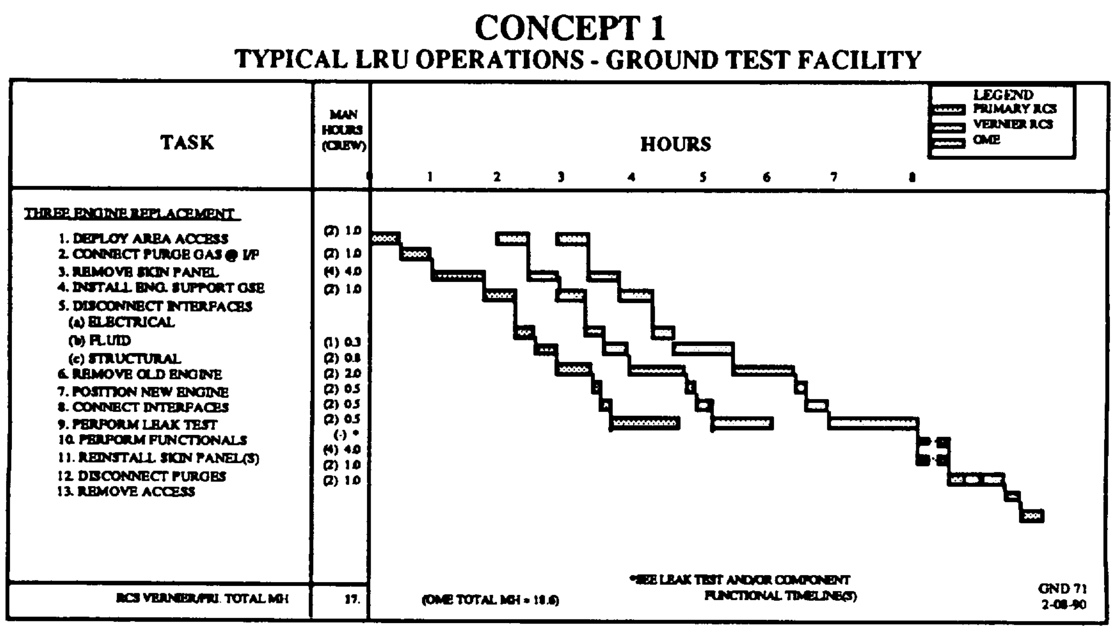
## CONCEPT 4
### TYPICAL COMPONENT FUNCTIONALS - GROUND TEST FACILITY




Expanded Functionals to Include Circulation Pump Testing



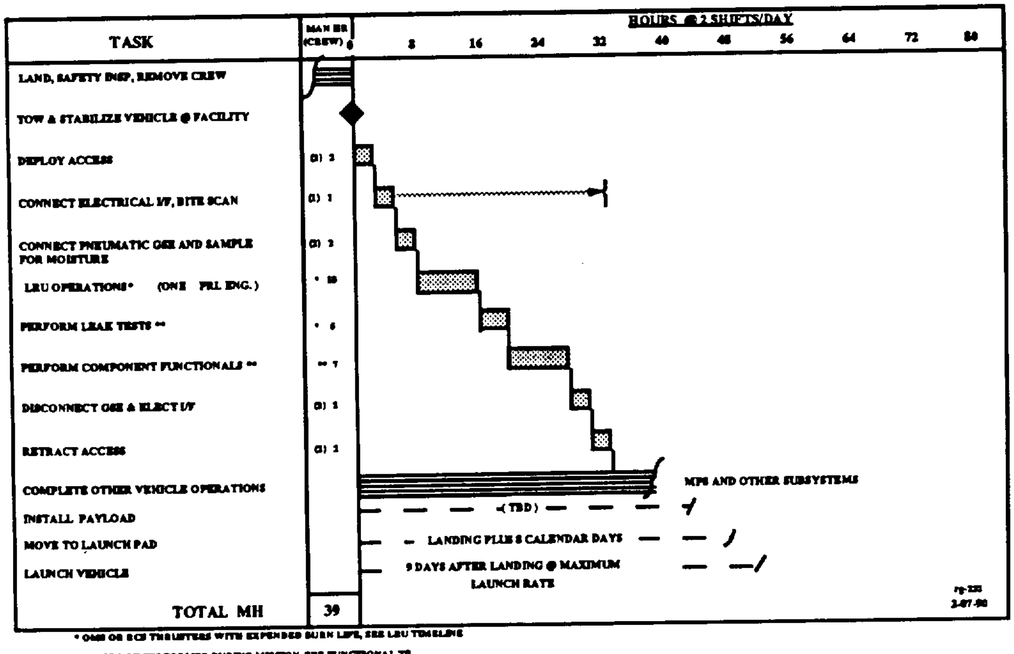

Turnaround Facility Leak Testing Time and Staff Requirements




**Engine Replacement Time and Staff Estimates**

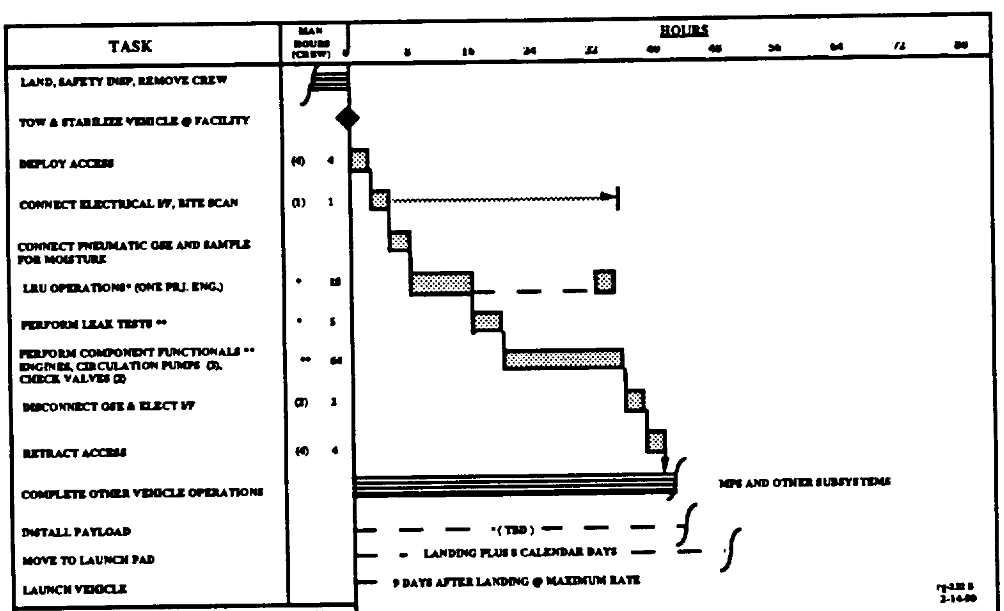
The development and identification of sub-tasks at the man-hour level, plus our experience with current Shuttle tasks, has resulted in the process manloading and times as shown in the following three timelines and direct (hands-on) staffing estimates for concepts 1, 4, and 13 (SOA). Support staff requirements have been developed in Appendix B. The fourth timeline represents a comparative "best" Shuttle processing timeline, based upon the shortest time to date for each sub-task.

**Concept 1**
**OMS/RCS Major Task Schedule-Ground Test Facility**




Total OMS/RCS Task Flow Times and Manloading (Concept 1)

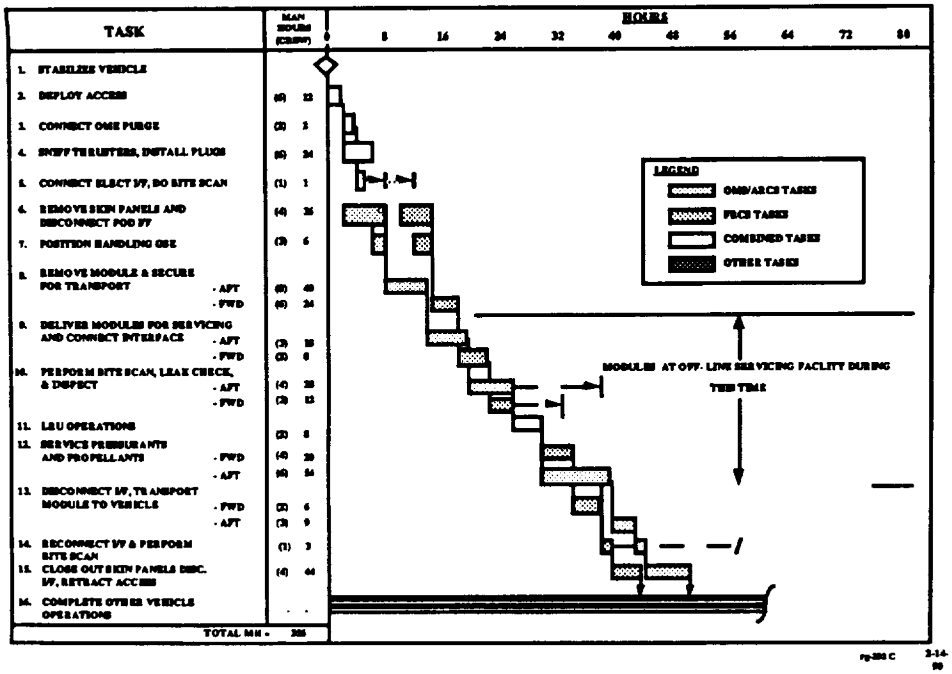
**Concept 4**
**OMS/RCS Major Task Schedule-Ground Test Facility**




* OMS OR RCS THRUSTERS WITH EXPENDED BURN LIFE, SEE LRU TIMELINE
** THOSE NOT PERFORMED DURING MISSION, SEE FUNCTIONAL TIMELINE

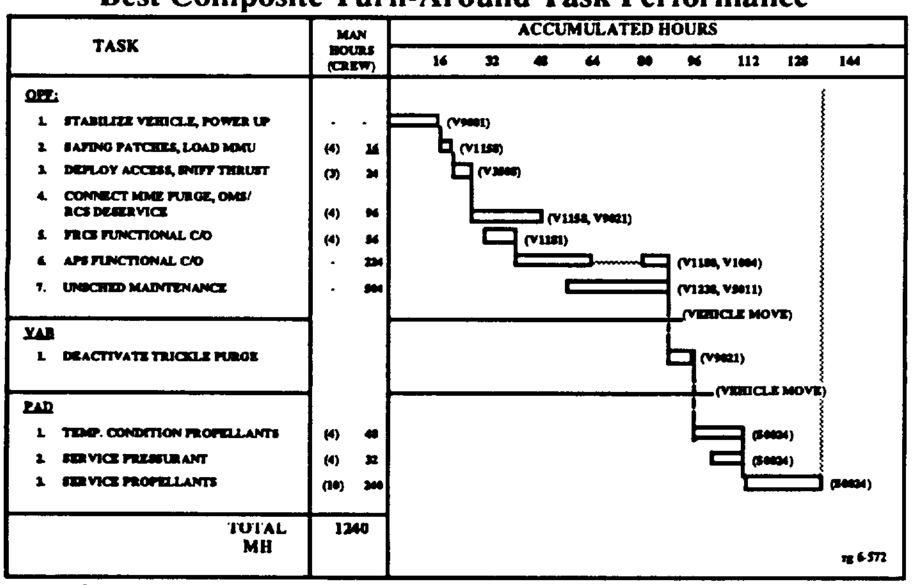
Total OMS/RCS Task Flow Times and Manloading (Concept 4)

## Concept 13 (SOA)
## Typical Turn-Around Facility Task Flow




**Total OMS/RCS Task Flow Times and Manloading for SOA Concept**

## STS OMS/RCS Tasks
## Best Composite Turn-Around Task Performance




**Shuttle Processing Timeline Shows Interruption by Other Vehicle Efforts**

The comparative Shuttle processing timeline shows relative times and manloading in the RCS area for comparison to the IHOT task flow. Note that these are task times, not total elapsed time, since other subsystem tasks are inserted during actual processing.

The accommodation of the mission model's three week mission and 12 launches per year (maximum on-orbit duration, maximum launch rate) by the concept 1, 4, and 13 timelines has been shown on the turnaround timeline in Appendix C, "AMLS Launch-to-Landing", to put the OMS/RCS task duration into perspective for this processing effort. Note that all three concepts can be accommodated at the maximum launch rate.

Comparative manloading for the three concepts and Shuttle's best composite are presented in the following table, and represent direct labor only. Indirect and base/range impacts can be assessed by multiplying by the factors developed earlier (Appendix B).

| ITEM | Concept 1 | Concept 4 | Concept 13 | STS |
|---|---|---|---|---|
| Turnaround processing for APS (Manhours) | 39 | 98 | 355 | 1240 |

**Comparative Manloading**

These reduced levels of ground operations have been achieved only through implementation of strict design rules and a test philosophy for both the flight vehicle and the ground systems that use current thinking toward improved processing techniques. The benefits for ground operations of IHOT hydrogen/oxygen IAPS concepts can be summarized as follows:

| | |
|---|---|
| Landing Site | • Purge on reentry (no residual OMS, FRCS - only ARCS<br>• No SCAPE (self-contained atmospheric protective ensemble) for crew (no toxic gases)<br>• Less GSE (gas sampling units), calibration, and cleaning |
| Turnaround Processing | • No helium blowdown (SCAPE), since no toxic/corrosive fluids to migrate<br>• No pods to remove; processing OMS/RCS in T/A facility concurrently with other tasks<br>• Maintenance intervals will be extended, since corrosive materials are not present.<br>• No screens or bladders to test in gaseous concept<br>• Pressurant can be loaded in T/A facility without a major "area clear" (increased safety factor on pressurant bottles)<br>• Elimination of idle time for entire crew<br>• Elimination of facility provisions and GSE for hypergol spill accommodation |
| Launch Pad | • No vacuum fill of manifolds (gaseous propellants, or circulation system for liquids)<br>• No special access for servicing<br>• No propellant conditioning, or vehicle temperature control for OMS/RCS<br>• Less sampling (SCAPE)<br>• Less GSE maintenance<br>• Elimination of idle time (other system technicians) during hypergol servicing or safing operations |

**Benefits of IHOT/IAPS for Enhanced Ground Operations**

5.4.2. Detailed Costing Comparison

**Statement of Problem**

In order to properly evaluate the cost benefits which result from implementation of an IAPS concept, it is necessary to evaluate all three concepts (1, 4, 13) on the basis of their LCC. The three aspects of LCC to be evaluated are DDT&E costs, production costs, and operational costs.

**Approach**

The general approach followed was to estimate the constituents of development and production cost by hardware component. Specific quantities and types of components were determined from the concept schematics (section 5.3). These schematics include the effects of redundancy and reliability criterion applicable to an AMLS vehicle. Individual WBS items for development and production are estimated from either parametric cost estimating relations (CERs, based on weight and other technical performance parameters), from engineering judgement, and/or based upon actual costs of comparable parts in the Shuttle Orbiter, where applicable. Also, learning curves have been applied to production costs when appropriate.

For DDT&E, and TFU (theoretical first unit) costs for items such as engines, estimates were based primarily upon analogy, using the Rocketdyne historical data base. Costs were based upon engines resembling those required for IHOT as closely as possible, and were adjusted to account for technical complexity, and size using parametric cost estimating relations[11]. Integration costs were included. Engine development, in turn, is broken down into "base R&T" (basic research which is generally propulsion-related, and not AMLS-specific), and that which would be charged directly to the AMLS program. It is acknowledged that this distinction is somewhat arbitrary, but the trend in current new-program development (STME, etc) is towards "clean-interface" designs, which may easily be adapted to a number of future vehicles. This spreads the development costs over a number of vehicles, and decouples engine development somewhat from the funding cycles of a specific program. AMLS-specific development for each engine is broken down into hardware (primarily for testing), labor (principally engineering), test-bed activity, and R&D oriented towards BITE.

For production, total costs are calculated by multiplying the number of items by the number of vehicles required. The number of vehicles necessary was based upon the "civil needs" data base and scenario developed by Rockwell in the Next Manned Transportation Study[12]. Component costs were based (where appropriate) on Shuttle actual costs, modified for technical complexity and physical characteristics such as weight, and volume/surface area (tanks). For the production costs, the TFU was modified by learning curves used for items purchased in significant quantities. Integration costs were also accounted for.

Operations costs are broken down into launch operations, and refurbishment. Launch operations costs per flight are a function of the labor hours of each major subactivity (as estimated in the previous section). Man-hour estimates are not merely "success-oriented", but rather reflect anticipated "average" values. The detailed costing data shows *significant* reductions in APS operations compared to conventional systems; even for the hypergolic system (Option 13). It should be understood that this is a reflection of a fundamental cultural change which must take place to enable IAPS development. This change incorporates concern for servicing and operation at the very earliest phases of system design, and emphasizes LCC over high performance. An integrated approach to APS development also recognizes that the best way to reduce operations costs is to eliminate additional interfaces (for multiple propellants and fluids), and share all interfaces which are absolutely required. In this manner, IHOT operations costs are almost eliminated, because all pad/ground interfaces are shared with MPS. Thus most operations involving these interfaces are absorbed by MPS and require no additional APS servicing.

The cost of IAPS refurbishment is based on expected equipment lifetime. Refurbishment costs for IHOT are based on a proportion (40%) of the production costs of an item.

**Assumptions**

The life cycle cost estimates for IAPS as applied to the AMLS vehicle is influenced profoundly by the mission model assumptions. These assump-

[11] Parametric Life Cycle List (LCC) As Concept Ranking Criterion, Journal of Parametrics, Vol. 10, February 1990.

[12] Next Manned Transportation Study, IR&D project, Space Transportation Systems Division, Rockwell International, September, 1989.

tions are detailed in the table below. The same assumptions were applied to all three IHOT concepts.

- 400 total flights, over 20 years, beginning in 2005, ending in 2024
- Peak flight rate 26/year, in 2007
- Average mission duration 7 days, assume takeoff and land at same site
- Average turnaround time, 23 days
- Effective flights/yr/vehicle, 11
- 3 Vehicles required to support max flight rate
- 4 Vehicles total (3, +1 backup)
- 100 flights per vehicle
- Engines refurbished every 30 flights

**LCC Mission Model Assumptions**

For the pressure-fed OMS engine of Option 1, development costs were based upon the Lunar Tracking Vehicle (LTV) / Lunar Exploration Vehicle (LEV) CERs. The expander-cycle OMS engine of Concept 4 was based upon the results of the Advanced Space Engine[13] study. The DDT&E costs for RCS for Options 1 and 4 were based upon the LTV/LEV study results, suitably modified for the differences of the two concepts. The development costs for Option 13 were based upon actual Shuttle data, incorporating the work which is currently underway on Shuttle-C.

Production costs for Options 1 and 4 OMS engines were based upon OTV values, modified by CERs. Option 1 was adjusted to delete the cost of turbomachinery. OMS production costs for Option 13 was based upon the actual costs for the last Shuttle purchase. Production costs for Option 1 primary RCS engines were assumed to be 20% less expensive to produce than the all-liquid engines of Option 4. The estimates for the hydrogen/oxygen vernier engines were based upon Space Station thruster data, with the Option 4 values 20% higher than the gaseous engines of Option 1. Primary and vernier thruster data for Option 13 were based upon Marquardt data incorporating the effects of low cost manufacturing technology.

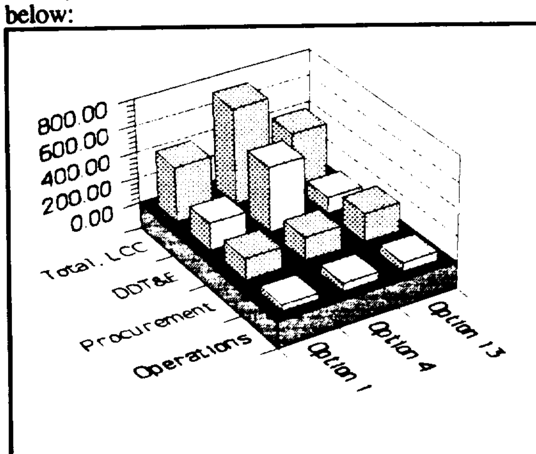
Production costs for tankage, and other distribution system components were based upon STS Orbiter CERs.

Operations costs for IHOT assumed labor costs of \$50/hr, with indirect costs 25% of direct costs for Options 1 and 4, and 50% for Option 13. Refurbishment costs for OMS (all options) were assumed to be 40% of the average production cost of the engines. For RCS, refurbishment was assumed to be 30% of the average production cost.

The discount rate was assumed to be 5% / year.

**Summary of Results**

The results of the LCC analysis of the IAPS concepts are summarized in the Table and Figure below:




**Comparison of Cost Elements for Selected IHOT Concepts**

| | Option | | |
|---|---|---|---|
| | 1 | 4 | 13 |
| DDT&E<br>Procurement<br>Operations | 208.0<br>164.4<br>48.6 | 494.5<br>178.7<br>58.5 | 123.5<br>214.6<br>68.6 |
| LCC, total, (undiscounted) | \$421M | \$731.7M | \$406.7M |
| LCC, discounted, to 1990 @ 5% | \$227M | \$405.4M | \$204.6M |

**LCC Summary Table**

Life cycle costs were computed for all three concepts, for a common flight mission requirement. The most important result to be drawn is that on an LCC basis, it is possible to develop an IAPS hydrogen/oxygen concept which is nearly identical in price to a hypergolic system. This is true even including the affect of IAPS development cost, and allowing for the development of an "operationally efficient" hypergolic system (IAPS Option 1 within 5% of the cost of Option 13). If development costs are *not* included, the IAPS concept (Option 1) offers a 33% cost reduction over an operationally efficient hypergolic system. It should be noted that the hypergolic

[13]Rocketdyne's $O_2/H_2$ Engine for Space Transfer Vehicles, Advanced Propulsion Engineering, Canoga Park, 20 October, 1989

system utilized for comparison in IHOT is *NOT* to be considered representative of current Shuttle costs. Rather, Option 13 was to represent the best possible improvement in operational efficiency and low cost to be expected of hypergolic systems; utilizing the latest developments in BITE and good systems engineering design practice.

It is important also to note that the development costs of OMS/RCS engines turned out to be the largest discriminator between the selected concepts. The fact that engine development, rather than operations, was the largest contributor to LCC was largely as result of the IHOT study groundrules. These, in part, emphasized the importance of considering the operational aspects of APS concepts in the earliest trade studies, rather than approaching operations as simply the implementation of an existing design.

The next nine tables summarize the costs and assumptions which resulted from the IHOT study. The first three of these describe the DDT&E cost elements for each Option. Additional detail on engine costing is provided in Appendix D. These charts are followed by a summary of procurement costs, and finally three tables summarizing the relative operational and refurbishment costs for each Option.

| DDT & E | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Base R & T* | | |
| • OMS Engine | 0 | |
| • RCS Primary Thruster | 5 | Demonstration of 16:1 engines |
| • RCS Vernier Thruster | 5 | " |
| • BITE | 6 | Demonstrate BITE/sensor viability (30% BITE DDT&E) |
| *AMLS-Specific Development* * | | |
| OMS Engine | | |
| Hardware | 17.5 | 5 Units, at $3.5M per Engine |
| Labor | 49 | - |
| Test Bed | 14 | No large Pressure-fed Engine stands available |
| BITE | 5 | Sensor development/integration into Engine |
| RCS Primary Thruster | | |
| Hardware | 3 | 10 Units plus supporting H/W, ~$180K/engine, 16:1 MR |
| Labor | 35 | Design, Test |
| Test Bed | 20 | Integrated; w/verniers |
| BITE | 5 | Sensor development/integration into Engine |
| RCS Vernier Thruster | | |
| Hardware | 1 | Minimum HW $ to support testing, ~$50K/engine |
| Labor | 25 | Smaller Engine, reflected in costs |
| Test Bed | 0 | Part of Primary Engine costs |
| BITE | 0 | " |
| BITE System Development | 14 | Development/implementation of AMLS BITE architecture |
| Other | 3.5 | |
| TOTALS (Base R & T) | 16 | |
| TOTALS (AMLS-specific) | 192 | |
| Total Development | 208 | |

**Option 1, Development Costs**

| DDT & E | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Base R & T* | | |
| • OMS Engine | 0 | |
| • RCS Primary Thruster | 5 | Liquid RCS Engine development |
| • RCS Vernier Thruster | 5 | " |
| • BITE | 9.3 | Demonstrate BITE/sensor validation & development (30% BITE DDT&E) |
| *AMLS-Specific Development* * | | |
| OMS Engine | | |
| Hardware | 72 | 15 development engines, 3 for component tests, @ ~$4M/engine |
| Labor | 255 | - |
| Test Bed | 0 | Pump-fed test stands available for application |
| BITE | 10 | Sensor development/integration into Engine |
| RCS Primary Thruster | | |
| Hardware | 3 | 10 Units plus supporting H/W, ~$220K/engine |
| Labor | 40 | Design, Test; adds vacuum jacket, recirculation pump activities |
| Test Bed | 30 | Integrated, w/verniers; " |
| BITE | 8 | Sensor development/integration into Engine; more components than "1" |
| RCS Vernier Thruster | | |
| Hardware | 1 | Minimum HW $ to support testing; ~$50K/engine |
| Labor | 30 | Smaller Engine, reflected in costs |
| Test Bed | 0 | Part of Primary Engine costs |
| BITE | 0 | " |
| BITE System Development | 21.7 | Development/implementation of AMLS BITE architecture |
| Other | 4.5 | |
| TOTALS (Base R & T) | 19.3 | |
| TOTALS (AMLS-specific) | 475.2 | |
| Total Development | 494.5 | |

**Option 4, Development Costs**

| DDT & E | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Base R & T* | | |
| • OMS Engine | 0 | No R & T required for SOA APS concept |
| • RCS Primary Thruster | 0 | " |
| • RCS Vernier Thruster | 0 | " |
| • BITE | 7.8 | Demonstrate BITE/sensor validation & development (30% BITE DDT&E) |
| *AMLS-Specific Development* * | | |
| OMS Engine | | |
| Hardware | 8 | 2 development engines, @ ~$4M/engine |
| Labor | 20 | Must requalify engines |
| Test Bed | 0 | Test stands available for application |
| BITE | 15 | Sensor development/integration into existing Engine |
| RCS Primary Thruster | | |
| Hardware | 1 | 3 Units plus supporting H/W, ~$.3M - .8M /engine |
| Labor | 15 | Must requalify engines |
| Test Bed | 0 | Existing |
| BITE | 10 | Sensor development/integration into existing Engine |
| RCS Vernier Thruster | | |
| Hardware | 1 | Minimum HW $ to support testing, 3 engines |
| Labor | 10 | Must requalify engines |
| Test Bed | 0 | Existing |
| BITE | 0 | Sensor development/integration into existing Engine |
| BITE System Development | 18.2 | Development/implementation of AMLS BITE architecture |
| Other | 17.5 | Includes $15M for fwd/aft module structure development |
| TOTALS (Base R & T) | 7.8 | |
| TOTALS (AMLS-specific) | 115.7 | |
| Total Development | 123.5 | |

**Option 13, Development Costs**

| PROCUREMENT | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Propulsion System Hardware* | | |
| • OMS Engine | 42 | |
| • RCS Primary Thruster | 13 | |
| • RCS Vernier Thruster | 4 | |
| • Tankage, misc. hardware | 83 | Tanks, valves, lines, regulators. |
| *GSE* | 1.9 | 2 facilities, based on ALS costs, escalated to FY90 $ |
| *BITE* | 20.5 | |
| Total Procurement | 164.4 | |

**Option 1, Procurement Costs**

| PROCUREMENT | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Propulsion System Hardware* | | |
| • OMS Engine | 48 | |
| • RCS Primary Thruster | 16 | |
| • RCS Vernier Thruster | 5 | |
| • Tankage, misc. hardware | 76.8 | Tanks, valves, lines, regulators. |
| *GSE* | 1.9 | 2 facilities, based on ALS costs, escalated to FY90 $ |
| *BITE* | 31 | |
| Total Procurement | 178.7 | |

**Option 4, Procurement Costs**

| PROCUREMENT | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Propulsion System Hardware* | | |
| • OMS Engine | 32 | |
| • RCS Primary Thruster | 22 | |
| • RCS Vernier Thruster | 13 | |
| • Tankage, misc. hardware | 98.8 | Tanks, valves, lines, regulators, and module structure |
| *GSE*** | 23.2 | Includes specialized hypergolic facilities |
| *BITE* | 25.6 | |
| Total Procurement | 214.6 | |

**Option 13, Procurement Costs**

| OPERATIONS | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Launch Operations* | | |
| • Direct Labor | 0.9 | Calculated from operational timelines |
| • Indirect Labor | 0.2 | 25% of Direct labor costs |
| • Base/Range Support | 0.2 | 25% of Direct labor costs |
| *Engine Refurbishment* | | |
| • OMS Engine | 33.6 | |
| • RCS Primary Thruster | 10.4 | |
| • RCS Vernier Thruster | 3.3 | |
| Total Operations | 48.6 | |

**Option 1, Operations Costs**

| OPERATIONS | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Launch Operations* | | |
| • Direct Labor | 2.2 | Calculated from operational timelines (98hr/flight, x400 flights) |
| • Indirect Labor | 0.6 | 25% of Direct labor costs |
| • Base/Range Support | 0.6 | 25% of Direct labor costs |
| *Engine Refurbishment* | | |
| • OMS Engine | 38.3 | |
| • RCS Primary Thruster | 12.8 | |
| • RCS Vernier Thruster | 4 | |
| Total Operations | 58.5 | |

**Option 4, Operations Costs**

| OPERATIONS | Cost ($M) | Notes/ Assumptions |
|---|---|---|
| *Launch Operations* | | |
| • Direct Labor | 7.8 | Calculated from operational timelines (98hr/flight, x400 flights) |
| • Indirect Labor | 3.9 | 50% of Direct labor costs |
| • Base/Range Support | 3.9 | 50% of Direct labor costs |
| *Engine Refurbishment* | | |
| • OMS Engine | 25.3 | |
| • RCS Primary Thruster | 17.4 | |
| • RCS Vernier Thruster | 10.3 | |
| Total Operations | 68.6 | |

**Option 13, Operations Costs**

## 5.5. Identification of Technology Requirements

In the IHOT study, work in the areas of concept definition, ground operations, and cost estimation identified a number of areas of critical technology development. These technology requirements were divided into two categories; enabling, and enhancing. Enabling technologies are those which must be developed and proven for the particular IAPS concept to reach operational status. Enhancing technologies are those which are not critical to the viability of a particular design, but rather provide specific additional features regarding cost, operational effectiveness, or performance. In the sections below, the critical enabling technologies will be described, and a timeline proposed for bringing each of them to a level of development which will support the AMLS program. This also allows the identification of areas of development which support multiple new vehicles, and where the development costs may be shared across programs.

A table of possible areas of enhancing technology is included last, which suggests additional areas of development supporting low-cost, operationally efficient integrated auxiliary propulsion systems.

### 5.5.1. Enabling Technology Requirements

The enabling technology requirements to support development of the IAPS concepts resulting from the IHOT study are summarized in the table below. In addition to a brief description of each technology area, a summary of the current status of the technology is included. The eight technology levels used are consistent with NASA terminology. The table also indicates which of the three IHOT concepts require the specific enabling technology.

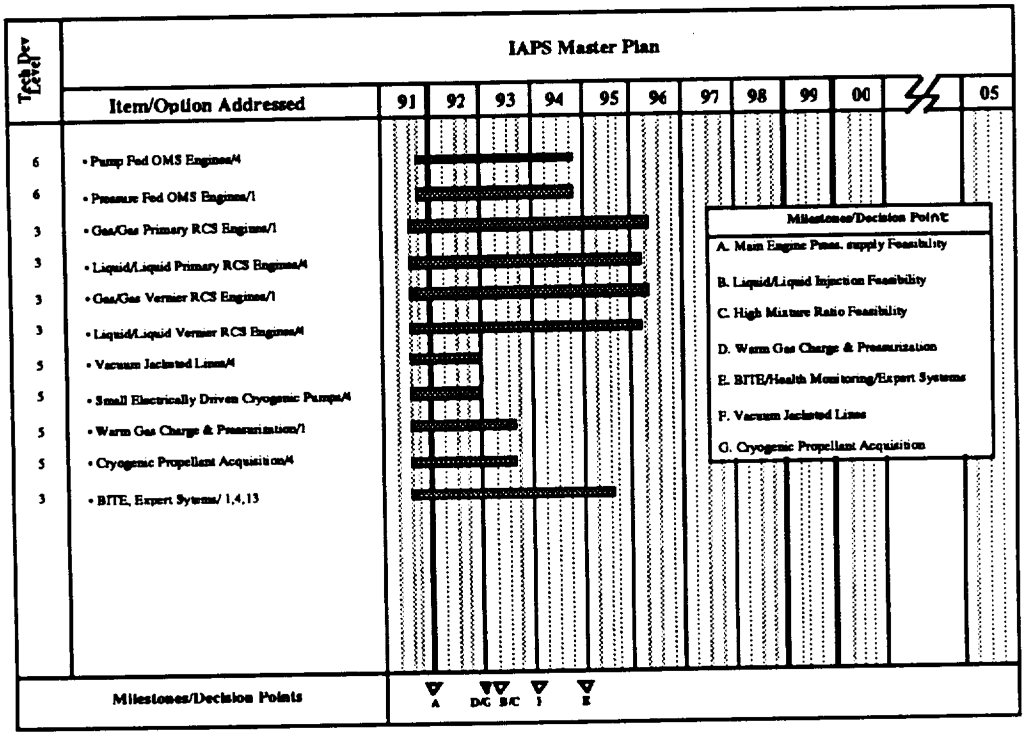
**Technology Development Levels**

1. Basic Principles Observed And Reported
2. Conceptual Design Formulated
3. Conceptual Design Test Performed Analytically Or Experimentally
4. Critical-Function Breadboard Demonstration
5. Component Or Brassboard Model Tested In Relevant Environment
6. Prototype Or Engineering Model Tested In Relevant Environment
7. Engineering Model Tested In Space
8. Baselined Into Production Design

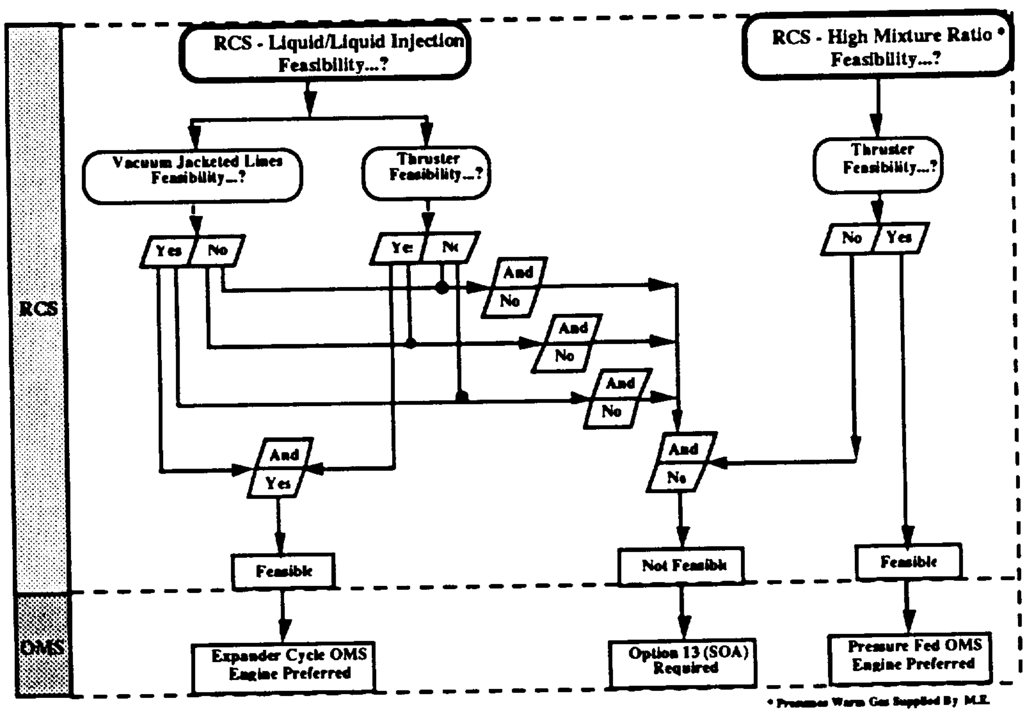
| Item | Description/Issue | Current Technology Development Level | Year Available IOC (T=8) | Decision Milestone (Year Of 1st Decision) | Option(s) Addressed | Enabling (Timeline Included) |
|---|---|---|---|---|---|---|
| OMS Engines | Pump or Pressure Fed, Zero G Operation | 6, 6 | 1994 | 1991 | 1, 4 | X |
| Primary RCS Engines | Liquid/Liquid Injection or High MR Gas (16:1), Zero G Operation | 3, 3 | 1996 | 1991 | 1, 4 | X |
| Vernier RCS Engines | Liquid/Liquid Injection or High MR Gas (16:1), Zero G Operation | 3, 3 | 1996 | 1991 | 1, 4 | X |
| Vacuum Jacketed Lines | Thermal Isolation At Interfaces, Boiloff Control | 5 | 1992 | N/A | 4 | X |
| Small Electric Cryogenic Pumps | Zero G Operation, Boiloff Control | 5 | 1992 | N/A | 4 | X |
| Integrated Control & Health Monitoring, Expert Systems & BITE | Integrated BITE/HM/Exp Systems, Minimize Ground Operations, Demonstrate Viability Of Monitoring IAPS Status and Problems (Go/No Go Decision for Next Flt) | 5 | | | 1, 4, 13 | X |
| Warm Gas Charge and Pressurization | Demonstrate Charging Of High Press Accum In Ascent Envir | 5 | 1993 | N/A | 1 | X |
| Cryogenic Propellant Acquisition | Guarantee Liquid At Injector (Liquid/Liquid RCS Engines) | 5 | 1993 | N/A | 1, 4 | X |

**IAPS Technology Assessment**

The following two charts illustrate the top-level technology maturation timelines, and how results may affect the selection of a specific IHOT concept (Option 1, 4, or 13).



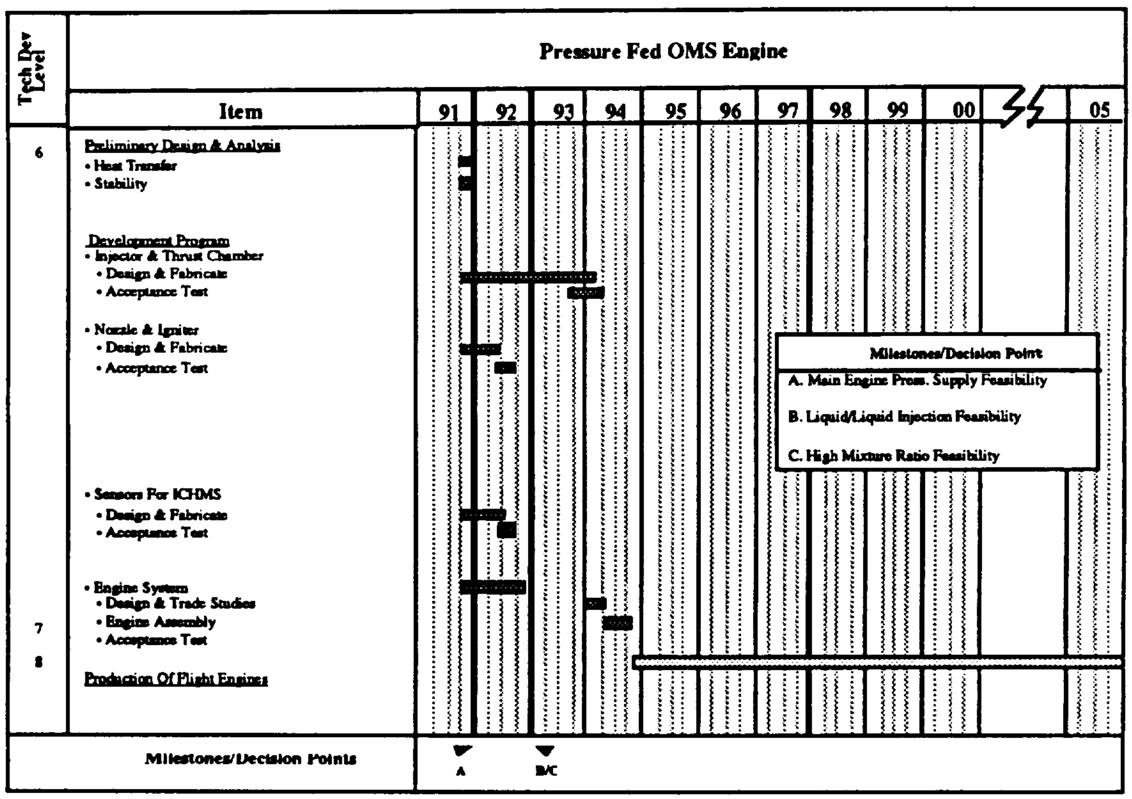

**IAPS Technology Master Plan**



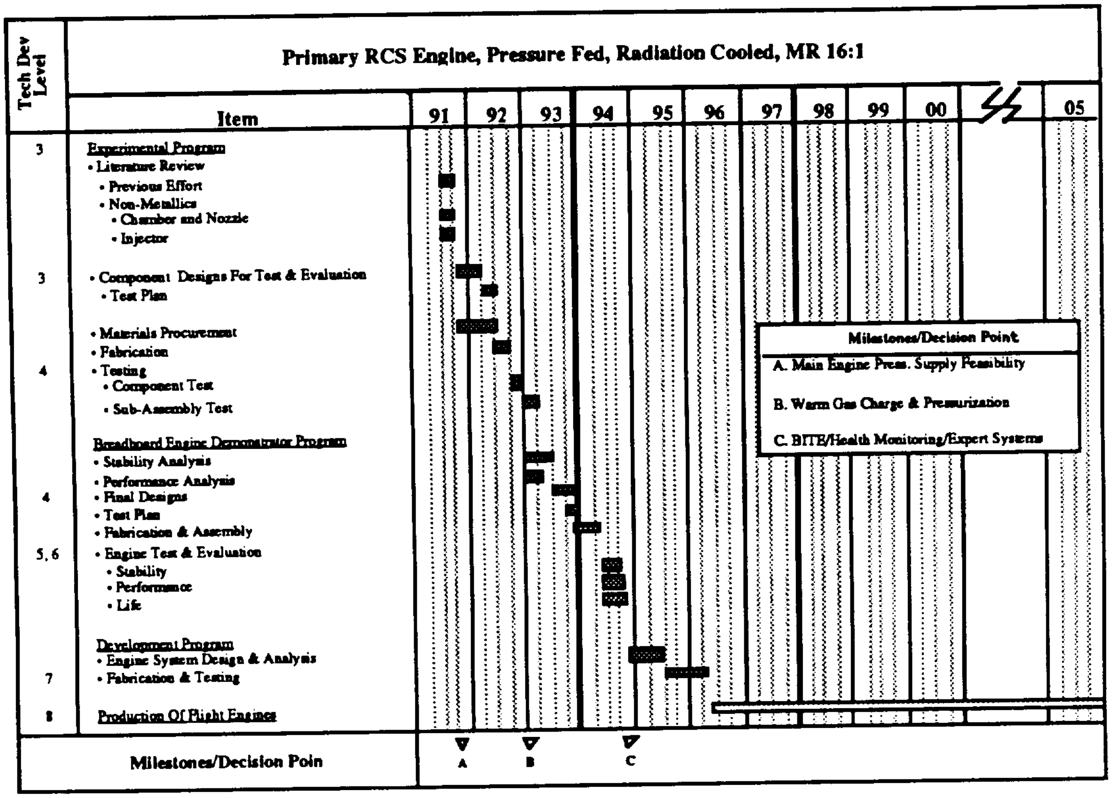

**IAPS Technology Development Logic**

Implicit in all three concepts is the development of BITE and the attendant expert systems necessary to allow dramatic reduction in ground operations cost. Without automation of ground operations and a "cultural change" in the attitude towards launch processing, IAPS concepts will not significantly alter the cost and complexity of auxiliary propulsion systems.

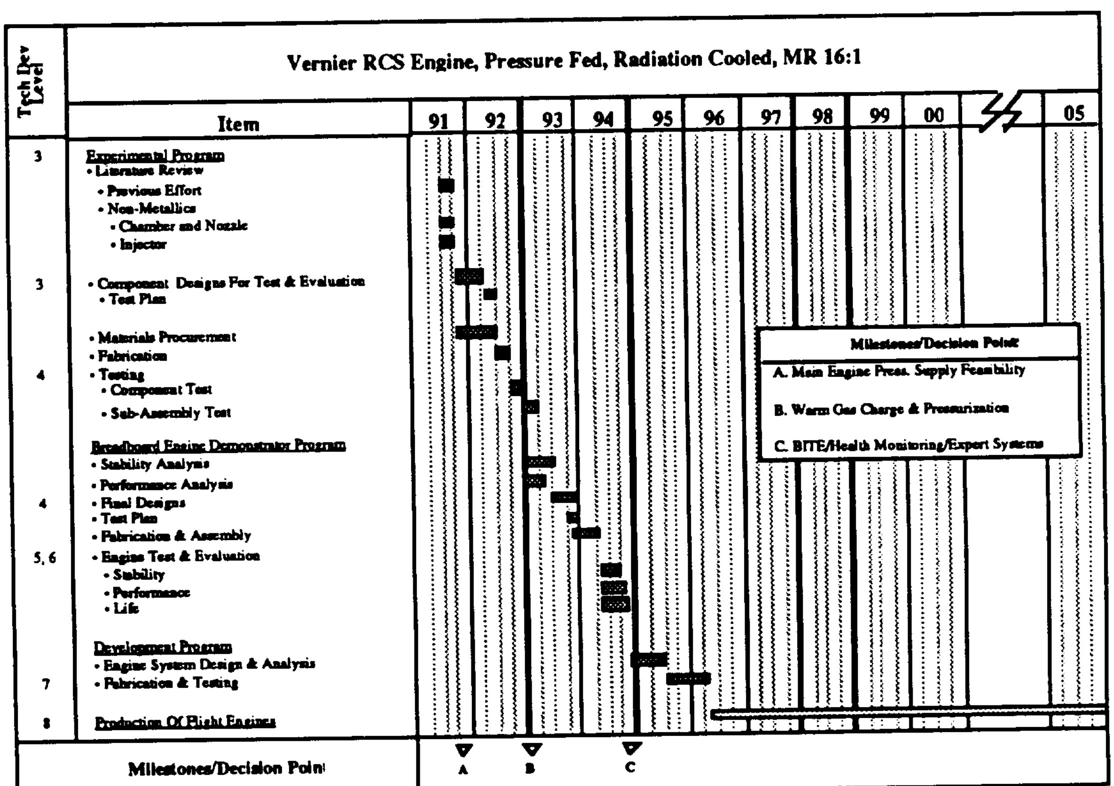
The next three charts present the technology development timeline estimates for the engine development necessary to support Option 1. As previously indicated, this concept utilizes a pressure fed $LH_2/LO_2$ OMS engine, with high mixture ratio (16:1) gaseous thrusters.




**Pressure Fed OMS Engine Timeline**

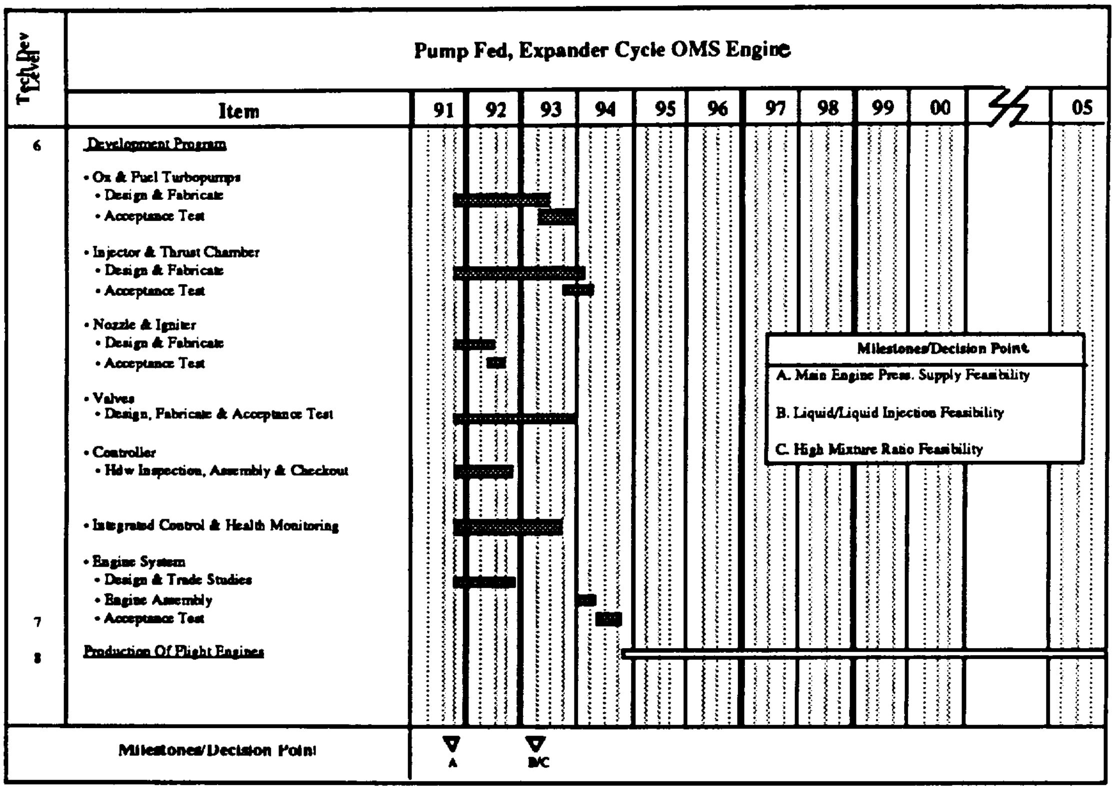



**Primary RCS Engine (MR 16 to 1) Timeline**

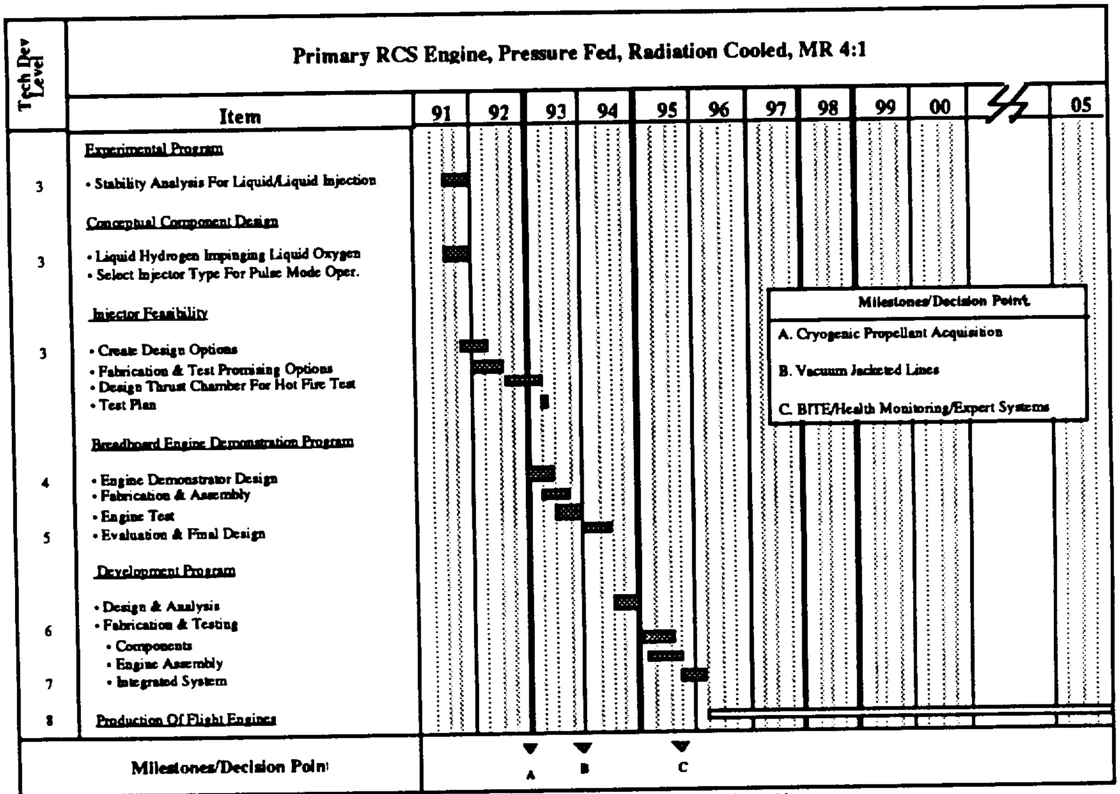



**Vernier RCS Engine (MR 16 to 1) Timeline**

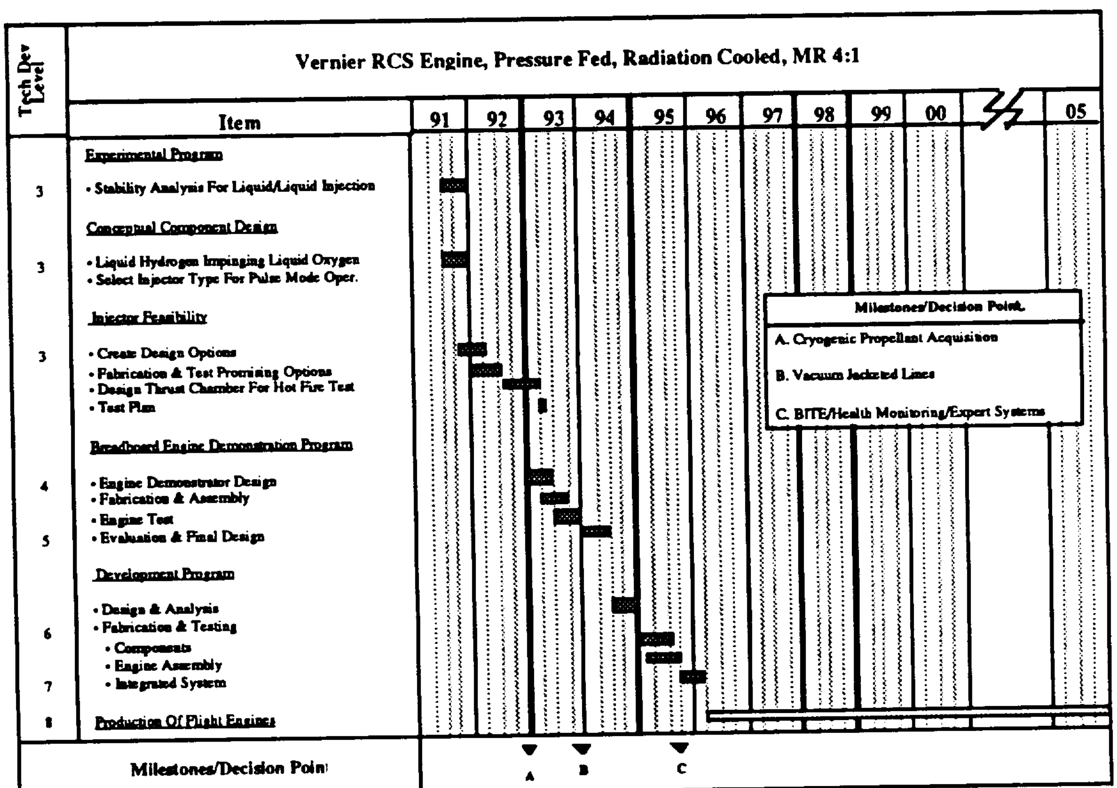
Option 4 presents a number of unique technological challenges in the area of engine development. The next three charts define the areas of emphasis to assure engine technology is available to support cryogenic auxiliary propulsion systems in an AMLS-like vehicle. Particularly in the area of RCS engines, maintaining propellants at the proper conditions and fluid phase is a significant challenge.




**Pump Fed Expander Cycle OMS Engine Timeline**

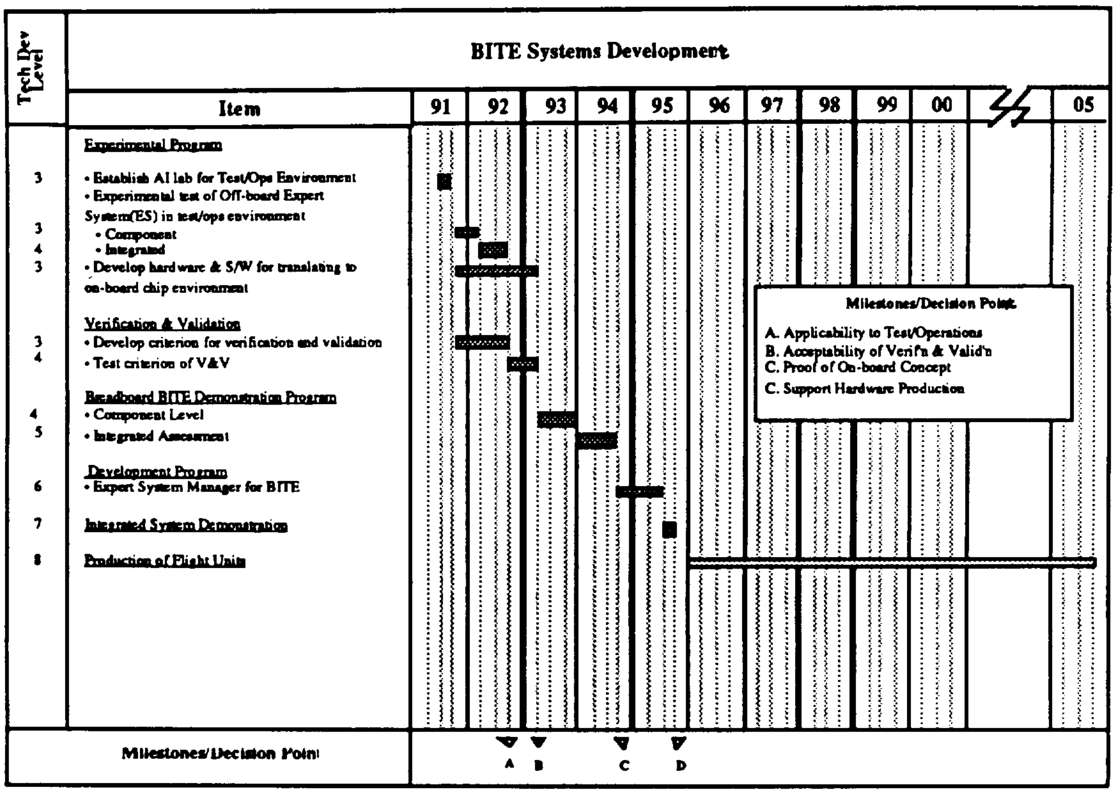



Primary RCS Engine (Liquid) Timeline



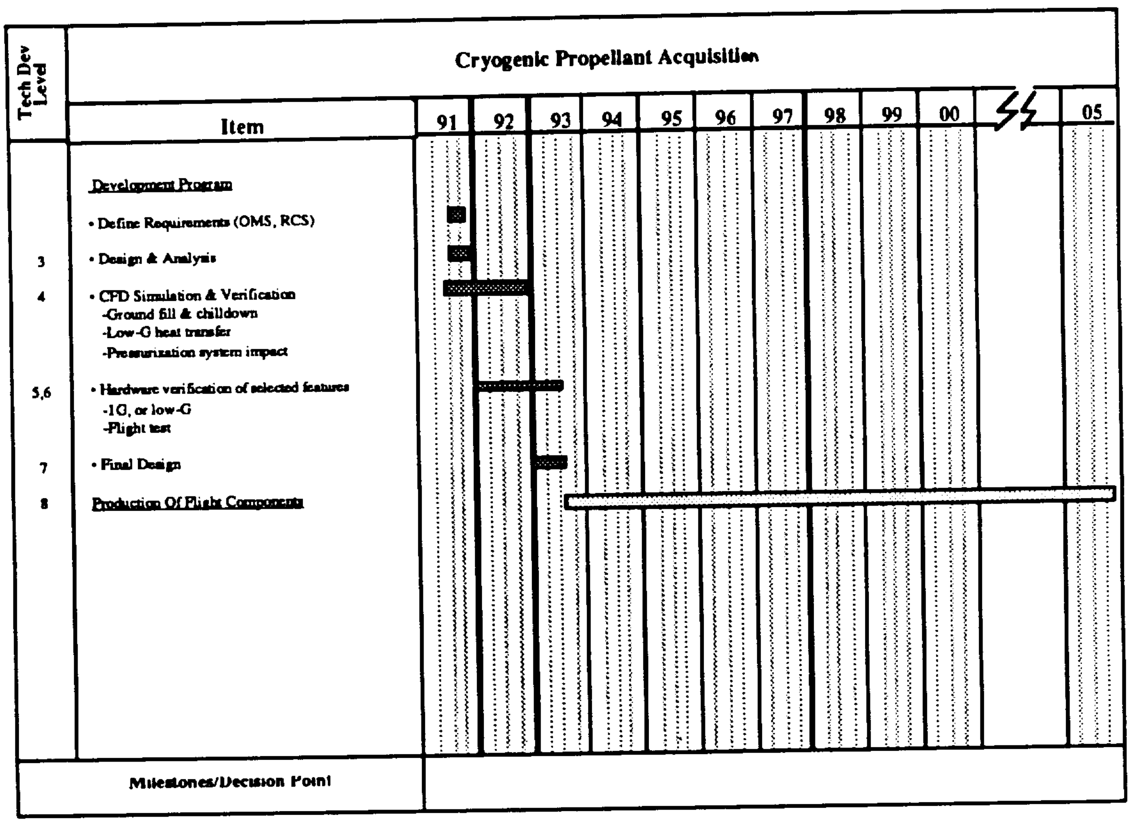

Vernier RCS Engine (Liquid) Timeline

Development of BITE and Expert Systems is a critical enabling technology for all three IHOT concepts. Even SOA (hypergolic) APS could benefit substantially from on-board test and leak-check capability, thus eliminating the need for most of the SCAPE operations. The chart below identifies some of the tasks and technologies which must precede the next generation of operationally efficient vehicles. The development of standard hardware, software, and BITE architectures must proceed to allow timely integration with propulsion and fluid distribution systems. Methods and criteria must also be developed and accepted regarding how BITE systems are to be verified and validated. BITE must also be integrated with expert systems to process the enormous amounts of data which will be generated. Finally, the prototype BITE/Expert System must be tested in an integrated system demonstration.



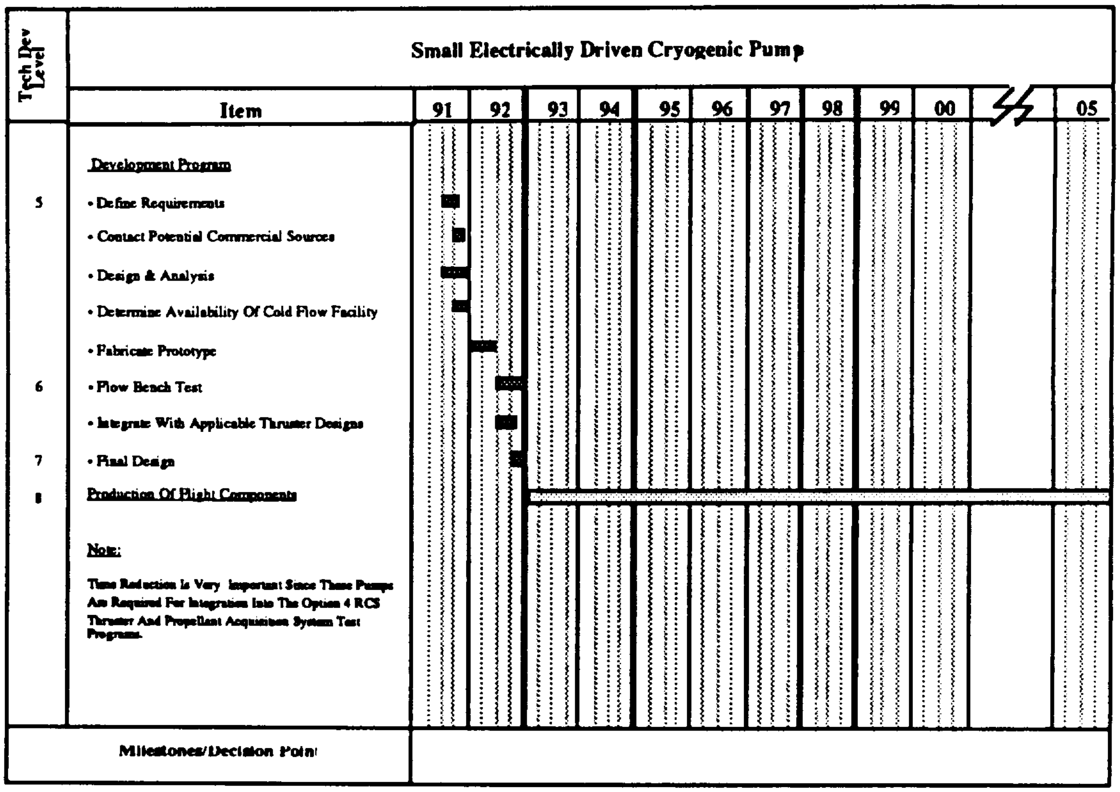

**BITE Systems Development Timeline**

Both Options 1 and 4 require some form of cryogenic propellant acquisition, retention, and transfer. Option 1 requires acquisition of liquids for the OMS operation, although an RCS settling burn would minimize the severity of the requirement. Option 4 would have similar OMS acquisition requirements, but much more stringent RCS propellant acquisition criteria. The Option 4 RCS tankage must maintain liquid propellant (at the proper conditions) at the tank/feed system interface, at all times. No settling burn will be available to the RCS system to simplify acquisition device design. This system must also be integrated with the recirculation system in Option 4, to guarantee liquid propellants at the engine interfaces.



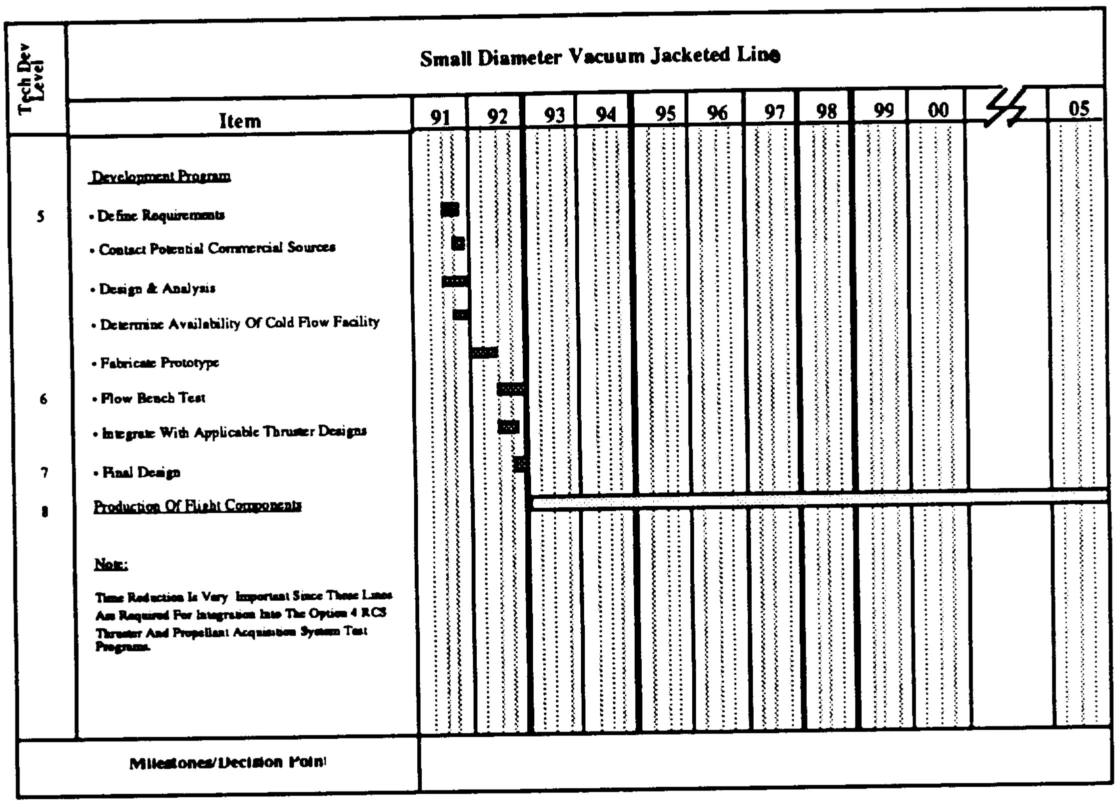

Cryogenic Propellant Acquisition Timeline

As mentioned above, Option 4 requires the development of a recirculation system to maintain liquid cryogens at the RCS engine interfaces. This will require the development of small electrically driven cryogenic pumps, and an integrated recirculation system. A necessary part of this technology development will be a thermal test bed to demonstrate the system effectiveness under simulated thermal load conditions. This should include the option of actual thruster firing.



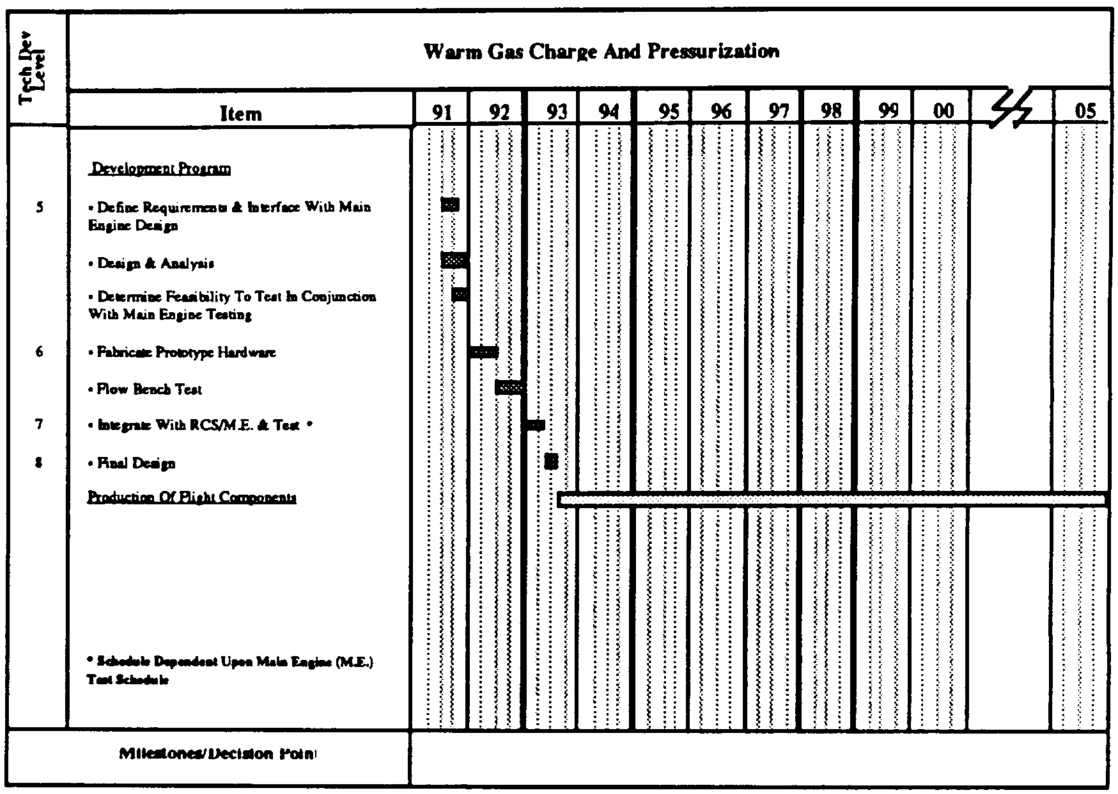

**Electrically Driven Cryogenic Pump Timeline**

The last piece of enabling technology required for the Option 4 recirculation system is the development of high performance vacuum jacketed lines. These lines will function both at low recirculation flows, and at high (thruster operation) flow rates. The challenge in development of these lines will include demonstration of thermal performance, techniques for self-test, and integrity verification.




**Small Diameter Vacuum Jacketed Line Timeline**

The development of reliable techniques for in-flight transfer of high-pressure propellant gases is one of the two critical technologies necessary for successful implementation of Option 1. This will require both analytical models of the processes involved, development testing of specific implementations, and potential integrated testing with future STME firings. Development of the warm-gas pressurization concepts and hardware must be sized to be consistent with STME characteristics, AMLS vehicle abort modes ($GH_2$, $GO_2$ gas also used to pressurize OMS tanks), and vehicle reliability criteria (high pressure interface directly with main engines).




**Warm Gas Charge and Pressurization Timeline**

### 5.5.2. Enhancing Technology Requirements

Enhancing technologies for IHOT include all possible developments which are not critical to the viability of the specific options, but rather provide enhanced cost, operational effectiveness, or performance. The following table suggests areas which, although not necessary for successful IAPS development, may provide specific benefits to the next generation of manned launch systems.

| Objective | Enhancing Technology Devel't |
|---|---|
| Integration with other AMLS systems | • Fuel Cell systems capable of using 'propellant-grade' cryogens<br>• Integration with MPS for IAPS propellant transfer, storage, conditioning, and acquisition<br>• Environmental control & life support systems (ECLSS) |
| Performance Enhancement | • Light weight, high pressure propellant storage tanks<br>• High performance thermal insulation, heat blocks, and active thermal control<br>• Develop/demonstrate active mixture ratio control of thrusters<br>• Qualification of high-reliability components to minimize redundancy req'ts for valves and thrusters |
| Decrease Manufacturing Costs | • Demonstrate and qualify low-cost materials as replacements for current aerospace-grade materials in IAPS components |
| Ground Operations Enhancement | • Develop quick-disconnect concepts for vehicle subsystem/ component removal to facilitate rapid return-to-flight<br>• Demonstrate leak detection concepts which may be built-in to vehicle interfaces<br>• Establish viability of 'neural-nets' to address limitations of current Expert Systems |

**Enhancing Technologies for IAPS**

## 6. CONCLUSIONS

The intent of the Integrated Hydrogen/Oxygen Technology study was to develop viable integrated auxiliary propulsion system (IAPS) concepts, using hydrogen and oxygen as propellants, which would be applicable to the next generation of manned launch systems. Unlike many previous studies, IHOT was to emphasize low cost and streamlined operations over high performance. Two IAPS concepts were developed, and their characteristics compared to a third concept which utilized conventional hypergolic propellants. From the earliest phases of concept selection through detailed design, cost and operations were evaluated and used as the primary design discriminators. The results of this analysis are summarized in the following table:

| ITEM | Option 1 | Option 4 | Option 13 |
|---|---|---|---|
| • Concept | • Gaseous $H_2/O_2$ RCS<br>• Press-fed Liquid $H_2/O_2$ OMS | • Liquid $H_2/O_2$ RCS<br>• Pump-fed Liquid $H_2/O_2$ OMS | • Press-fed Hypergolic OMS & RCS |
| • Total Tankage Volume ($ft^3$) | 2234 $ft^3$ | 1096 $ft^3$ | 433 $ft^3$ |
| • Mass Properties<br>• Dry Wt (lb)<br>• Propellant+Press't (lb)<br>• Loaded APS, (lb) | <br>11338<br>23998<br>35336 lb | <br>5336<br>21104<br>26440 lb | <br>3693*<br>30868<br>34561 lb |
| • Turnaround Processing Time for APS (Manhours) | 39 manhours | 98 manhours | 355 manhours |
| • Undiscounted LCC, $ | $421M | $731.7M | $406.7M |

* Does not include weight of forward/ aft module structure

**Summary of Key IHOT Study Results**

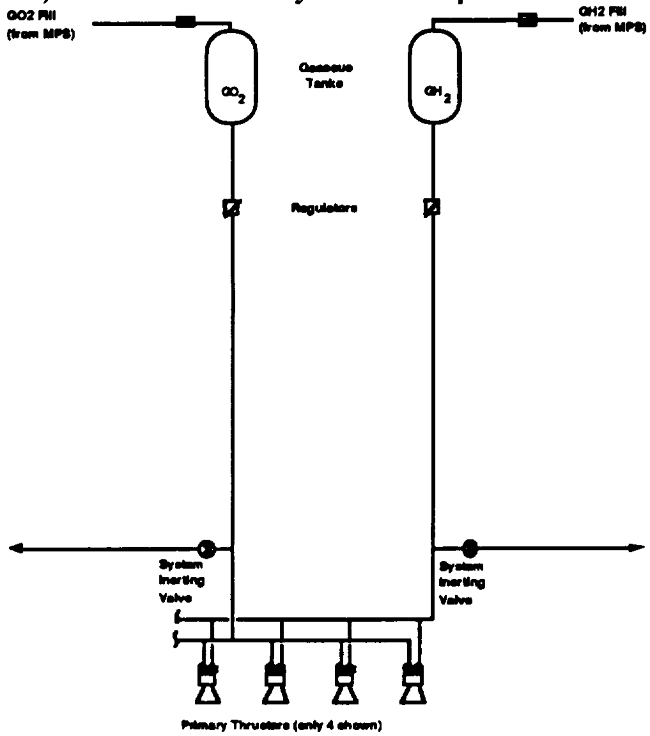
Option 1 in particular compares very favorably with the hypergolic concept on the basis of both cost, and total system weight. Option 4 has significantly higher life cycle costs (LCC, due primarily to engine development), but has significantly lower system weight and better packaging efficiency.

Both hydrogen/oxygen IAPS concepts developed, however, resolve the issues of corrosiveness, toxicity, and possible governmental regulation that are likely to eliminate hypergolic propellants (particularly hydrazine and monomethylhydrazine) from future applications.

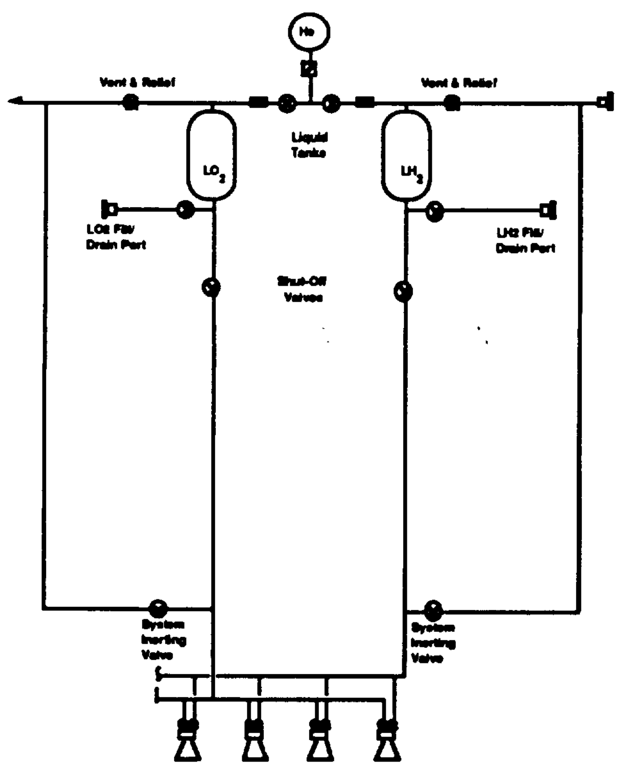
In addition to defining the proposed IAPS concepts and their benefits, the IHOT study addressed the needs of supporting technology. Timelines have been developed for critical areas of enabling technology to support the development of these systems for the next generation of manned launch vehicles.

# 7. APPENDICES

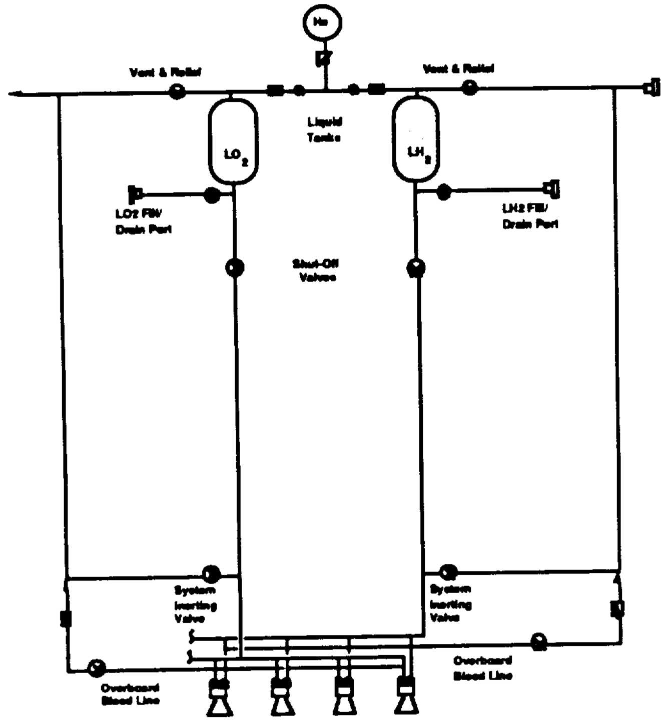
## 7.1. Appendix A, Initial IHOT System Concepts




OPTION 1

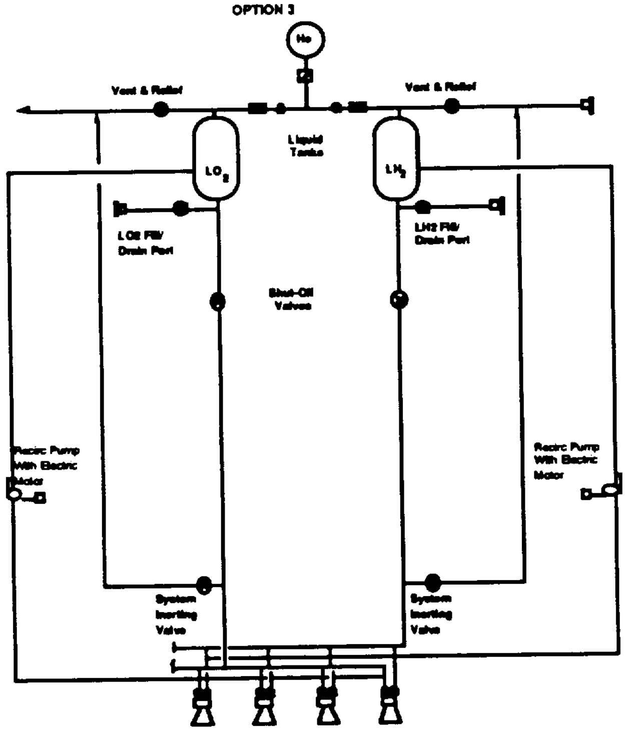



OPTION 2



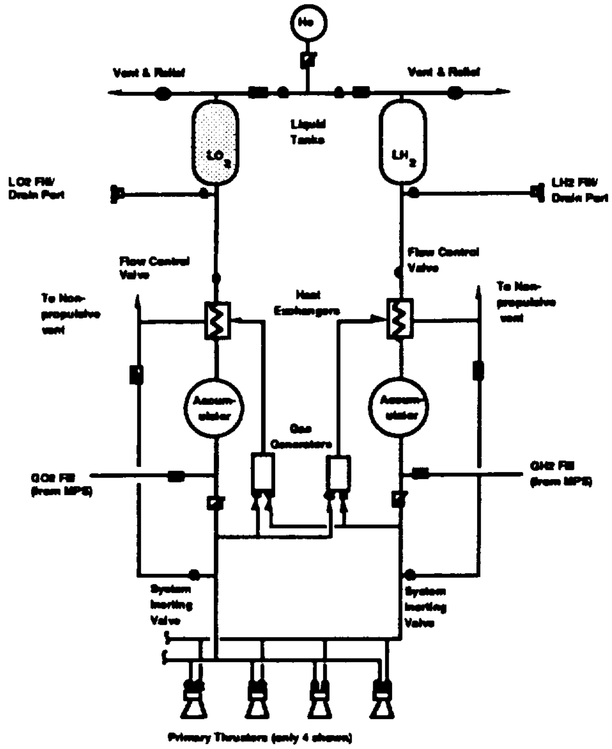

Primary Thrusters (only 4 shown)

OPTION 3

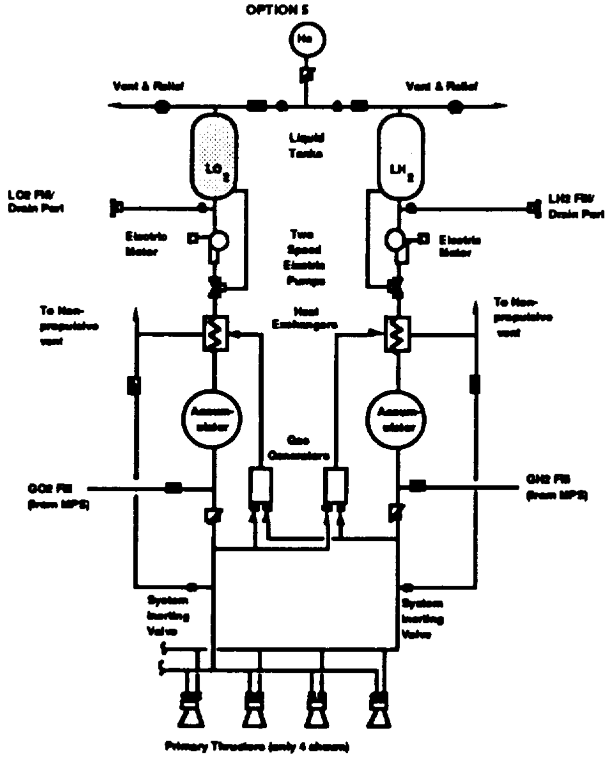



Primary Thrusters (only 4 shown)

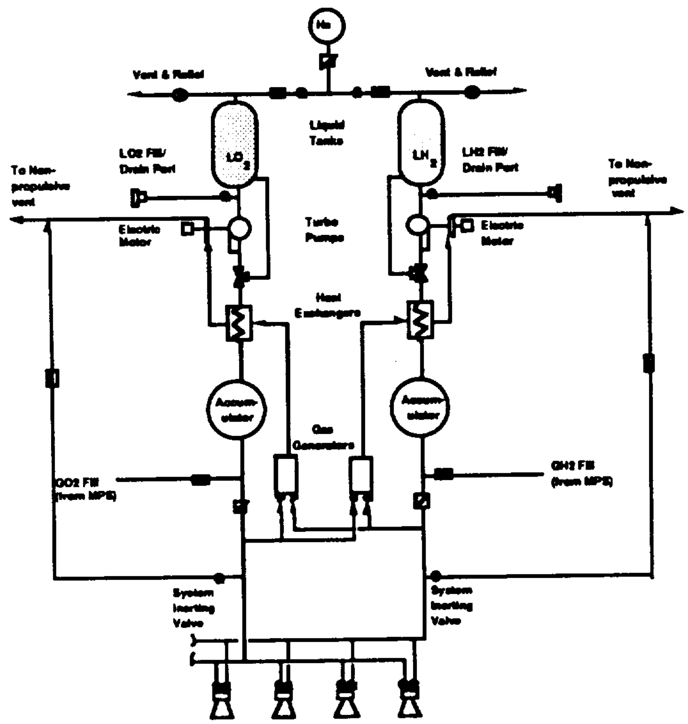
OPTION 4




OPTION 5

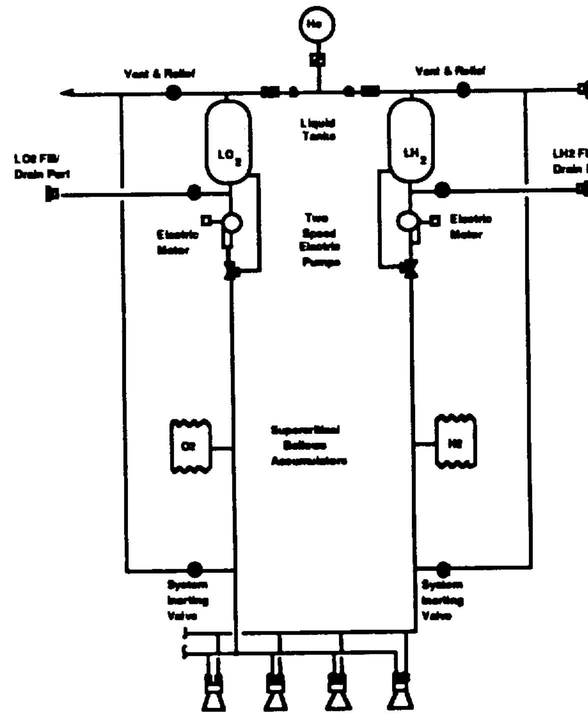



OPTION 6



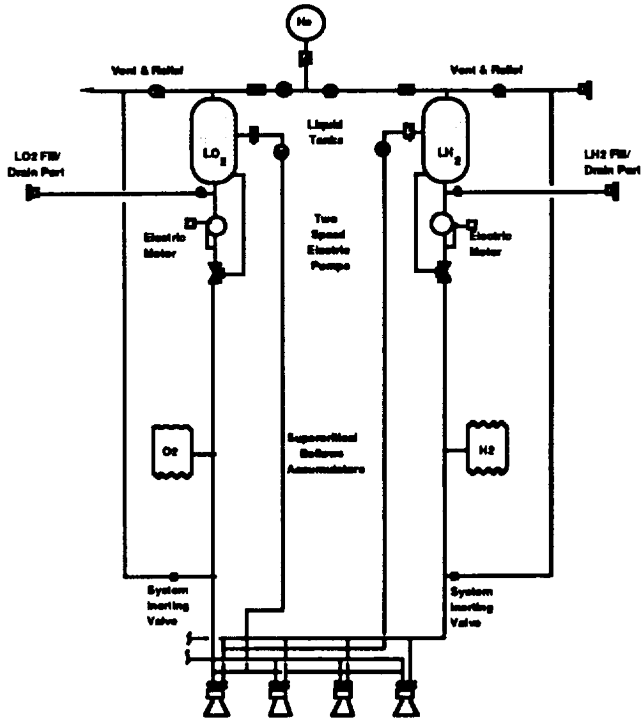

Primary Thrusters (only 4 shown)

OPTION 7

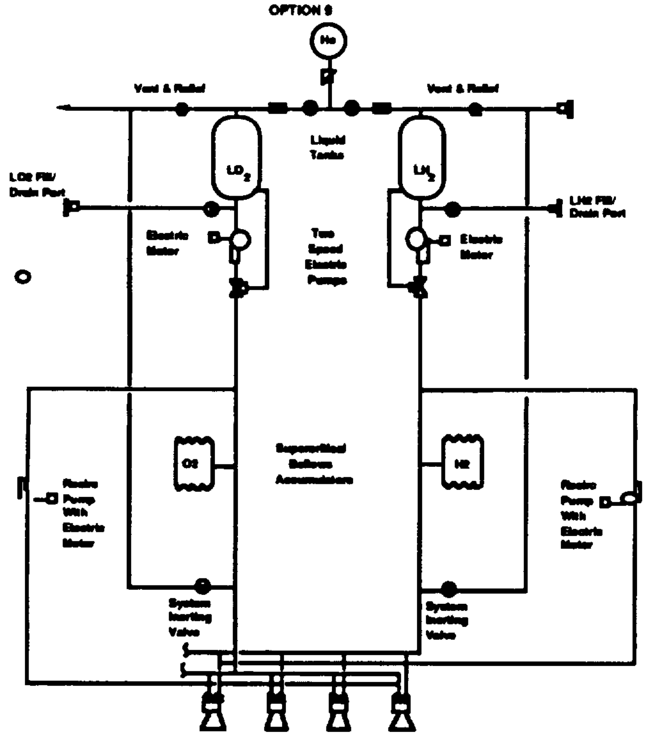



Primary Thrusters (only 4 shown)

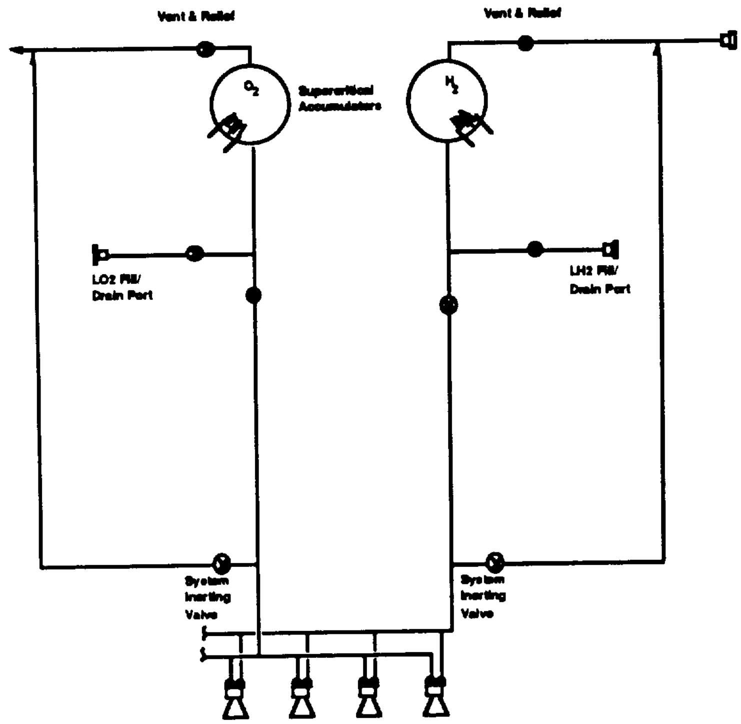
OPTION 8



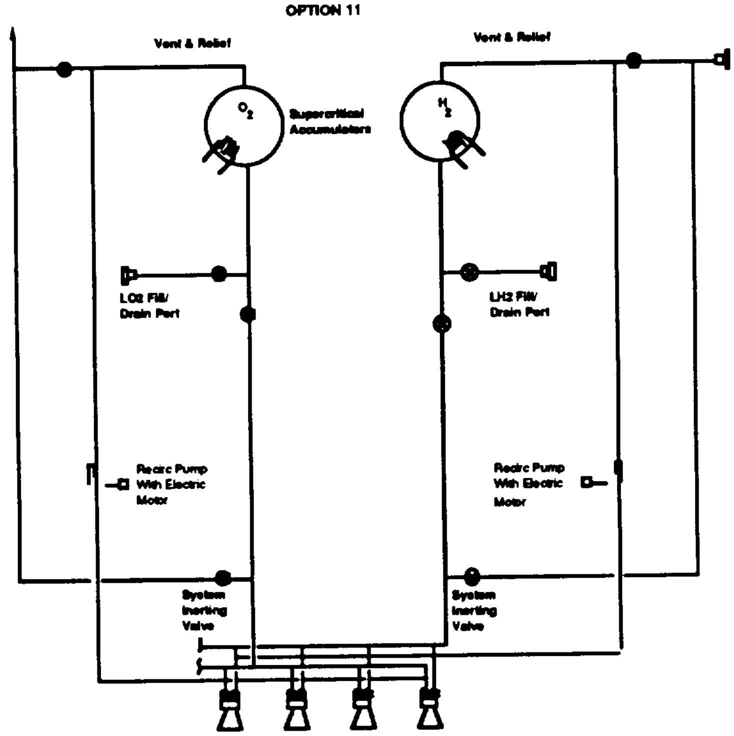

Primary Thrusters (only 4 shown)
OPTION 9




Primary Thrusters (only 4 shown)
OPTION 10




Primary Thrusters (only 4 shown)
OPTION 11




Primary Thrusters (only 4 shown)
OPTION 12

## 7.2. Appendix B, Relative Contributors to Concept Operations

This appendix includes three sections:

- A description of the difference between "turnaround", and "return-to-flight"
- A description of how the ground operations assessment was performed for the 13 initial options
- The summary charts for the operational evaluation.

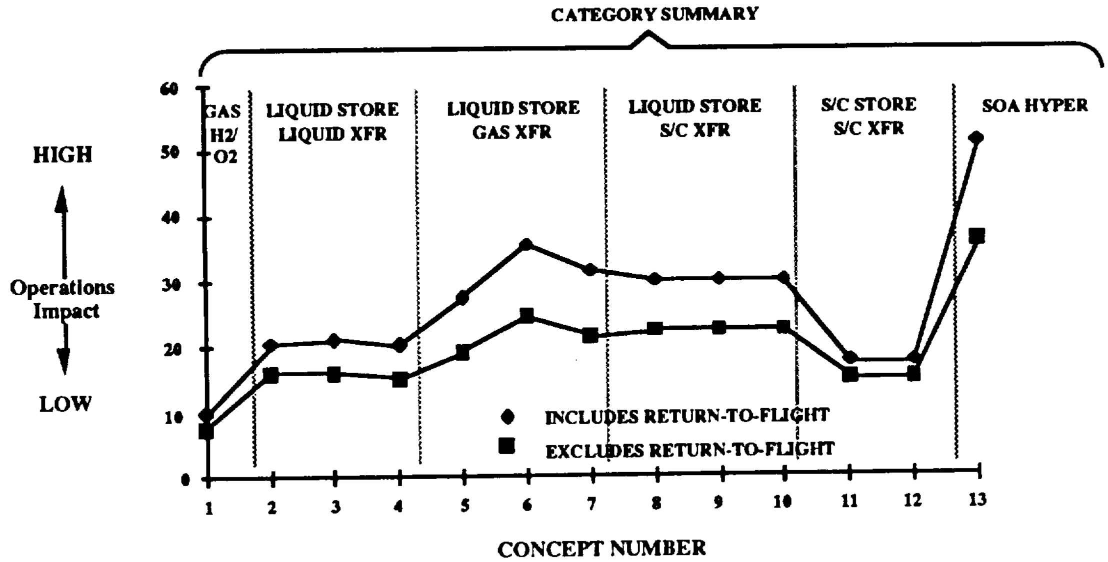
The ground operations tasks required to support any mission may be divided into three major areas: turnaround processing (equivalent to the Shuttle's Orbiter Processing Facility, OPF), the launch pad, and the end of mission runway operations which include the orbiter tow from the runway to the OPF.

An additional task assessment was added to this portion of the study in an attempt to provide further discrimination between the 13 concepts. This was the return-to-flight effort that would be required prior to the first flight or following a stand-down period. This processing could not rely upon prior flight data, as is proposed for turnaround processing, and thus a larger amount of ground support equipment (GSE) - and the accompanying staff - would be required to supply the necessary stimuli for system pre-flight processing tasks. An estimated ability to use BITE for 70% of the tasks was chosen for turnaround processing, and for only 30% of the return-to-flight processing. These numbers are reflected in the total evaluation of the operations required for each concept.

The process for generation of the operations assessment of the 13 concepts relied on an assessment of the component types, quantities, and complexities as noted on the functional schematics (Appendix A). These schematics were assessed to evaluate the level of manpower and equipment required to support the task flow throughout a mission cycle; ie, launch and on-orbit, landing, and turnaround processing. Those tasks that require task-specific GSE can be itemized and factored for BITE, and these item counts form the left half of each assessment page (end of this appendix). The GSE is first counted as if there were no BITE available, and then if an assumed amount of processing can be supported by BITE only. This factored count of GSE on each concept is then scaled as 1 - 3 for a less complex runway operation, but scaled as 1 - 5 for turnaround, return-to-flight, or launch pad processing.

The right half of each area in the summary tables below addresses the direct, or hands-on crew required to operate the equipment during each specific phase of the processing, and the man-hours needed to perform the tasks. The manhour totals are normalized (as with the GSE), and the resultant data tabulated for each potential APS concept. The scaled labor data for each concept has been factored for two items: indirect labor, such as scheduling, quality assurance, design support, etc.; and Base/Range support like lab support (cleaning, calibration, sample analysis), propellant/pressurant supply, and computer services. These labor factors were uniform at 0.25 for all oxygen/hydrogen concepts, but were raised to 0.5 for the hypergolic concept, primarily due to the added propellant cost and SCAPE (self-contained-air-breathing-protective-ensemble) support required during propellant servicing, pressurant venting, sampling or maintenance (LRU) tasks both on the vehicle and facility systems. The corrosive nature of hypergolic oxidizer reduces the service life of system components and maintenance intervals, especially on facility distribution systems, over those which would be required for cryo systems.

The impact of each concept was then totaled, with and without the return-to-flight effort, and plotted as shown below.




**RCS Relative Scoring - Ground Operations**

# RCS RUNWAY OPERATIONS

| GSE REQUIREMENTS | | | | | | SCALED GSE IMPACT (1-3) | CONCEPT ID NO. | CREW (DIRECT) | | | SCALED LABOR IMPACT (1-3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GAS SAMPLE (SAFETY) | VENT/ BURN | GND PWER | AIR PURGE | ACCESS | TOTAL GSE | | | TIME (HR) | SIZE | MH | |
| 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1.0 | 2 | 2 | 1 |
| 1 | 1 | 0 | 1 | 1 | 4 | 2 | 2 | 2.0 | 4 | 8 | 2 |
| 1 | 1 | 0 | 1 | 1 | 4 | 2 | 3 | 2.0 | 4 | 8 | 2 |
| 1 | 1 | 0 | 1 | 1 | 4 | 2 | 4 | 2.0 | 4 | 8 | 2 |
| 1 | 1 | 0 | 1 | 1 | 4 | 2 | 5 | 2.0 | 4 | 8 | 2 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 6 | 2.5 | 6 | 15 | 3 |
| 1 | 1 | 0 | 1 | 1 | 4 | 2 | 7 | 2.0 | 4 | 8 | 2 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 8 | 2.5 | 6 | 15 | 3 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 9 | 2.5 | 6 | 15 | 3 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 10 | 2.5 | 6 | 15 | 3 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 11 | 2.5 | 6 | 15 | 3 |
| 1 | 1 | 1 | 1 | 1 | 5 | 3 | 12 | 2.5 | 6 | 15 | 3 |
| 2 | 0 | 0 | 2 | 2 | 4 | 2 | 13 | 2.0 | 8* | 16 | 3 |

* INCLUDES SCAPE BACK-UP CREW

0 = NONE REQUIRED
1 = REQUIRED
2 = MULTIPLE EQUIPMENT

**Runway Operations**

# ORBITER PROCESSING FACILITY
# RCS TURNAROUND PROCESSING
# (70% BITE ASSUMED)

| GSE REQUIREMENTS - NUMBER OF ITEMS | | | | | | | TOTAL GSE | | SCALED GSE IMPACT (1-5) | CONCEPT ID NO. | CREW (DIRECT) | | | SCALED LABOR IMPACT (1-5) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DRAIN/ VENT | ACCESS/ HANDLING | FUNCT TEST | INTERFACES | | | LEAK CHECK | NO BITE | BITE (X 0.3) | | | TIME (HR) | SIZE | MH | |
| | | | PURGE | ELEC | MECH | | | | | | | | | |
| 2 | 1 | 4 | 1 | 2 | 6 | 1 | 17 | 5 | 1 | 1 | 10 | 4 | 40 | 1 |
| 3 | 2 | 6 | 1 | 2 | 7 | 3 | 24 | 7 | 1 | 2 | 16 | 4 | 64 | 1 |
| 3 | 2 | 8 | 1 | 2 | 8 | 4 | 28 | 8 | 1 | 3 | 20 | 4 | 80 | 1 |
| 3 | 2 | 8 | 1 | 2 | 9 | 4 | 29 | 10 | 2 | 4 | 20 | 4 | 80 | 1 |
| 5 | 5 | 12 | 1 | 2 | 11 | 7 | 43 | 13 | 3 | 5 | 34 | 6 | 204 | 3 |
| 5 | 6 | 13 | 1 | 3 | 11 | 8 | 48 | 14 | 3 | 6 | 38 | 8 | 304 | 5 |
| 5 | 6 | 12 | 1 | 3 | 11 | 9 | 47 | 14 | 3 | 7 | 36 | 8 | 288 | 4 |
| 5 | 4 | 10 | 1 | 2 | 7 | 5 | 34 | 11 | 3 | 8 | 28 | 6 | 168 | 3 |
| 5 | 4 | 10 | 1 | 3 | 7 | 6 | 36 | 14 | 3 | 9 | 28 | 6 | 168 | 3 |
| 5 | 4 | 10 | 1 | 3 | 7 | 7 | 37 | 14 | 3 | 10 | 28 | 6 | 168 | 3 |
| 2 | 1 | 4 | 1 | 4 | 4 | 2 | 28 | 8 | 1 | 11 | 10 | 4 | 40 | 1 |
| 2 | 1 | 6 | 1 | 4 | 4 | 2 | 20 | 6 | 1 | 12 | 12 | 4 | 48 | 1 |
| 5 | 10* | 8 | 1 | 4 | 8 | 4 | 40 | 12 | 3 | 13 | 32 | 10* | 320 | 5 |

* INCLUDES REMOVAL AND TRANSFER TO A REMOTE SITE

**Turnaround Processing**

# RCS LAUNCH PAD SERVICING

| GSE REQUIREMENTS | | | | | | TOTAL GSE | SCALED GSE IMPACT (1-5) | CONCEPT ID NO. | CREW (DIRECT) | | | SCALED LABOR IMPACT (1-5) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLES | | INTERFACES | | FLUID* LOAD | ACCESS | | | | TIME (HR) | SIZE | MH | |
| FLUID | AMBIENT | FLUID | ELEC | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 2 | 5 | 4 | 20 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 3 | 5 | 4 | 20 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 4 | 5 | 4 | 20 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 5 | 5 | 4 | 20 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 6 | 5 | 4 | 20 | 3 |
| 3 | 2 | 2 | 2 | 2 | 1 | 12 | 3 | 7 | 6 | 4 | 24 | 3 |
| 3 | 2 | 2 | 2 | 2 | 1 | 12 | 3 | 8 | 6 | 4 | 24 | 3 |
| 3 | 2 | 2 | 2 | 2 | 1 | 12 | 3 | 9 | 6 | 4 | 24 | 3 |
| 3 | 2 | 2 | 2 | 2 | 1 | 12 | 3 | 10 | 6 | 4 | 24 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 11 | 4 | 4 | 16 | 3 |
| 2 | 2 | 2 | 2 | 2 | 1 | 11 | 2 | 12 | 4 | 4 | 16 | 3 |
| 4 | 2 | 4 | 2 | 2 | 2 | 16 | 5 | 13 | 12 | 12 | 144 | 5 |

* HELIUM LOAD PERFORMED AT ORBITER PROCESSING FACILITY. HYPERGOL SERVICING PERFORMED OFF-LINE USING SCAPE AND BASCK-UP CREW.

SERVICING PERFORMED AT OFF-LINE FACILITY

**Launch Pad Servicing**

# ORBITER PROCESSING FACILITY
# RCS RETURN-TO-FLIGHT PROCESSING
# (30% BITE ASSUMED)

| GSE REQUIREMENTS | | | | | | TOTAL GSE | | SCALED GSE IMPACT (1-5) | CONCEPT ID NO. | CREW (DIRECT) | | | SCALED LABOR IMPACT (1-5) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VENT/ DRAIN | ACCESS/ HANDLING | FUNCT TEST | LEAK CHECK | INTERFACES | | NO BITE | BITE (X 0.7) | | | TIME (HR) | SIZE | MH | |
| | | | | FLUID | ELEC | | | | | | | | |
| 2 | 1 | 14 | 1 | 11 | 4 | 33 | 23 | 1 | 1 | 15 | 6 | 90 | 1 |
| 3 | 3 | 21 | 3 | 12 | 4 | 46 | 32 | 2 | 2 | 23 | 6 | 138 | 1 |
| 3 | 3 | 25 | 4 | 13 | 4 | 52 | 36 | 2 | 3 | 27 | 6 | 162 | 2 |
| 3 | 3 | 25 | 4 | 14 | 4 | 53 | 36 | 2 | 4 | 27 | 6 | 162 | 2 |
| 5 | 6 | 40 | 7 | 15 | 4 | 77 | 54 | 4 | 5 | 45 | 8 | 360 | 3 |
| 5 | 7 | 44 | 8 | 15 | 6 | 85 | 60 | 5 | 6 | 50 | 10 | 500 | 4 |
| 5 | 7 | 42 | 9 | 15 | 6 | 84 | 60 | 5 | 7 | 48 | 10 | 480 | 4 |
| 5 | 5 | 32 | 5 | 12 | 4 | 63 | 44 | 3 | 8 | 36 | 8 | 288 | 3 |
| 5 | 5 | 34 | 6 | 12 | 6 | 68 | 48 | 3 | 9 | 38 | 8 | 304 | 3 |
| 5 | 5 | 32 | 7 | 12 | 6 | 68 | 48 | 3 | 10 | 36 | 8 | 288 | 3 |
| 2 | 1 | 14 | 2 | 8 | 8 | 35 | 24 | 1 | 11 | 15 | 6 | 90 | 1 |
| 2 | 1 | 20 | 2 | 8 | 8 | 40 | 28 | 1 | 12 | 21 | 6 | 126 | 1 |
| 5 | 10 • | 40 | 8 | 20 | 8 | 91 | 64 | 5 | 13 | 80 | 12 | 960 • | 5 |

• INCLUDES HANDLING AND SCAPE BACK-UP

**Return to Flight Processing**

## 7.3. Appendix C, Evaluation of Vehicle Turnaround/Dwell Time Requirements

**Statement of Problem**
The minimum time available for each AMLS flight vehicle to dwell in the turnaround processing facility must be determined. This establishes the maximum time allowable for ground processing tasks, and the OMS/RCS portion must fit well within this envelope and not cause significant serial time impact to the other vehicle system checkouts.

**Approach**
The AMLS mission model must be assessed against both the facilities available and the number of vehicles available in the fleet. The resultant timeline must be comparable to other studies toward more operationally efficient manned vehicles in the AMLS era. The longest mission during the highest launch rate is to be sought for program support capability.

**Assumptions**
Current AMLS program information defines the following parameters:

a. launch rate will be 48 launches per year, max
b. four vehicles will always be available to flight operations (with one backup, total of 5)
c. the longest flight mission is expected to be 21 days between launch and landing
d. a 360 day year will be used for planning, to account for major holidays.

The following assumptions have also been made for this study, due to the lack of specific AMLS data:

e. The vehicle will land at the launch site
f. runway operations and delivery to the vehicle processing facility will require one-half day (12 hours)
g. cargo operations will be a 1 day (24 hour) serial impact
h. launch pad operations will be a 1 1/2 day (36 hour) serial impact, since one-half of launch day is mission day number-1.

**Summary of analysis**
Assuming the program parameters listed above, the launch interval at the pad will be as follows:

$$\frac{(360 \text{ days/yr})}{(48 \text{ launches/yr})/4 \text{ vehicles}} = 30 \text{ days/launch/vehicle}$$

The minimum ground processing time available for a vehicle must be extracted from the launch interval per vehicle, less the maximum mission time, or:
30 - 21 = 9 calendar days (x24, =216 hours)

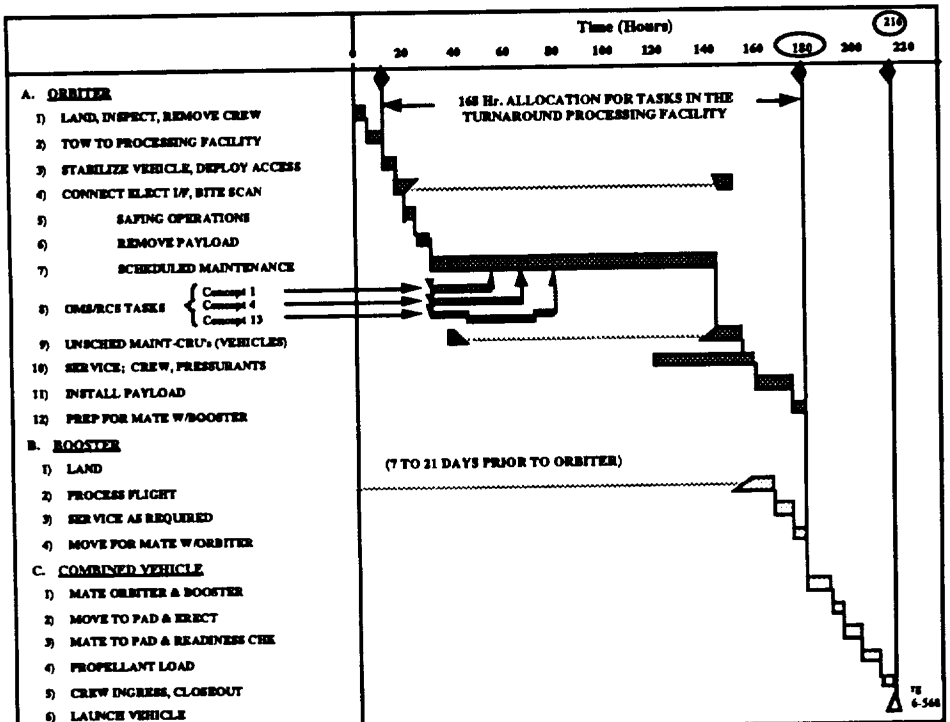
The impact of runway, cargo, and launch pad operations must also be assessed, leaving:

9 - 0.5 - 1 - 1.5 = 6 days (144 hours @ 3 shifts)

**Discussion of results and conclusions**
The 216 hour processing timeline for this mission presents a challenge equal to the original Shuttle 160 hour timeline, since a 5-day week would reduce the work time residual, after a weekend allowance, to 168 hours.

The "circa 2000" turnaround estimate for an operationally efficient vehicle is also comparable, at 154 hours between launch and landing. Note that the turnaround processing facility has been allocated 101 serial hours in the referenced study, which is also acceptable for the processing of all three concepts in this study. The figure shown below presents a turnaround timeline estimate for the AMLS vehicle for this study.

## AMLS Launch-To-Landing




**IHOT Study Turnaround Time Conforms to Contemporary Efficient Processing Studies**

| ITEM | Concept 1 | Concept 4 | Concept 13 | STS |
|---|---|---|---|---|
| Turnaround processing for APS (Manhours) | 39 | 98 | 355 | 1240 |
| Timeline reqts for APS (Hours) | 32 | 40 | 50 | 110 |
| Serial impact for APS helium and propellant servicing (Hours) | 0 | 2 | 5 | 22 |
| Days that vehicle is in: | | | | |
| Processing facility | 6 | 6 | 6 | 72* |
| Ground flow | 9 | 9 | 9 | 105* |
| * avg planned for 1990 launches | | | | |

**Impacts and Dwell Times for Processing will Improve Significantly Over Shuttle**

The serial impacts to the processing for each of the concepts of this study are shown in the table above. Turnaround processing time represents the total *manhours* required to process the vehicle APS, while the *timeline requirements* represent the total serial accumulation of APS activities on the vehicle. It should be noted that due to parallel processing efforts, the APS timeline requirements represent varying degrees of serial impact to the vehicle, depending on the specific concept.

These reductions in impact have been accomplished through design considerations for ground operations problems experienced during the manned Shuttle program, and in the previous unmanned programs. Descriptions of significant impact solutions have been listed in the following table, where the concepts of this study are compared with the Shuttle.

| Issue | Design Solution |
|---|---|
| RCS/OMS servicing at pad requires an area clear for about 22 hours and GSE can sustain blast damage. | Concept 1 avoids pad operations completely for RCS, and OMS cryo load is in parallel with MPS load. Concept 4 loads both RCS &OMS together with MPS. SOA concept 13 is loaded off-line |
| RCS/OMS temperature conditioning includes land lines and pad GSE | Circulation and sampling is performed in conjunction with MPS, since a common interface is used for both OMS/RCS and MPS, in cryo concepts 1&4. |
| RCS/OMS helium loading at the pad is a serial time area clear impact. Area access is restricted at flight pressure and GSE can sustain blast damage. | Helium tank structural ratings will allow other unrestricted work around the vehicle both during and following helium loading operations. |
| OMS pod removal has been a time-consuming task on Shuttle | AMLS design can accommodate a single OMS/RCS pod at the aft end, that is designed for easy, fast removal and reinstallation on a horizontal base. |
| Leak testing has required numerous mechanical interfaces for external test equipment | Built-in test equipment and expert systems have the potential to eliminate most interfaces except electrical, which need no cleaning |

**Timeline Impacts Have been Addressed During Design**

## 7.4. Appendix D, Engine Development Costs for IHOT Concepts.

The following table summarizes the engine development costs for the IHOT IAPS concepts. These data were utilized in the determination of the detailed costing estimates of Section 5.4.2.

| | Option 1 | | Option 4 | | SOA | |
|---|---|---|---|---|---|---|
| | Cost ($M) | Notes | Cost ($M) | Notes | Cost ($M) | Notes |
| **OMS Engine** | | $3.5M/Engine | | $4M/Engine | | $4M/Engine |
| Hardware | 17 | 5 Units | 72 | 15 dev.eng;3comp.test | 8 | 2 Units |
| Labor | 49 | - | 255 | - | 20 | Requalify |
| Test Bed | 14 | No large P-fed stands | 0 | Existing | 0 | Existing |
| BITE | 5 | yes | 10 | yes | 15 | Must add to ex. design |
| Cluster Test | 0 | - | 0 | - | 0 | - |
| Technology Acquis'n | 0 | - | 0 | - | 0 | - |
| Total | 85 | | 337 | | 43 | |
| *Uncertainty* | *10* | *HW+ labor* | *33* | *10%* | *14* | *Add'l engs; Exist.cost* |
| | *-14* | *No test bed* | *-33* | *-10%* | *-10* | *Decreased BITE $* |
| **RCS Primary** | | $180K, 16:1 MR | | $220K, avg,liq/liq. | | $.8M->.3M |
| Hardware | 3 | 10 Units | 3 | 10 units | 1 | 3 Units |
| Labor | 35 | Design, Test | 40 | Vac.jacket, recirc. | 15 | Requalify, labor |
| Test Bed | 20 | Int'd; w/verniers | 30 | " | 0 | Existing |
| BITE | 5 | | 8 | More comp's | 10 | Must add to ex. design |
| Cluster Test | 0 | Integrated | 0 | Integrated | 0 | - |
| Technology Acquis'n | 10 | 16:1 demonstration | 10 | Thrusters only | 0 | - |
| Total | 73 | | 91 | | 26 | |
| *Uncertainty* | *15* | *30% labor+$3M HW* | *50* | *Orbital testing* | *1* | *2 more engines* |
| | *-10* | *Can mod'y exist.t-bed* | *-10* | *Vac.jacket easy* | *-5* | *BITE simpler* |
| **RCS Vernier** | | $50K/Engine | | $50K - $100K / engine | | |
| Hardware | 1 | Minimum HW $ | 1 | Minimum HW $ | 1 | 3 Units |
| Labor | 25 | Smaller Engine | 30 | Smaller Engine | 10 | Requalify |
| Test Bed | 0 | Part of Primary | 0 | Part of Primary | 0 | Existing |
| BITE | 0 | " | 0 | " | 0 | Must add to ex. design |
| Cluster Test | 0 | " | 0 | " | 0 | - |
| Technology Acquis'n | 0 | " | 0 | " | 0 | - |
| Total | 26 | | 31 | | 11 | |
| *Uncertainty* | *8* | *30% labor+$1M HW* | *9* | | *1* | |
| | *0* | | *0* | | *-1* | |
| | **Mean** | **Uncertainty** | **Mean** | **Uncertainty** | **Mean** | **Uncertainty** |
| ***Totals($x10^6)*** | ***184*** | ***33*** | ***459*** | ***92*** | ***80*** | ***16*** |
| | | ***-24*** | | ***-43*** | | ***-16*** |

**Engine Development Cost Summary**

## 7.5. Appendix E, Baseline Thruster Parameter Definition

### STATEMENT OF THE PROBLEM

Determine the baseline thruster parameters for options 1 and 4. These parameters are to include thrust level, mixture ratio, nozzle area ratio, chamber pressure, inlet pressure, inlet temperature and associated delivered vacuum performance.

### DESCRIPTION OF APPROACH

Select thrust levels, nozzle area ratios and chamber pressures parameters that are consistent with the current STS. Use a "black box" for the option 4, OMS thruster (parameters based on available data). For consistency, use the same mixture ratio for option 1 and 4 OMS thrusters. Select the RCS thruster mixture ratios that correspond to the peak delivered vacuum performance. Assume an injector delta pressure and energy release efficiency.

Use JANNAF method for performance prediction (kinetic, boundary layer, divergence and energy release efficiencies are used to degrade the theoretical performance).

Take advantage of available performance prediction tools:

- ISP89, V1.1
- TWEPP, V1.3
- APSCOD

### ASSUMPTIONS LIST

The following assumptions were used:

- Injector delta pressure (oxidizer and fuel side): 20 % of Pc
- Pressure Fed OMS engine, regen jacket pressure drop: 40 % of Pc
- Energy release efficiency: 0.995
- Inlet oxygen/hydrogen enthalpy for option 1, RCS-primary thruster are equal
- Standard inlet conditions for all liquid/liquid thrusters
- 3 OMS thrusters (equivalent STS, OMS thrust)

### SUMMARY OF ANALYSIS

The delivered performance for the Option 1 and 4 RCS thrusters and the Option 1 OMS engine were predicted by determining the theoretical vacuum performance (one dimensional equilibrium expansion) at a chamber pressure of 100 psia and a chamber temperature of 400 deg-R. The theoretical performance was then degraded by applying associated loss terms. The ISP89 software was used for determining the theoretical performance and the TWEPP software was used for determining the loss terms. These values were compared to APSCOD values and were found to be within 2 seconds of the APSCOD predictions.

The Option 4 OMS thruster (expander cycle) performance was obtained from reference material (RI/RD84-112). The associated parameters (mixture ratio, chamber pressure, area ratio) were selected based on the available data. The reported thrust level was 3000 lbf in the reference material. No attempt was made to adjust the performance for the actual thrust level (4000 lbf). The inlet temperatures and pressures represent the inlet to the "black box"(pump inlet). The inlet temperatures represent the normal boiling point temperatures. The inlet pressures were arbitrarily selected (15 psia, the pumps have a low NPSH requirement). The literature suggests that adequate vapor pressure should preclude pump cavitation problems. The theoretical performance and loss terms are estimates and are based on the reported delivered performance values from RI/RD84-112.

### RESULTS AND CONCLUSIONS

The results are tabulated in the following table.

## OPTION 1 Baseline Engine Performance

| | OMS | ACS - Primary | ACS Vernier |
|---|---|---|---|
| Pc, psia | 100 | 100 | 100 |
| T $O_2$, deg-R | 161 | 400 | 400 |
| T $H_2$, deg-R | 34 | 399 | 400 |
| P $O_2$, psia | 120 | 120 | 120 |
| P $H_2$, psia | 160 | 120 | 120 |
| Hf $O_2$, kcal/mole | -3.102 | -0.5577 | -0.5577 |
| Hf $H_2$, kcal/mole | -2.154 | -0.5577 | -0.5577 |
| Epsilon | 55:1 | 22:1 | 22:1 |
| MR | 6:1 | 16:1 | 16:1 |
| $F_{vac}$, lbf | 4000 | 870 | 50 |
| Eta $_{ere}$ | 0.995 | 0.995 | 0.995 |
| Eta $_{kin}$ | 0.96676 | 0.96754 | 0.95957 |
| Eta $_{div}$ | 0.99262 | 0.99149 | 0.99149 |
| Eta $_{bl}$ | 0.97971 | 0.98036 | 0.97385 |
| Isp $_{ode}$, sec | 455.1 | 331.9 | 331.9 |
| Isp $_{del}$, sec | 425.7 | 310.5 | 305.9 |

## OPTION 4 Baseline Engine Performance

| | OMS | ACS - Primary | ACS Vernier |
|---|---|---|---|
| Pc, psia | 800 | 150 | 150 |
| T $O_2$, deg-R | 161 | 161 | 161 |
| T $H_2$, deg-R | 34 | 34 | 34 |
| P $O_2$, psia | 15 | 180 | 180 |
| P $H_2$, psia | 15 | 180 | 180 |
| Hf $O_2$, kcal/mole | -3.102 | -3.102 | -3.102 |
| Hf $H_2$, kcal/mole | -2.154 | -2.154 | -2.154 |
| Epsilon | 100:1 | 22:1 | 22:1 |
| MR | 6:1 | 4:1 | 4:1 |
| $F_{vac}$, lbf | 4000 | 870 | 50 |
| Eta $_{ere}$ | ~0.995 | 0.995 | 0.995 |
| Eta $_{kin}$ | ~0.99127 | 0.98902 | 0.98542 |
| Eta $_{div}$ | ~0.99295 | 0.99149 | 0.99149 |
| Eta $_{bl}$ | ~0.98140 | 0.98114 | 0.97489 |
| Isp $_{ode}$, sec | 480.9 | 442.7 | 442.7 |
| Isp $_{del}$, sec | 462.2 | 423.8 | 419.5 |

## 7.6. Appendix F, Thruster Weight and Envelope Sizing

### STATEMENT OF THE PROBLEM

Determine the weight and envelope for the RCS vernier, RCS primary and OMS thrusters (Options 1 and 4).

### DESCRIPTION OF APPROACH

Utilize available Rocketdyne analytical tools and reference data.

### ASSUMPTIONS LIST

The following assumptions apply to the Option 1 thrusters:

- RCS primary thruster is radiation cooled (radiated from exit plane to space)
    - Materials of Construction - S. S. with thermal barrier
    - Epsilon - 22:1
    - Pc - 100 psia
    - Isp delivered - 310.5 sec
    - Thrust - 870 lbf
    - MR - 16:1
    - Inlet Pressure - 120 psia (20 % injector Δp)
    - Inlet Temperature - 400 deg-R
    - Nozzle percent length - 80 %
    - Nozzle thrust coefficient - 1.771
- RCS vernier thruster is radiation cooled (radiated form exit plane to space)
    - Materials of Construction - S. S. with thermal barrier
    - Epsilon - 22:1
    - Pc - 100 psia
    - Isp delivered - 305.9 sec
    - Thrust - 50 lbf
    - MR - 16:1
    - Inlet Pressure - 120 psia (20 % injector Δp)
    - Inlet Temperature - 400 deg-R
    - Nozzle percent length - 80 %
    - Nozzle thrust coefficient - 1.745
- OMS thruster is regeneratively cooled
    - Materials of Construction - S. S. (columbium or graphite extension)
    - Epsilon - 55:1
    - Nozzle extension attach area ratio - 25:1
    - Pc - 100 psia
    - Isp delivered - 425.7 sec
    - Thrust - 4000 lbf
    - MR - 6:1
    - Inlet Pressure, Oxidizer - 120 psia (20 % injector Δp)
    - Inlet Pressure, Fuel - 160 psia (60 % injector/nozzle Δp)
    - Inlet Temperature, Oxidizer - 161 deg-R
    - Inlet Temperature, Fuel - 34 deg-R
    - Nozzle percent length - 80 %
    - Nozzle thrust coefficient - 1.858

The following assumptions apply to the Option 4 thrusters:

- RCS primary thruster is radiation cooled
    - Materials of Construction - S. S. with thermal barrier
    - Epsilon - 22:1
    - Pc - 150 psia
    - Isp delivered - 423.8 sec
    - Thrust - 870 lbf
    - MR - 4:1
    - Inlet Pressure - 180 psia (20 % injector Δp)
    - Inlet temperature, Fuel - 34 deg-R
    - Inlet temperature, Oxidizer - 161 deg-R
    - Nozzle percent length - 80 %
    - Nozzle thrust coefficient - 1.733
- RCS vernier thruster is radiation cooled
    - Materials of Construction - S. S. with thermal barrier
    - Epsilon - 22:1
    - Pc - 150 psia
    - Isp delivered - 419.5 sec
    - Thrust - 50 lbf
    - MR - 4:1
    - Inlet pressure - 180 psia (20 % injector Δp)
    - Inlet temperature, Fuel - 34 deg-R
    - Inlet temperature, Oxidizer - 161 deg-R
    - Nozzle percent length - 80 %
    - Nozzle thrust coefficient - 1.716
- OMS thruster is regeneratively cooled
    - Materials of Construction - ED copper, Nickel, Graphite
    - Epsilon - 100:1
    - Pc - 800 psia
    - Isp delivered - 462.2 sec
    - Thrust - 4000 lbf
    - MR - 6:1

- Inlet pressure - 15 psia (low pressure pump inlet)
- Inlet temperature, Fuel - 34 deg-R
- Inlet temperature, Oxidizer - 161 deg-R
- Nozzle percent length - 170.9 %
- Nozzle thrust coefficient - 1.937

SUMMARY OF ANALYSIS

The *Thruster Weight, Envelope and Performance Program.*(TWEPP) was utilized for providing input values for the *Engine* program. The thruster weight and envelope values were generated for the Option 1 and 4 vernier and primary RCS thrusters and the Option 4 OMS thruster using the *Engine* program. The *Engine* program is similar to the weight and envelope subroutine found in the *TWEPP* program except that a different reference thruster design is utilized. The TWEPP reference thruster design data is from the *Large Space System Cryogenic Deployment System Study*, (AFRPL-TR 83-022). The reference thruster is regeneratively cooled with a thrust level of 500 lbf.

The *Engine* program allows the user to change the design parameters (using engineering judgement). Reference design data for a radiation cooled, oxygen/hydrogen thruster in the thrust class of interest was not available. Reference data for the low pressure OMS thruster was also unavailable.

The Engine program is a "physical model" and was originally part the *Motor Optimal Design and Evaluation Code*, Air Force Astronautics Laboratory, Edwards Air Force Base. The model is documented in the *Expanded Liquid Engine Simulation* program, Technical Information Manual, Charles E. Taylor, Aerojet Techsystems Co., August, 1984.

The Option 1 OMS engine weight and was extracted from *Rocketdyne's $O_2/H_2$ Engine for Space Transfer Vehicles* (RI/RD84-112, revised: 20 October 1989). The envelope was generated using the *Engine* program.

The thruster weight includes the following component weights:

- Injector
- Chamber
- Nozzle extension (as applicable)
- Thrust mount
- Support hardware (6.5 percent of total)
- Igniter

The Option 4, OMS engine weight includes the following component weights:

- Propellant ducts
- Turbopumps
- Harnesses and sensors
- Control lines
- Ignition system
- Injector
- Chamber
- Thrust mount

The envelope parameters are defined below:

- Length - Distance from the thruster interface plane to the nozzle exit plane.
(The pump inlet and thrust mount are at the interface plane for the Option 4, OMS engine ).

- Diameter - Maximum diameter of the thruster (nozzle exit plane).

RESULTS AND CONCLUSIONS

The weight and envelope data are tabulated below:

| Option | Thruster Type | Weight | Length | Diameter |
|---|---|---|---|---|
| | | lbm | inches | inches |
| 1 | Vernier | 9.3 | 10.0 | 2.8 |
| 1 | Primary | 34.6 | 23.0 | 11.7 |
| 1 | OMS | 225.8 | 63.0 | 38.8 |
| 4 | Vernier | 5.3 | 7.0 | 2.3 |
| 4 | Primary | 22.0 | 29.8 | 9.7 |
| 4 | OMS | 181.8 | 70.0 | 18.1 |

**Option 1, 4 Thruster Size and Weight**

## 7.7. Appendix G, Flow Control Component Weight Estimation

### STATEMENT OF PROBLEM

Determine the unit weight of valves and regulators for the OMS, ACS-Primary, and ACS Vernier thrusters of Option 1 and 4.

### DESCRIPTION OF APPROACH

Based on the required flow rate, the density of the fluid, and the pressure drop across a valve, an Equivalent Orifice Diameter (EOD) can be computed from a formula in the Crane Co. Technical Paper #410, "Flow of Fluids Through Valves, Fittings and Pipes". With an EOD value, the weights of various valves and regulator are found by using the weight algorithms as suggested by J. A. McClanahan (IL No. APA89-92). These algorithms represent the fitted weight data of pneumatically actuated valves documented in the "Space Engine Design Handbook" (R-8000P-1, Jan. 1969).

### ASSUMPTIONS LIST

The thruster parameters are as follows:

| | | | OPTION 1 | | |
|---|---|---|---|---|---|
| | Area Ratio | Pc (Psia) | Del Isp (Sec) | Thrust (lbs) | MR |
| Primary | 22.0 | 100.0 | 310.5 | 870.0 | 16.0 |
| Vernier | 22.0 | 100.0 | 305.9 | 50.0 | 16.0 |
| OMS | 55.0 | 100.0 | 425.7 | 4000.0 | 6.0 |
| | | | OPTION 4 | | |
| | Area Ratio | Pc (Psia) | Del Isp (Sec) | Thrust (lbs) | MR |
| Primary | 22.0 | 150.0 | 423.8 | 870.0 | 4.0 |
| Vernier | 22.0 | 150.0 | 419.5 | 50.0 | 4.0 |
| OMS | 100.0 | 800.0 | 462.2 | 4000.0 | 6.0 |

**Thruster Characteristics**

The following assumptions were made

- The maximum number of thrusters firing at any one time for the ACS-Primary, ACS Vernier, and OMS are 2, 4 , and 3, respectively, to establish the maximum manifold flowrate
- All valves are either open or closed. There are no throttling valves
- Check valves and regulators are mechanically actuated. Only the propellant valves are electrically actuated
- Pneumatically actuated and electrically actuated valve weights are equal
- Ventilation and relief flow of liquid tank is 10% of the flow to the thrusters

## SUMMARY OF ANALYSIS

Limited correlation was performed between the predicted component weights and actual hardware weights of previous and existing systems (Peacekeeper, Atlas, Delta, ALS, etc) to provide some level of confidence.

## CONCLUSIONS and RECOMMENDATIONS

The component weight estimates for Option 1 are as follows:

| | m (lbs/sec) | ΔP (psid) | EQD (inch) | weight (lbs) |
|---|---|---|---|---|
| • ACS Oxidizer | | | | |
| • Main iso valve | 13.94 | 9.35 | 1.76 | 6.56 |
| • Regulator | 13.94 | 200.0 | 0.818 | 17.59 |
| • ACS iso valve | 5.89 | 12.0 | 1.76 | 6.56 |
| • ACS-Primary iso valve | 2.64 | 12.0 | 1.28 | 5.38 |
| • ACS Vernier iso valve | 0.154 | 6.0 | 0.367 | 2.03 |
| • Refill valve | 13.94 | 12.0 | 1.65 | 6.31 |
| • ACS Fuel | | | | |
| • Main iso valve | 1.71 | 12.0 | 1.16 | 5.04 |
| • Regulator | 1.71 | 200.0 | 0.573 | 13.90 |
| • ACS iso valve | 0.369 | 12.0 | 0.883 | 4.16 |
| • ACS-Primary iso valve | 0.165 | 7.25 | 0.724 | 3.58 |
| • ACS Vernier iso valve | 0.0096 | 6.0 | 0.183 | 1.09 |
| • Refill valve | 1.71 | 12.0 | 1.16 | 5.04 |
| • OMS Oxidizer | | | | |
| • Pressurant iso valve | 8.05 | 12.0 | 2.06 | 7.18 |
| • Vent & relief valve | 2.42 | 12.0 | 0.89 | 3.14 |
| • Refill valve | 26.58 | 12.0 | 1.31 | 5.48 |
| • Iso valve to injector | 8.05 | 12.0 | 0.724 | 3.58 |
| • OMS Fuel | | | | |
| • Pressurant iso valve | 1.34 | 12.0 | 1.69 | 6.38 |
| • Vent & relief valve | 0.403 | 12.0 | 0.45 | 1.90 |
| • Refill valve | 4.43 | 12.0 | 1.07 | 4.76 |
| • Iso valve to injector | 1.34 | 12.0 | 0.59 | 3.04 |

**Option 1 Component Weight Estimates**

The component weight estimates for Option 4 are as follows:

| | m (lbs/sec) | ΔP (psid) | EOD (inch) | weight (lbs) |
|---|---|---|---|---|
| • ACS Oxidizer | | | | |
| • He iso valve (in front of regulator) | 0.446 | 6.0 | 0.46 | 2.47 |
| • He regulator | 0.446 | 200.0 | 0.191 | 6.72 |
| • He iso valve (in front of chk valve) | 0.446 | 6.0 | 0.62 | 3.18 |
| • He check valve | 0.446 | 6.0 | 0.62 | 1.22 |
| • He refill valve | 0.446 | 6.0 | 0.46 | 2.47 |
| • LOX vent & relief valve | 0.367 | 6.0 | 0.40 | 1.72 |
| • LOX Refill valve | 4.03 | 6.0 | 0.61 | 3.12 |
| • ACS iso valve | 3.67 | 4.62 | 0.62 | 3.18 |
| • ACS-Primary iso valve | 1.64 | 6.0 | 0.39 | 2.14 |
| • ACS Vernier iso valve | 0.095 | 3.0 | 0.11 | 0.69 |
| • ACS Fuel | | | | |
| • He iso valve (in front of regulator) | 0.721 | 6.0 | 0.58 | 3.02 |
| • He regulator | 0.721 | 200.0 | 0.243 | 7.88 |
| • He iso valve (in front of chk valve) | 0.721 | 6.0 | 0.79 | 3.84 |
| • He check valve | 0.721 | 6.0 | 0.79 | 1.53 |
| • He refill valve | 0.721 | 5.05 | 0.61 | 3.12 |
| • Fuel vent & relief valve | 0.092 | 6.0 | 0.25 | 1.19 |
| • Fuel Refill valve | 1.01 | 5.80 | 0.61 | 3.12 |
| • ACS iso valve | 0.92 | 4.51 | 0.62 | 3.18 |
| • ACS-Primary iso valve | 0.411 | 6.0 | 0.39 | 2.14 |
| • ACS Vernier iso valve | 0.024 | 3.0 | 0.11 | 0.69 |
| • OMS Oxidizer | | | | |
| • Vent & relief valve | 2.23 | 12.0 | 1.21 | 4.20 |
| • Refill valve | 24.48 | 12.0 | 1.26 | 5.34 |
| • Iso valve to injector | 7.42 | 6.0 | 0.826 | 3.96 |
| • OMS Fuel | | | | |
| • Vent & relief valve | 0.371 | 12.0 | 0.669 | 2.54 |
| • Refill valve | 4.08 | 12.0 | 1.03 | 4.64 |
| • Iso valve to injector | 1.24 | 6.0 | 0.672 | 3.38 |

**Option 4 Component Weight Estimates**

## 7.8. Appendix H, High Mixture Ratio Thrusters for IHOT Applications

### STATEMENT OF PROBLEM

Determine performance of oxygen, hydrogen thrusters at mixture ratio 16:1. Identify applicable technology issues.

### DESCRIPTION OF APPROACH

- Collect test data in the range of the MR of interest
- Use unclassified literature data bases
- Consult with Rocketdyne experts.

### ASSUMPTIONS LIST

- Mixture ratios to be investigated : Near 16:1 (equal volume cryo tanks).
- Hot fire performance only.

### SUMMARY OF ANALYSIS

The data sources searched were:

- NERAC (New England Research Applications Center)
- RTIS (Rockwell Technical Information Systems)
- NASA RECON Database
- DTIC (Defense Technical Information Center Database).

Rockwell personnel contacted: Vance Jacqua (formerly of Combustion Devices); J. Vrolyk, Advanced Programs.

### RESULTS AND CONCLUSIONS

The literature search did not yield hot-fire data above MR of 8:1.

The Rocketdyne experts define a "cutting torch" range of mixture ratios from 7.5 to 16. In this range most materials are destroyed.

The materials problem for a MR of 16:1 is a major technology issue.

There may be a combustion stability problem with liquid on liquid injection (Option 4).

## 7.9. Appendix I, Accumulator Blow Down Analysis

### STATEMENT OF PROBLEM

During throttling or "blow down" of a propellant tank, the tank pressure decreases and its temperature changes in accordance to the Joule-Thomson effect. In this analysis, for an initial tank pressure and temperature, the final tank temperature is determined after an amount of propellant is removed isentropically.

### DESCRIPTION OF APPROACH

The final tank temperature, $T_f$, can be computed from the following isentropic relationship

$$\frac{T_f}{T_i} = \left(\frac{P_f}{P_i}\right)^{(\gamma-1)/\gamma}$$

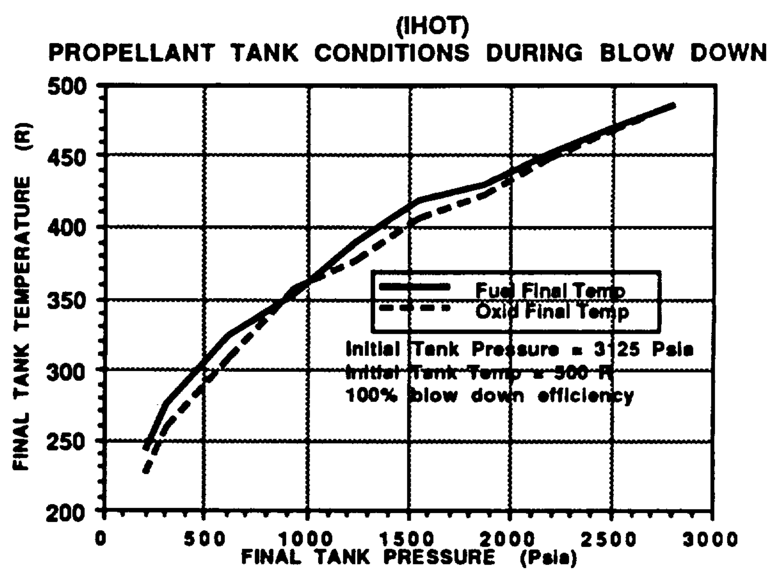
where $P_f$ is the final tank pressure after some propellant mass is removed, $P_i$ and $T_i$ are initial tank pressure and temperature, respectively, and $\gamma$ is the specific heat ratio of the propellant.

### ASSUMPTIONS LIST

- The propellants in tanks are gaseous hydrogen and oxygen
- The initial pressure and temperature of both propellant tanks are 3125 Psia and 500°R, respectively
- Assume 100% blow down efficiency
- Assume the process is isentropic and the propellants behave like ideal gases
- The specific heat ratio of the propellant is found from the initial conditions and is assumed constant throughout the process

### SUMMARY OF ANALYSIS

For the given system, the final tank temperature corresponding to a given tank pressure is depicted in the attached figure. In general, the oxidizer tank gets "colder" than the fuel tank for the same pressure drop. Note that if the process is not isentropic, the final tank temperature would be higher than that of an isentropic process. This figure can be used to find the required final conditions of the tank if one parameter, either temperature or pressure, is known. For example, if the fuel tank temperature is not to fall below 300°R, the tank pressure should not be allowed to drop under 500 Psia.




**Propellant Tank Conditions During Blowdown**

## 7.10. Appendix J, Engine Performance Excursions

### STATEMENT OF PROBLEM

This task is to study the variations in the mixture ratio of the thruster, MR, and in its performance resulting from the change of the propellant injection temperature or the change of chamber pressure at injector end, $P_c$.

### DESCRIPTION OF APPROACH

• Establish a baseline thruster and calculate its propellant flow rates
• Vary the propellant temperature and compute the new propellant flow rates. In general, the propellant flow rate is found from

$$\dot{m} = C_d \sqrt{\rho \Delta P}$$

where $C_d$ is the discharge coefficient, $\rho$ is the propellant density, and $\Delta P$ is the pressure differential across the injector. For the case with only the injection temperature is varied, $C_d$ and $\Delta P$ remain constant; and thus the new flow rate can be calculated from

$$\dot{m}_{new} = \dot{m}_{old} \sqrt{\frac{\rho_{new}}{\rho_{old}}}$$

For the case with $P_c$ is changed, only $C_d$ remains constant; and the new flow rate is

$$\dot{m}_{new} = \dot{m}_{old} \sqrt{\frac{\rho_{new} \Delta P_{new}}{\rho_{old} \Delta P_{old}}}$$

• Compute the new MR from the new propellant flow rates
• Use the computer code TWEPP to get the delivered vacuum specific impulse. Iteration on the vacuum thrust is needed to achieve similar thrust chamber in geometry

### ASSUMPTIONS LIST

The following parameters and assumptions were used in the analysis of a typical ACS-Primary thruster with gaseous $O_2/H_2$ as the injection propellants

- The baseline vacuum thrust , $P_c$, and injection temperature are, respectively, 1000 lbs, 100 Psia, and 500°R
- The baseline mixture ratio is 16:1
- The temperatures of both propellants are the same
- The pressure drops across the injector for both propellants are relatively high, at 30% of $P_c$, to achieve high stability margin for the combustor. The higher the pressure drop will decouple more effectively any disturbance in the combustor chamber from that of the feed system
- The area ratio of the nozzle is 100:1

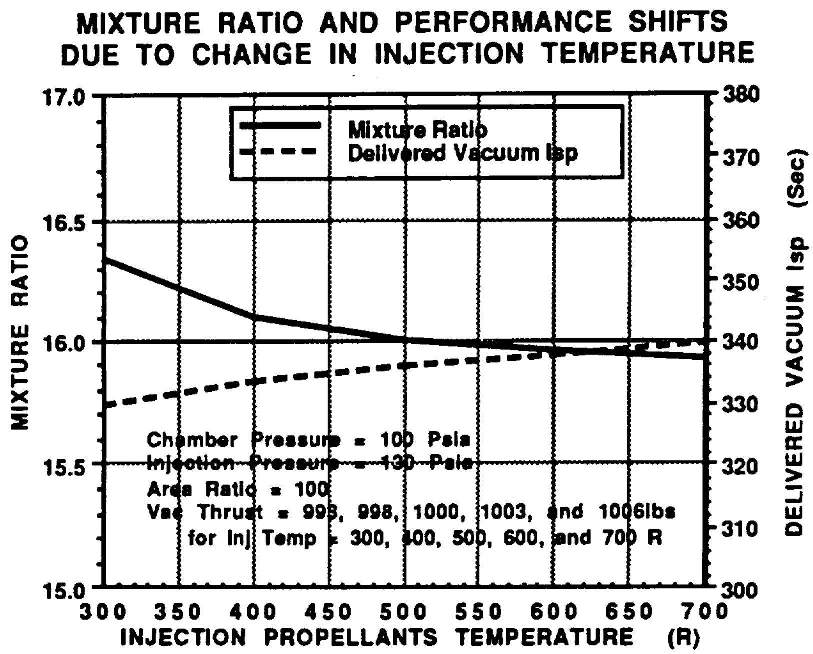
### SUMMARY OF ANALYSIS

The thruster off-design MR and its associated performance were computed for propellant temperature from 300 to 700°R and these values are depicted in the attach figure. The figure shows that MR generally decreases with higher temperature because the oxidizer density varies more, in percentage term, from its 500°R baseline value than the fuel density for the same temperature change. Consequently, the oxidizer flow rate has greater change than that of the fuel. The figure also shows that for this system with high MR, higher propellant temperature results in an increase in delivered vacuum specific impulse. With constant $P_c$ and area ratio, this change is contributed by the higher enthalpy of the warmer propellants and by the lower MR which increases the temperature of the combustion gas. The percentage changes of MR and the delivered specific impulse from the baseline 500°R were also computed and were found insignificant. At 300°R, MR is 2.1% higher and the delivered specific impulse is 1.8% lower than the values at 500°R. On the other hand at 700°R, MR is 0.44% lower and the delivered specific impulse is 1.2% higher.

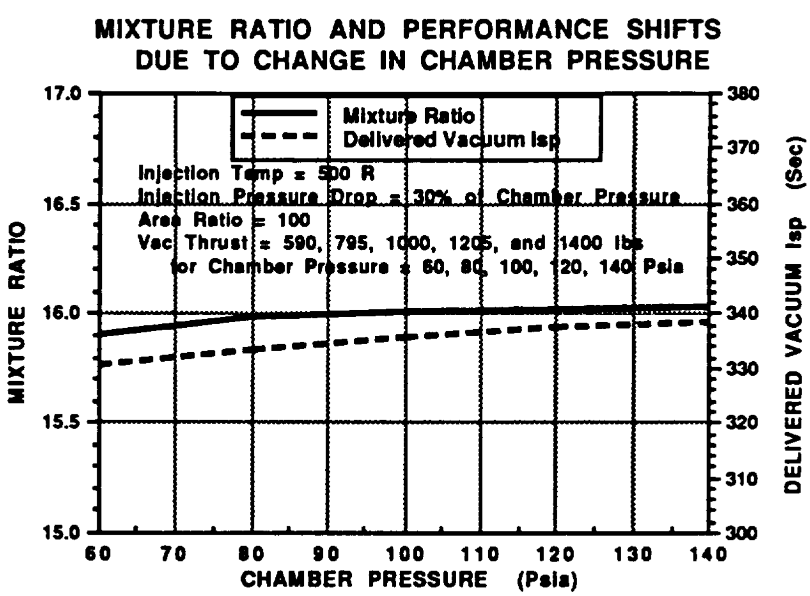
The next attached figure shows the variations of thruster MR and its delivered vacuum specific impulse for $P_c$ from 60 to 140 Psia. It is noted that MR is increased with higher $P_c$ because the oxidizer density varies more, in percentage term, from its 100 Psia baseline value than the fuel density for the same temperature change. Consequently, the oxidizer flow rate has larger change than that of the fuel. The figure also shows that for this system with high MR, higher $P_c$ results in an increase in delivered vacuum specific impulse. As area ratio is kept constant, this change is contributed mainly by the higher $P_c$ which increases the velocity of the combustion gas. This effect must more than offset the increase in MR that decreases the temperature of the combustion gas. The percentage changes of MR and the delivered specific impulse from the baseline $P_C$ were also computed and were found insignificant. At 60 Psia, MR is 0.6% lower and the delivered specific impulse is 1.6% lower than the values at 100 Psia. At 140 Psia, MR is 0.12% higher and the delivered specific impulse is 0.8% higher.

## CONCLUSIONS /RECOMMENDATIONS

The ACS-Primary thruster (gas/gas, injected) in this analysis shows negligible shifts in mixture ratio and delivered vacuum performance over the range of injection temperatures (300 - 700°R) and chamber pressures (60 - 140 Psia).




**Engine Mixture Ratio and Performance Shifts vs Injection Temperature**




**Engine Mixture Ratio and Performance Shifts vs Chamber Pressure**

## 7.11. Appendix K, Selected Option 1 RCS Trades

### STATEMENT OF THE PROBLEM

Determine the ACS volume and weight sensitivities to the following:

- Selected vernier thruster working fluid (gaseous oxygen or hydrogen)
- Primary and vernier thruster propellant inlet temperature
- Primary thruster mixture ratio

### DESCRIPTION OF APPROACH

A spreadsheet was constructed using Lotus 123 for estimating the system volume and weight. NBS real fluid property data was generated and incorporated into the spreadsheet. Delivered thruster performance data was generated (using TWEPP and ISP89 software) and incorporated into the spreadsheet. Composite tankage performance factor data was incorporated into the spreadsheet (scaled SCI data).

### ASSUMPTIONS

The following assumptions were used for the analysis:

- Only the propellant and accumulator weights are included in the ACS weight estimate.
- Only the propellant volume is included in the ACS volume estimate
- All ACS impulse functions are included in the analysis
  - Total Impulse - 749,192 lbf-sec
  - Vernier impulse (fwd and aft) - 148,104 lbf-sec
  - Primary impulse (fwd and aft) - 601,088 lbf-sec
- Thruster performance predicted using a blowdown temperature of 450, 400, and 350 deg-R as the assumed thruster inlet temperature (except in Table 5).
- Thruster area ratios- 22:1
- Thruster chamber pressures, 150 psia
- Thurster inlet pressure, 195 psia (1.3 * Pc, regulated)
- Accumulator initial pressure, 3125 psia
- Accumulator initial temperature, 560 deg-R
- Accumulator final pressure - 200 psia
- Final delta-pressure across the regulator is assumed at 5 psid

### SUMMARY OF ANALYSIS

The fraction of the total impulse assigned to the vernier engines is calculated to be 19.8 %, based on a Vernier thruster requirement of 148,104 lbf-sec, and is produced using either room temperature oxygen gas (Cases 1 and 2) or room temperature hydrogen gas.(Cases 3 and 4) The balance of the impulse (601,088 lbf-sec) is produced by the Primary thrusters utilizing oxygen gas and hydrogen gas at low mixture ratios of 3, 4,and 5, (Cases 1 and 3), and at high mixture ratios of 15, 16 and 17, (Cases 2 and 4).

A brief analysis determined the propellant weight, the accumulator weight and the propellant volume in each of the cases shown in Table 1. The results are shown in Table 3. A comparison of the parameters of interest are shown in Table 4.

Refering to Table 4, the lightest system, is Case #2, Run 402, where the vernier utilizes oxygen gas only (Initially at room temperature and then blown down) for propellant, and where the primary thrusters burn oxygen and hydrogen gas at a mixture ratio of 15. The smallest volume of propellants is also shown as Case #2, but in Run 502., at a mixture ratio of 17. However, the differences between these two runs is small enough so that other considerations will determine which is the most desirable.

In the runs and results shown in Table 4 the thruster inlet temperature was held constant at the lowest and final tank outlet temperature during each blowdown; in contrast, the runs shown in Table 5 assume that the thruster inlet temperature is held constant at a temperature near the average of the propellant tank starting and final temperatures.

The fact that using oxygen gas as a monopropellant turns out to be the lightest (instead of hydrogen) is contrary to the conclusion usually reached when only the propellant weight is considered instead of the combined weight of the propellants and the propellant tanks.

### RESULTS AND CONCLUSIONS

The propellant of choice for the ACS vernier engines, based on this limited preliminary study, is room temperature oxygen gas rather than room temperature hydrogen gas. The rational for this conclusion follows.



C-2

- The volume and weight of the stored propellants and their associated tanks is substantially less.
- The probability of having a hydrogen leak is reduced since the number of propellant lines and components containing hydrogen is substantially reduced. Hydrogen has a far greater propensity to leak than oxygen.
- It may be that an excess of oxygen as compared to hydrogen is available to the system, in which case the room temperature oxygen gas vernier thrusters would serve to relieve the imbalance to some extent rather than exacerbating it if hydrogen were used as the propellant.

**Table 1. Case Descriptions for the Option 1 ACS System Analysis**

| | Total Impulse lb-sec | Percent Total Impulse | Propellants | Mixture Ratio |
|---|---|---|---|---|
| Case #1 The VERNIER THRUSTERS are supplied only with OXYGEN GAS propellant starting at a temperature of 560 R and ending at the final blowdown tank outlet temperature. | 148,104 | 19.8 | Oxygen Gas | NA |
| Each of the PRIMARY THRUSTERS is supplied with OXYGEN GAS and HYDROGEN GAS as propellants, at temperatures as above. | 601,088 | 80.2 | O2 & H2 Gas | 3 |
| Case #2 Same as case #1, above, except the Mixture Ratio 16. | Ditto | Ditto | Ditto | 16 |
| Case #3 The VERNIER THRUSTERS are supplied only with HYDROGEN GAS propellant starting at a temperature of 560 R and ending at the final blowdown tank outlet temperature. | 148,104 | 19.8 | Hydrogen Gas | NA |
| Each of the PRIMARY THRUSTERS is supplied with OXYGEN GAS and HYDROGEN GAS, as propellants, at temperatures as above. | 601,088 | 80.2 | O2 & H2 Gases | 3 |
| Case #4 Same as Case #3, above, except the Mixture Ratio is 16 | Ditto | Ditto | Ditto | 16 |
| Total impulse, PRIMARY plus VERNIER | 749,088 | | | |

## Table 2. Vernier Thrusters Performance (Monopropellants)

| Propellant Gas | Chamber Pressure | Expansion Ratio | Inlet Pressure | Inlet Temperature | Specific Impulse |
|---|---|---|---|---|---|
| O2 | 150 | 22 | 195 | 350 | 55.7 |
| O2 | 150 | 22 | 195 | 400 | 59.5 |
| O2 | 150 | 22 | 195 | 450 | 63.1 |
| H2 | 150 | 22 | 195 | 350 | 218.9 |
| H2 | 150 | 22 | 195 | 400 | 234.2 |
| H2 | 150 | 22 | 195 | 450 | 248.6 |

# Table 3. ACS PRIMARY Performance

| | | Mixture Ratio | | | | |
|---|---|---|---|---|---|---|
| Thrust, lbf | 870 | | | | | |
| Expansion Ratio | 22 | | | | | |
| Inlet Temperature (Degrees R) | | | 350 | 400 | 450 | 455 |
| Specific Impulse sec | | 3 | 438.0 | 439.9 | 442.0 | 442.2 |
| | | 4 | 436.8 | 438.2 | 439.8 | 4439.9 |
| | | 5 | 429.3 | 430.4 | 431.6 | 431.7 |
| | | 15 | 319.2 | 319.9 | 320.7 | 320.85 |
| | | 16 | 312.2 | 312.9 | 313.7 | 314.4 |
| | | 17 | 305.7 | 306.5 | 307.3 | 308.1 |

## Table 4A. Matrix to Show Sensitivity of Weight and Volume to Tank Final Blowdown Temperature and to Primary Thruster Mixture Ratio.

| Case # | Run # | Inlet Temp | Gas Type | Volume cu.ft | Weight lbm | M.R. |
|---|---|---|---|---|---|---|
| 1 | 90 | 300 R | O2 | 682 | 10,673 | 3 |
| 2 | 90 | 300 | O2 | 449 | 9,611 | 16 |
| 3 | 90 | 300 | H2 | 1394 | 13,395 | 3 |
| 4 | 90 | 300 | H2 | 1162 | 12,333 | 16 |
| 1 | 100 | 350 | O2 | 654 | 10,093 | 3 |
| 2 | 100 | 350 | O2 | 427 | 9,052 | 16 |
| 3 | 100 | 350 | H2 | 1304 | 12,575 | 3 |
| 4 | 100 | 350 | H2 | 1077 | 11,534 | 16 |
| 1 | 101 | 400 | O2 | 632 | 9,625 | 3 |
| 2 | 101 | 400 | O2 | 409 | 8,599 | 16 |
| 3 | 101 | 400 | H2 | 1203 | 11,919 | 3 |
| 4 | 101 | 400 | H2 | 1007 | 10,893 | 16 |
| 1 | 102 | 450 | O2 | 616 | 9,283 | 3 |
| 2 | 102 | 450 | O2 | 395 | 8,270 | 16 |
| 3 | 102 | 450 | H2 | 1173 | 11,401 | 3 |
| 4 | 102 | 450 | H2 | 952 | 10,387 | 16 |

Note: The thruster inlet temperature is assumed constant at final tank blowdown temperature. Table 5 shows results with this temperature at the average of the initial and final tank temperatures.

| Case # | Run # | Inlet Temp. | Gas Type | Volume cu.ft | Weight lbm | M.R. |
|---|---|---|---|---|---|---|
| 1 | 200 | 350 R | O2 | 577 | 9,509 | 4 |
| 2 | 200 | 350 | O2 | 427 | 9,502 | 16 |
| 3 | 200 | 350 | H2 | 1227 | 11,991 | 4 |
| 4 | 200 | 350 | H2 | 1077 | 11,534 | 16 |
| 1 | 201 | 400 | O2 | 577 | 9,064 | 4 |
| 2 | 201 | 400 | O2 | 409 | 8,613 | 16 |
| 3 | 201 | 400 | H2 | 1155 | 11,344 | 4 |
| 4 | 201 | 400 | H2 | 1007 | 10,893 | 16 |
| 1 | 202 | 450 | O2 | 541 | 8,715 | 4 |
| 2 | 202 | 450 | O2 | 395 | 8,270 | 16 |
| 3 | 202 | 450 | H2 | 1098 | 10,833 | 4 |
| 4 | 202 | 450 | H2 | 952 | 10,387 | 16 |
| 1 | 300 | 350 | O2 | 531 | 9,186 | 5 |
| 2 | 300 | 350 | O2 | 427 | 9,052 | 16 |
| 3 | 300 | 350 | H2 | 1180 | 11,668 | 5 |
| 4 | 300 | 350 | H2 | 1077 | 11,534 | 16 |

## Table 4B. Matrix to Show Sensitivity of Weight and Volume to Tank Final Blowdown Temperature and to Primary Thruster Mixture Ratio.

| Case # | Run # | Inlet Temp | Gas Type | Volume cu.ft | Weight lbm | M.R. |
|---|---|---|---|---|---|---|
| 1 | 301 | 400 R | O2 | 511 | 8,746 | 5 |
| 2 | 301 | 400 | O2 | 409 | 8,613 | 16 |
| 3 | 301 | 400 | H2 | 1109 | 11,025 | 5 |
| 4 | 301 | 400 | H2 | 1007 | 11,893 | 16 |
| 1 | 302 | 450 | O2 | 496 | 8,401 | 5 |
| 2 | 302 | 450 | O2 | 395 | 8,270 | 16 |
| 3 | 302 | 450 | H2 | 1053 | 10,518 | 5 |
| 4 | 302 | 450 | H2 | 952 | 10,387 | 16 |
| 1 | 400 | 350 | O2 | 654 | 10,093 | 3 |
| 2 | 400 | 350 | O2 | 429 | 9,017 | 15 |
| 3 | 400 | 350 | H2 | 1304 | 12,575 | 3 |
| 4 | 400 | 350 | H2 | 1079 | 11,499 | 15 |
| 1 | 401 | 400 | O2 | 633 | 9,639 | 3 |
| 2 | 401 | 400 | O2 | 412 | 8,579 | 15 |
| 3 | 401 | 400 | H2 | 1230 | 11,919 | 3 |
| 4 | 401 | 400 | H2 | 1009 | 10,859 | 15 |

| Case # | Run # | Inlet Temp. | Gas Type | Volume cu.ft | Weight lbm | M.R. |
|---|---|---|---|---|---|---|
| 1 | 402 | 450 R | O2 | 616 | 9,283 | 3 |
| 2 | 402 | 450 | O2 | 398 | 8,236 | 15 |
| 3 | 402 | 450 | H2 | 1173 | 11,401 | 3 |
| 4 | 402 | 450 | H2 | 954 | 10,354 | 15 |
| 1 | 500 | 350 | O2 | 654 | 10,093 | 3 |
| 2 | 500 | 350 | O2 | 425 | 9,087 | 17 |
| 3 | 500 | 350 | H2 | 1304 | 12,575 | 3 |
| 4 | 500 | 350 | H2 | 1075 | 11,569 | 17 |
| 1 | 501 | 400 | O2 | 633 | 9,639 | 3 |
| 2 | 501 | 400 | O2 | 407 | 8,648 | 17 |
| 3 | 501 | 400 | H2 | 1230 | 11,919 | 3 |
| 4 | 501 | 400 | H2 | 1005 | 10,927 | 17 |
| 1 | 502 | 450 | O2 | 616 | 9,283 | 3 |
| 2 | 502 | 450 | O2 | 393 | 8,304 | 17 |
| 3 | 502 | 4560 | H2 | 1173 | 11,401 | 3 |
| 4 | 502 | 450 | H2 | 950 | 10,421 | 17 |

Note: The thruster inlet temperature is assumed constant at final tank blowdown temperature. Table 5 shows results with this temperature at the average of the initial and final tank temperatures.

## TABLE 5. SYSTEM WEIGHT AND VOLUME VS MIXTURE RATIO (Holding thruster inlet temperature constant at the average tank outlet temperature)

| Case # | Run # | Gas | O2/H2 Is sec | Volume cu.ft | Weight lbm | Mixture R |
|---|---|---|---|---|---|---|
| 1 | 100-A2 | O2 | 442.2 | 630.4 | 9,497.1 | 3 |
| 2 | 100-A2 | O2 | 314.4 | 404.7 | 8,463.1 | 16 |
| 3 | 100-A2 | H2 | 442.2 | 1201.7 | 11,681.8 | 3 |
| 4 | 100-A2 | H2 | 314.4 | 976.0 | 10,647.9 | 16 |
| 1 | 200-A2 | O2 | 439.9 | 554.3 | 8,922.5 | 4 |
| 2 | 200-A2 | O2 | 314.4 | 404.7 | 8,463.1 | 16 |
| 3 | 200-A2 | H2 | 439.9 | 1125.6 | 11,107.3 | 4 |
| 4 | 200-A2 | H2 | 314.4 | 976.0 | 10,647.9 | 16 |
| 1 | 300-A2 | O2 | 431.7 | 508.6 | 8,604.5 | 5 |
| 2 | 300-A2 | O2 | 314.4 | 404.7 | 8,463.1 | 16 |
| 3 | 300-A2 | H2 | 431.7 | 1079.9 | 10,789.3 | 5 |
| 4 | 300-A2 | H2 | 314.4 | 976.8 | 10,647.9 | 16 |
| 1 | 400-A2 | O2 | 442.2 | 630.4 | 9,497.1 | 3 |
| 2 | 400-A2 | O2 | 320.9 | 407.5 | 8,435.6 | 15 |
| 3 | 400-A2 | H2 | 442.2 | 1201.7 | 11,681.8 | 3 |
| 4 | 400-A2 | H2 | 320.9 | 978.8 | 10,620.4 | 15 |
| 1 | 500-A2 | O2 | 442.2 | 630.4 | 9,497.1 | 3 |
| 2 | 500-A2 | O2 | 308.1 | 402.5 | 8,495.9 | 17 |
| 3 | 500-A2 | H2 | 442.2 | 1201.7 | 11,681.8 | 3 |
| 4 | 500-A2 | H2 | 308.1 | 973.8 | 10,660.7 | 17 |

- Initial Tank Temperature: 560 R
- Final Tank Temperature: 350 R
- Avg Thruster Inlet Temperature: 455 R
- Specific Impulse for O2 Gas: 63.4 sec
- Specific Impulse for H2 Gas: 249.0 sec

## 7.12. Appendix L, RCS, OMS Engine Performance Maps

### STATEMENT OF PROBLEM

The task analyzes the effects on the delivered vacuum performance caused by the changes in the thruster mixture ratio, MR, and in chamber pressure at injector end, $P_c$.

### DESCRIPTION OF APPROACH

For moderate changes in $P_c$, a typical ACS-Primary thruster was used to predict its performance over a wide range of MR (1 - 20). The computer code TWEPP was employed to obtain the delivered vacuum specific impulse.

For large changes in $P_c$, an OMS thruster was used in the analysis. The code TWEPP was again applied to get the thruster performance. The data of the SSME using the code TWEPP was also included for comparison purposes.

### ASSUMPTIONS LIST

The ACS-Primary thruster with gaseous $O_2/H_2$ as the propellants has the following baseline parameters

- The vacuum thrust is 1000 lbs
- The injection temperatures of both propellants are 500°R
- The pressure drops across the injector for both propellants are relatively high, at 30% of $P_c$, to achieve high stability margin for the combustor
- The area ratio of the nozzle is 100:1

The OMS thruster with liquid $O_2/H_2$ as the propellants has the following baseline parameters

- The vacuum thrust is 6000 lbs
- The enthalpy of formation values for fuel and oxidizer are -2.154 and -3.102 kcal/mole, respectively
- The pressure drops across the injector for both propellants are relatively high, at 30% of $P_c$, to achieve high stability margin for the combustor
- The area ratio of the nozzle is 55:1

The SSME with liquid $O_2/H_2$ as the propellants has the following baseline parameters

- The vacuum thrust is 471300 lbs at 100% power level
- $P_c$ at this power level is 3006 Psia
- The enthalpy of formation values for fuel and oxidizer are -2.154 and -3.102 kcal/mole, respectively
- The area ratio of the nozzle is 77:1

### SUMMARY OF ANALYSIS

The delivered vacuum specific impulse for the ACS-Primary thruster is shown in the attached figure for $P_c$ equals 75, 100, and 150 Psia. In general, the specific impulse peaks at MR about 4, then starts to drop off. Apparently, at MR of 4 and higher, the combustion gas becomes heavier since it is more fuel lean. Thus, the delivered specific impulse must decrease in order for the thruster to deliver the same vacuum thrust. At any MR, the performance is better at higher $P_c$. This is because higher $P_c$ increases the velocity of the combustion gas. To keep the same thrust, the mass flow rate of the combustion gas must be decreased.

The next attached figure shows the performance data of an OMS thruster operating with $P_c$ equals 150 and 3006 Psia. The figure also includes the data of the SSME operating at 100% power level. Similar trend is observed in this figure and previous one, i.e., the performance peaks at some certain MR then becomes worse at higher MR. It is noted that the OMS thruster at $P_c$ of 150 Psia has maximum performance at MR about 4; while the highest delivered specific impulse of the OMS thruster at $P_c$ of 3006 Psia and the SSME occurs at MR of 5. The main reason is the much higher combustion gas velocity in the thruster with very high chamber pressure.

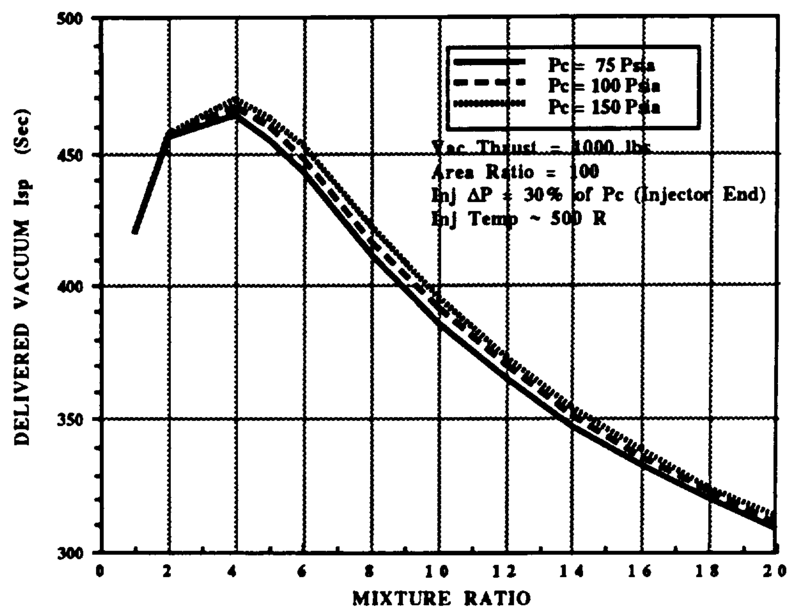
### CONCLUSIONS/ RECOMMENDATIONS

The following conclusions can be made from this analysis

- The performance of a thruster maximizes at a certain mixture ratio. For thruster with chamber pressure from 75 to 150 Psia, this occurs at about 4. For higher chamber pressure, ~3000 Psia, the maximum point is at 5

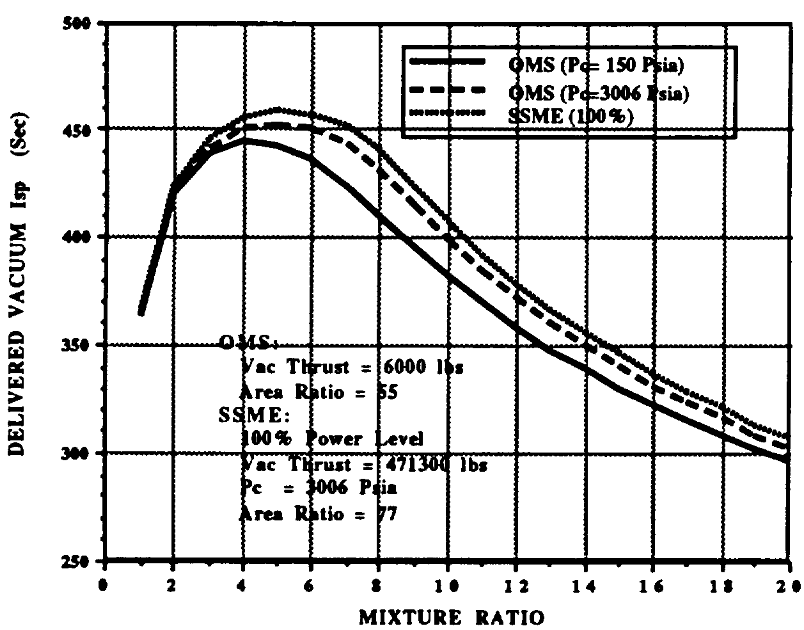
- For a thruster that delivers the same thrust, at a given mixture ratio, increasing the chamber pressure results in better performance
- For a thruster that delivers the same thrust, increasing the chamber pressure shifts the maximum performance point to a higher mixture ratio

PERFORMANCE VS. MIXTURE RATIO




**RCS Engine Performance, versus Mixture Ratio**

PERFORMANCE VS. MIXTURE RATIO




**OMS Engine Performance, versus Mixture Ratio**

## 8. REFERENCES

References have been included in the body of the Final Report text, for clarity.