SPACE TRANSPORTATION BOOSTER ENGINE (STBE) CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
11 SEPTEMBER 1986

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SUMMARY • A. Weiss

CONTROL SYSTEM AND HEALTH MONITOR STUDIES • R. Brewster

D. Nguyen

THROTTLING ON-DESIGN/OFF-DESIGN STUDY • W. Bissell

Combustion Devices Studies • P. Megen

A. Eastland

Turbomachinery Studies • A. Weiss

Subsystem Optimization Approach • A. Weiss

Task 2 Status Review • T. Weiss

Task 1 Summary • T. Weiss

Introduction • F. Kirby

AGENDA
SECOND QUARTERLY REVIEW
STBE CONFIGURATION STUDY
STUDY OBJECTIVES

THE OVERALL OBJECTIVE OF THIS ENGINE STUDY IS TO IDENTIFY CANDIDATE ENGINE CONFIGURATIONS WHICH ENHANCE VEHICLE PERFORMANCE AND PROVIDE OPERATIONAL FLEXIBILITY AT LOW COST. THE SPECIFIC OBJECTIVES ARE LISTED ON THIS CHART.
STUDY OBJECTIVES

- The 1995 Ioc Engine Preliminary Programmatic Planning and Analysis
- Develop a Technology Plan for the 2000 Ioc Engine
- Prepare a Conceptual Design for Each Configuration
- Select one Optimum Engine for Each Time Period
- Identify and Evaluate Candidate Lox/Ic Engine Configurations

1995 Ioc and a Late 2000 Ioc for the Advanced Space Transportation System for an Early
STBE STUDY TO BE ACCOMPLISHED IN 5 TASKS

IN TASK 1, THE REQUIREMENTS FOR THE STBE WERE DETERMINED AND 24 POTENTIAL CANDIDATE ENGINE CONFIGURATIONS IDENTIFIED AND SCREENED. THE 9 MOST PROMISING CANDIDATES ARE CARRIED INTO TASK 2

IN TASK 2 NINE (9) ENGINE CANDIDATES (6 FOR 1995 IOC AND 3 FOR 2000 IOC) WILL BE EVALUATED IN DEPTH TO DEFINE THE OPTIMUM MAJOR SUBSYSTEMS FOR EACH


IN TASK 4, CONCEPTUAL DESIGNS WILL BE PREPARED FOR BOTH THE 1995 AND 2000 IOC ENGINES. THE DESIGN FOR THE 1995 CONFIGURATION WILL BE IN SUFFICIENT DEPTH TO CONDUCT PRELIMINARY PROGRAMMATIC PLANNING

IN TASK 5, THE PRELIMINARY PROGRAMMATIC PLANNING AND ANALYSIS WILL BE COMPLETED.
StBE Study To Be Accomplished In 5 Tasks
AGENDA
SECOND QUARTERLY REVIEW
STE CONFGURATION STUDY
This chart shows the flow diagram for the task 1 effort. The inputs were derived from NASA-MSFC studies and prior rocketdyne in-house studies. They were used to identify 24 candidate engine configurations. These were reduced to 19 after a preliminary technical evaluation. Engine flow schematics and performance optimization balances were then prepared for the 19 engine configurations. An assessment and ranking process which considered engine reliability, weight, life cycle cost, propellant bulk density and risk was used to select 6 configurations to support a 1995 IOC and 3 configurations to support a 2000 IOC. These 9 configurations were carried into task 2.
TASK 1 - IDENTIFICATION OF CANDIDATE STDE CONFIGURATIONS

INPUTS

STUDIES

OUTPUTS

LONG LIFE
- COST
- LOW OPERATIONS
GOALS

1990

1986

TECHNOLOGY LEVEL

STAGED COMBUSTION
- GAS GENERATOR
- CYCLES

COOLANTS

FUELS

LO2

LH2

Coolants

Select engine configurations

2000 engine

Fuel, LH2, LO2

G.4 cycle

CO2, H2

4.6 cycle

Configurations

Select 3 configurations

2000 engine configuration

1995 engine configuration

Configurations

Long life

Cost

Low operations

Input factors

Vehicle requirements

Engine requirements

Thrust

Life

Throttling

TCO

Propellants

LOX/LO2

LOX/CH4

LOX/Rp-1

LOX/C2H8

Identify candidate configurations

Develop schematics

Engine balances and optimized

Assessment and ranking

Outputs
SPACE TRANSPORTATION BOOSTER ENGINE REQUIREMENTS

THE PRIMARY ENGINE REQUIREMENTS WERE INPUT TO THE STBE STUDY CONTRACTORS BY NASA-MSFC. THE REQUIREMENTS FOR MAIN CHAMBER PRESSURE AND PUMP INLET PRESSURE WERE DEVELOPED BY ROCKETDYNE FROM DISCUSSIONS WITH THE STAS CONTRACTORS AND IN-HOUSE STUDIES. A HIGH $p_c$, HIGH PERFORMANCE ENGINE ENHANCES VEHICLE PERFORMANCE AND COST. ELIMINATION OF THE BOOST PUMPS SIMPLIFIES THE TURBOMACHINERY.
BOOST PUMPS
PUMP INLET PRESSURE SUFFICIENT TO NOT REQUIRE
FOR MAXIMUM VACUUM ISP
MAIN COMBUSTION CHAMBER PRESSURE OPTIMIZED

ROCKETDYNE DEVELOPED

CLOSED LOOP THRUST/MOTION CONTROL
GIMBAL ANGLE = 6 DEGREE SQUARE PATTERN
BURN TIME = 160 SEC MAX
THROTTLE RANGE = +0.2% -20%
FUEL = T.B.D.

100 MISSIONS DESIGN LIFE
25 MISSIONS TO OVERHAUL
ENGINE LIFE @ RATED THRUST
MAXIMUM THRUST = 750K (@ SL)
RATED THRUST = 625K @ SL
NASSA-MSC SUPPLIED

ENGINE REQUIREMENTS
SPACE TRANSPORTATION BOOSTER
CANDIDATE ENGINES FOR TASK 1
STUDY IDENTIFIED

TWENTY-FOUR CANDIDATE CONFIGURATIONS WERE IDENTIFIED FOR EVALUATION. HALF WERE DEFINED WITH 1986 TECHNOLOGY AND THE OTHER HALF WITH 1990 TECHNOLOGY. FIVE CONFIGURATIONS WERE THEN REJECTED BY AN ENGINEERING PRE-SCREEN.
1500K FOR REFERENCE ONLY – NOT USED IN SCREENING PROCESS

750K AND 1500K

2 THROUST LEVELS EVALUATED FOR 1995 CANDIDATES

5 OF 24 CANDIDATES REJECTED DUE TO LACK OF FEASIBILITY OR ADVANTAGE

12 TO SUPPORT A 1995 LAUNCH DATE

24 CANDIDATES CONSIDERED

STUDY IDENTIFIED CANDIDATE ENGINES FOR TASK 1
CANDIDATE STBE CONFIGURATIONS FOR TASK 1

These were the 19 candidates that were evaluated. Of these, 3 were at 1500 \( \text{kFb} \) thrust and are for comparison purposes only. This left 16 engines to be evaluated and screened down to the 9 that were recommended for task 2 component evaluation.
<table>
<thead>
<tr>
<th>Propellant</th>
<th>Lox/LH2</th>
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<td></td>
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<tr>
<td>8 CH</td>
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<td>8 CH</td>
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</tbody>
</table>

**Candidate STBE Configurations for Task 1**
SUMMARY OF TECHNICAL ENGINE DATA

THIS CHART SUMMARIZES THE TECHNICAL (NON-COST) DATA USED IN DETERMINING THE LIFE CYCLE COST PARAMETERS FOR THE SCREENING PROCESS.
THUS, THE F-1 ENGINES WEIGHT WAS HALVED TO BE COMPATIBLE.

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<td>61.5</td>
<td>7880</td>
<td>11</td>
<td>56</td>
<td>12</td>
<td>3</td>
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2000 ENGINE CANDIDATES

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<td>8000</td>
<td>1</td>
<td>9</td>
<td>10</td>
<td>9</td>
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</table>

1995 ENGINE CANDIDATES

<p>| | | | | | | | | |</p>
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<thead>
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<tr>
<td>TECHNOICAL LEVEL</td>
<td>SUCCESS PROBABILITY</td>
<td>COMPLEXITY</td>
<td>B/L</td>
<td>W/L</td>
<td>ISP</td>
<td>VACUUM</td>
<td>NUMBER</td>
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<td>392</td>
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<td>34</td>
<td>7</td>
<td>9</td>
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SUMMARY OF TECHNICAL ENGINE DATA
SUMMARY OF ENGINE COST DATA

The production, development, certification, and O&S costs, estimated for the sixteen STBE candidates in the two IOC groups are listed. The costs were obtained using Rocketdyne's suite of parametric cost models with the principal input parameters as shown. All engines are at the 750 KLBS SL thrust level, corresponding to about 850 KLBS vacuum thrust. The last column, engine LCC, is the sum of all cost elements.
SUMMARY OF VEHICLE LIFE CYCLE COST ELEMENTS

THE SIX INDIVIDUAL LCC ELEMENTS WHICH, WHEN SUMMED, RESULT IN THE OVERALL COST SCREENING CRITERION, \( \Sigma(\Delta LCC_V) \), ARE LISTED FOR ALL ENGINE CANDIDATES OF THE TWO IOC GROUPS.
### 1995 Engine Candidates

<table>
<thead>
<tr>
<th>IMPACT</th>
<th>COST</th>
<th>LIFE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RISK</td>
<td>DENSITY</td>
<td>RELIABILITY</td>
</tr>
</tbody>
</table>

### 2000 Engine Candidates

| 2000 | 0.074 | 916 | 0.969 | 2.111 | 0.207 | (0.0.1.964) | (0.0.1.161) | 19 |
| 2.979 | 651 | 0.743 | 0.074 | 0.074 | 0.074 | (0.0.1.976) | (0.0.1.161) | 18 |
| 2.894 | 98.9 | 0.974 | 0.084 | 0.084 | 0.084 | (0.0.1.898) | (0.0.1.161) | 17 |
| 1.980 | 1.12 | 1.12 | 0.980 | 0.980 | 0.980 | (0.0.1.980) | (0.0.1.161) | 16 |
| 0.943 | 0.51 | 0.51 | 0.943 | 0.943 | 0.943 | (0.0.1.943) | (0.0.1.161) | 15 |
| 0.327 | 0.327 | 0.327 | 0.327 | 0.327 | 0.327 | (0.0.1.327) | (0.0.1.161) | 14 |
| 0.357 | 0.357 | 0.357 | 0.357 | 0.357 | 0.357 | (0.0.1.357) | (0.0.1.161) | 13 |
| 0.410 | 0.410 | 0.410 | 0.410 | 0.410 | 0.410 | (0.0.1.410) | (0.0.1.161) | 12 |
| 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | (0.0.1.450) | (0.0.1.161) | 11 |

**FY 86 $B**

**SUMMARY OF VEHICLE LIFE CYCLE COST ELEMENTS —**
THE ENGINE CANDIDATES ARE RANKED ACCORDING TO THEIR OVERALL COST CRITERION, $\Sigma(\Delta L C C, \nu)$. THE MINIMUM VALUE OF THE OVERALL COST CRITERION LEADS TO THE HIGHEST RANKED ENGINE.
<table>
<thead>
<tr>
<th></th>
<th>2000 Engine Candidates</th>
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</tr>
</thead>
<tbody>
<tr>
<td>LH2</td>
<td>LOX/RP-1/LH2</td>
<td>6</td>
<td>0</td>
<td>$0.060</td>
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<tr>
<td>LO2</td>
<td>LOX/C3H8</td>
<td>12</td>
<td>0</td>
<td>$0.442</td>
</tr>
<tr>
<td>LO2</td>
<td>LOX/RP-1</td>
<td>11</td>
<td>0</td>
<td>$1.235</td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th>1995 Engine Candidates</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellants</td>
<td>Coolant</td>
<td>Cycle Impact</td>
<td>Cost</td>
<td>Engine Number</td>
</tr>
<tr>
<td>LH2</td>
<td>LOX/RP-1/LH2</td>
<td>6</td>
<td>0</td>
<td>$0.068</td>
</tr>
<tr>
<td>CH4</td>
<td>LOX/RP-1/CH4</td>
<td>5</td>
<td>0</td>
<td>$0.295</td>
</tr>
<tr>
<td>LH2</td>
<td>LOX/C3H8</td>
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<td>0</td>
<td>$0.442</td>
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<tr>
<td>C3H8</td>
<td>LOX/RP-1/C3H8</td>
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<td>LH2</td>
<td>LOX/RP-1</td>
<td>1</td>
<td>0</td>
<td>$0.983</td>
</tr>
</tbody>
</table>

**TASK I ENGINES SELECTED**
AGENDA
SECOND QUARTERLY REVIEW
STBE CONFIGURATION STUDY

SUMMARY • A. Weiss
CONTROL SYSTEM AND HEALTH MONITOR STUDIES • R. Brewster
D. Nguyen
THROTTLING ON-DESIGN/OF-P-DESIGN STUDY • W. Blissett
COMBUSTION DEVICES STUDIES • P. Meehan
TURBOMACHINERY STUDIES • A. Eastland
SUBSYSTEM OPTIMIZATION APPROACH • A. Weiss

TASK 2 STATUS REVIEW • A. Weiss
TASK 1 SUMMARY • F. Kirby
INTRODUCTION
TASK 2 - EVALUATION OF CANDIDATE STBE CONFIGURATIONS

THE OBJECTIVES OF TASK 2 ARE DESCRIBED ON THIS CHART. MOST OF THE EFFORT WILL BE DIRECTED TOWARD IN-DEPTH STUDIES OF THE THREE MAJOR SUBSYSTEMS LISTED TO DEFINE THE OPTIMUM SUBSYSTEM FOR EACH CANDIDATE ENGINE. SUPPORTING STUDIES, AS REQUIRED, WILL BE CONDUCTED TO PROVIDE A BASIS FOR SELECTION OF THE OPTIMUM SUBSYSTEM.
TECHNOLOGY STATUS
OPERATIONAL FLEXIBILITY
VEHICLE COMPATIBILITY
FACILITIES
FMEA
HAZARDS
RISK
LCC

Conduct supporting studies to provide basis for selection

CONTROL AND HEALTH MONITORING SYSTEM
TURBOMACHINERY
THRUST CHAMBER ASSEMBLY

Which optimize the selected candidate engines

Conduct system and subsystem trade studies to define features

OBJECTIVES

CANDIDATE STEE CONFIGURATIONS

TASK 2 — EVALUATION OF
TASK 2 - EVALUATION OF CANDIDATE STBE CONFIGURATIONS FLOW DIAGRAM

THIS CHART PRESENTS THE FLOW DIAGRAM FOR THE TASK 2 EFFORT.

THE 9 ENGINE CONFIGURATIONS FOR IN-DEPTH STUDY WERE DEFINED IN TASK 1. BASELINE ENGINE PARAMETERS IN TASK 1 WERE BASED ON 750K LBS THRUST, AND FIXED ORIFICE CONTROLS. THROTTLING WAS NOT CONSIDERED. THE VEHICLE TRADE FACTORS WERE DEVELOPED BY ROCKETDYNE IN ORDER TO MEET THE SCHEDULE.

IN TASK 2 THE ENGINE BALANCES WILL BE RE-RUN BASED ON REVISED GROUND RULES WHICH CONSIDER THE ACTUAL VEHICLE AND ENGINE REQUIREMENTS RELATIVE TO THRUST AND THROTTLING.

IN-DEPTH COMPONENT TRADE STUDIES WILL BE CONDUCTED IN THE AREAS OF TURBOMACHINERY, COMBUSTION DEVICES, AND CONTROLS AND HEALTH MONITORING.

SUBSYSTEM SCREENING WILL UTILIZE UPDATED VEHICLE FACTORS BASED ON STAS CONTRACTORS INPUTS.

NEW BALANCES WILL BE RUN FOR THE 9 ENGINE CONFIGURATIONS AFTER THE OPTIMUM SUBSYSTEMS ARE DEFINED.
EVALUATION OF CANDIDATE STBE CONFIGURATIONS APPROACH

THE OVERALL APPROACH TO TASK 2 IS A PARALLEL EFFORT. FIXED DESIGN POINT BALANCES ARE USED TO CONDUCT SUBSYSTEM TRADE STUDIES FOR THE TURBOMACHINERY AND COMBUSTION DEVICES. IN PARALLEL A THROTTLING CONFIGURATION IS DEVELOPED FOR EACH ENGINE AND A BALANCE GENERATED AT THE 750K LB THRUST POINT. AN OFFDESIGN MODEL IS THEN UTILIZED TO PREDICT PERFORMANCE AT 625K LB THRUST. THE CONTROL SYSTEM WILL THEN BE SCOPE FROM THE BALANCE DATA AND A VALVE SENSITIVITY STUDY.

THE TURBOMACHINERY AND COMBUSTION DEVICES WILL THEN BE RE-EVALUATED AGAINST THE THROTTLING CONFIGURATIONS, WITH ADJUSTMENTS MADE AS REQUIRED. FINAL OPTIMIZED BALANCES WILL THEN BE RUN FOR EACH (THROTTLING) CONFIGURATION ENGINE. THE DATA WILL BE USED TO SELECT THE BEST 1996 AND 2000 ENGINE CANDIDATE USING THE APPROVED EVALUATION AND SELECTION CRITERIA PLAN.
Configure Engines

Generate new engine balances for the optimized throttling configuration

Reevaluate selected subsystems for throttling configuration

Ance and value sensitivity study

Define control system requirements based on engine balance

Mane at 625 kip thrust operating point

Use off-design computer model to predict engine performance

Generate engine balances for the throttling configurations

Develop throttling configuration for each engine candidate

Combustion devices

Turbomachinery

Design point engine balances as baseline

Conduct subsystem trade studies using 750 kip thrust fixed

STBE Systems Analyses Approach
TASK 2 - SYSTEM ANALYSES FLOW DIAGRAM

THIS FLOW DIAGRAM SHOWS HOW THE FIXED POINT DESIGN COMPONENT STUDIES WILL BE RE-EVALUATED WITH THE THROTTLING ENGINE BALANCES TO FINALIZE THE COMPONENT CONFIGURATIONS PRIOR TO GENERATING OPTIMIZED BALANCES.
LH$_2$ COOLED ENGINE GROUNDRULE CHANGES

These are the changes from the Task 1 Groundrules incorporated into the fixed design point balances. They affect the hydrogen cooled engines only.
### Net Impact of Ground Rule Changes

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<thead>
<tr>
<th>Effect</th>
<th>Reason</th>
<th>Change</th>
<th>Parameter/Component</th>
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</thead>
<tbody>
<tr>
<td>Pump Weight &amp; LH2 Turb. Dyne</td>
<td>Development Time</td>
<td></td>
<td></td>
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<tr>
<td>Increase P for Near-Term</td>
<td>Design Margin</td>
<td>Eliminate AAS Near-Term</td>
<td>Hydrostatic Bearings</td>
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<tr>
<td>Decrease P for Near-Term</td>
<td>The Applicability &amp; Consistency with SSM</td>
<td>Upper Limit of 0.55 Added</td>
<td>Pump Stage Head</td>
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<tr>
<td>Increase P for Impoved Perf</td>
<td></td>
<td>Tip Speed Limit Changed to LH2 Pump</td>
<td>LH2 Pump Stages</td>
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**LH2 Cool Engine Ground Rule Changes**
STBE FIXED POINT DESIGN CHARACTERISTICS
(1995 ENGINES)

THIS CHART SUMMARIZES THE FIXED POINT BALANCE DATA FOR THE 1995 IOG ENGINES.
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**NOTES:**
- F.R. = FUEL RICH
- D.M. = DIAMETER (in.)
- L.N. = LENGTH (in.)
- W.E. = WEIGHT (lb)
- LH2 Pump Pd (psia)
- LOX Pump Pd (psia)

**SPECIFICATIONS:**
- Chamber Pressure (psia)
- Specific Impulse (s)
- Turbine Gas Type
- Turbine Drive Gas
- Coolant
- Propellant Cycle
- Thrust (Kip)

**Engine Number:**
- 1

**Category:**
- LH2-Cooled
- FUEL-COOLED
STBE FIXED POINT DESIGN CHARACTERISTICS
(2000 ENGINES)

THIS CHART SUMMARIZES THE FIXED POINT BALANCE DATA FOR THE 2000 10C ENGINES.
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(2000 Engines)

STE FIXED POINT DESIGN CHARACTERISTICS
STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA
TURBOMACHINERY AGENDA

THIS IS THE AGENDA FOR THE TURBOMACHINERY SECTION OF THIS PRESENTATION
TURBOMACHINERY AGENDA

- INTRODUCTION
- APPROACH LOGIC
- REQUIREMENTS
- GROUND RULES
- TURBOMACHINERY CANDIDATES
- FINAL SELECTION APPROACH
STBE TURBOMACHINERY STUDIES

THE OBJECTIVE OF THE TURBOMACHINERY STUDY IS TO SELECT THE TURBOPUMPS THAT CREATE THE OPTIMUM TURBOMACHINERY SYSTEM FOR EACH OF THE NINE ENGINES SELECTED IN TASK I.

TO ACHIEVE THIS, VIABLE TURBOMACHINERY SYSTEMS WERE CONSIDERED FOR EACH ENGINE, THE MOST PROMISING OF THESE WERE IDENTIFIED THROUGH AN ENGINEERING SCREENING PROCESS AND RECOMMENDED FOR LIFE CYCLE COST ANALYSIS, WHERE THE OPTIMUM SYSTEM FOR EACH ENGINE WILL BE SELECTED.

CURRENTLY, THE ENGINEERING SCREENING PROCESS IS COMPLETE FOR FOUR OF THE NINE ENGINES, WITH THE OTHER FIVE IN WORK. THESE ENGINES ARE ENGINE 1 (LOX/RP-1, RP-1 COOLED), ENGINE 3 (LOX/METHANE, METHANE COOLED), ENGINE 4 (LOX/RP-1, HYDROGEN COOLED), AND ENGINE 6 (LOX/METHANE, HYDROGEN COOLED), AND ARE ALL CURRENT TECHNOLOGY ENGINES.
ENGINE (1, 3, 4, 6)
SCREENING COMPLETE FOR FOUR

STATUS
ENGINE THROUGH LIFE CYCLE COST ANALYSIS
SELECT OPTIMUM CONFIGURATION FOR EACH
ENGINEERING SCREENING PROCESS
RECOMMEND PROMISING SYSTEMS THROUGH
SYSTEMS FOR EACH ENGINE
IDENTIFY CANDIDATE TURBOMACHINERY

APPROACH
THE NINE CANDIDATE ENGINES
SELECT OPTIMUM TURBOMACHINERY FOR
OBJECTIVE

STBE TURBOMACHINERY STUDIES
TURBOMACHINERY SELECTION APPROACH

PUMP (OR HYDRAULIC FLOW CIRCUIT) CONFIGURATIONS CONSISTING OF COMBINATIONS OF BOOST (OR LOW PRESSURE) PUMPS, MAIN PUMPS AND KICK PUMPS ARE SIZED WITHIN THE SPECIFIED GROUND RULES TO SATISFY THE ENGINE BALANCE REQUIREMENT OF DELIVERED FLOW, AND INLET AND DISCHARGE PRESSURE. COMPUTER PROGRAMS DEVELOPED DURING IN-HOUSE STUDIES ALLOW DESIGN PARAMETERS TO BE VARIED OVER A WIDE RANGE TO ENSURE COMPONENT OPTIMIZATION. THESE PUMP CONFIGURATIONS ARE SCREENED ON THE BASIS OF MAIN PUMP SPEED (HIGH SPEED GIVING SMALLER TURBINE DIAMETER, LARGER TURBINE BLADE HEIGHT-REDUCING THE LIKELIHOOD OF PARTIAL ADMISSION, AND LOWER MAIN PUMP WEIGHT), POWER (LOWER REQUIRED POWER REDUCING TURBINE FLOW RATE AND INCREASING ENGINE SPECIFIC IMPULSE), WEIGHT AND COMPLEXITY. PROMISING CONFIGURATIONS ARE CARRIED FORWARD FOR SIZING OF THE TURBINE (OR HOT GAS CIRCUIT) CONFIGURATION. IN THIS PHASE TURBINES ARE SIZED WITHIN THE SPECIFIED GROUND RULES TO DRIVE THE RECOMMENDED PUMP CONFIGURATIONS USING VALUES OF INLET PRESSURE AND OVERALL PRESSURE RATIO TAKEN FROM THE ENGINE BALANCES. SINGLE SHAFT TURBINE ARRANGEMENTS (FUEL AND OXIDIZER PUMPS DRIVEN BY A SINGLE TURBINE), DUAL SHAFT TURBINE ARRANGEMENTS (FUEL AND OXIDIZER PUMPS DRIVEN BY SEPARATE TURBINES) AND TURBINES FOR THE HYDROGEN PUMPS, WHERE REQUIRED, ARE ALL CONSIDERED IN THIS PHASE, USING COMBINATIONS OF IMPULSE AND REACTION TURBINE STAGES. ROCKETDYE'S GASPAT PATH COMPUTER PROGRAM, WHICH IS A PROVEN TURBINE DESIGN TOOL, WAS USED FOR THIS PHASE. AFTER A FURTHER SCREENING PROCESS, BASED ON TURBINE FLOW RATE, SYSTEM WEIGHT, SYSTEM ENVELOPE AND SYSTEM COMPLEXITY, A LIFE CYCLE COST ANALYSIS SELCTS THE OPTIMUM TURBOMACHINERY CONFIGURATION FOR EACH ENGINE. THE OFF DESIGN PERFORMANCE OF THE SELECTED CONFIGURATION IS CHECKED TO ENSURE ACCEPTABLE EFFICIENCY AND MARGINS AT BOTH 750K THRUST AND 625K THRUST, AND IF NECESSARY THE PROCESS IS REPEATED.
TURBOMACHINERY SELECTION APPROACH
TURBOMACHINERY REQUIREMENTS FOR SELECTED ENGINES

This table lists the turbomachinery requirements (pump flowrates, inlet pressures and discharge pressures, turbine inlet pressures and overall pressure ratios) as set by the nine engine cycles under consideration.
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<th>Overall</th>
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<th>Turbine, Inlet</th>
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Selected Engines

Turbomachinery Requirements For
PHILOSOPHY FOR COMPONENT SIZING

TO REDUCE THE SIZE OF THE CONFIGURATION MATRIX WHILE ENSURING THAT EVERY FAVORABLE SYSTEM WAS CONSIDERED, THE KNOWLEDGE GAINED FROM IN-HOUSE STUDIES WAS USED TO ESTABLISH THE CANDIDATE SYSTEMS.

TYPICAL DUCT LOSSES BETWEEN TURBOMACHINERY COMPONENTS (INCLUDING VOLUTE AND BABYPANTS INLET LOSSES) WERE INCLUDED TO ENSURE ACCURATE MODELING OF THE SYSTEMS.

GROUNDRULES FOR THE HYDRODYNAMIC AND AERODYNAMIC DESIGN PARAMETERS WERE SET TO ENSURE EFFICIENT COMPONENT OPERATION FOR THE SPECIFIED 100 MISSION LIFE.

GROUNDRULES IMPOSED BY STRUCTURAL AND MECHANICAL LIMITS WERE SET ACCORDING TO THE SPECIFIED TECHNOLOGY LEVELS. THE 1990 TECHNOLOGY LEVEL LIMITS REPRESENT ROCKETDYNE'S BEST ESTIMATE OF WHAT THE TECHNOLOGY ADVANCES WILL BE IF A REASONABLE EFFORT IS MADE TO ACHIEVE THOSE ADVANCES.

SIGNIFICANT SIZE, WEIGHT AND PERFORMANCE PENALTIES ARE INCURRED WHEN THE HYDROGEN PUMP SPEED IS REDUCED TO THAT OF THE FUEL OR LOX PUMP.
Component Sizing Philosophy for
HYDRAULIC FLOW CIRCUIT CONFIGURATIONS

THE FOUR HYDRAULIC FLOW CIRCUITS THAT WERE CONSIDERED ARE: MAIN PUMP ONLY, MAIN PUMP + KICK PUMP, BOOST PUMP + MAIN PUMP, AND BOOST PUMP + MAIN PUMP + KICK PUMP

A MAIN PUMP ONLY REPRESENTS THE SIMPLEST CONFIGURATION.

FOR PROPELLANT COOLED CYCLES, TWO DELIVERY PRESSURES ARE REQUIRED FOR THE COOLANT - A LOWER PRESSURE FOR THE NOZZLE COOLANT CIRCUIT AND A HIGHER PRESSURE FOR THE THRUST CHAMBER JACKET COOLANT CIRCUIT. A CONFIGURATION WITH A MAIN PUMP AND A KICK PUMP ON A SINGLE SHAFT, IN WHICH ONLY THE FLOW REQUIRED BY THE THRUST CHAMBER JACKET COOLANT CIRCUIT IS PUMPED TO THE HIGHER PRESSURE BY THE KICK PUMP, GENERALLY REQUIRES THE MINIMUM POWER.

BOOST PUMPS CAN BE ADDED UPSTREAM OF EITHER OF THE ABOVE CONFIGURATIONS TO INCREASE THE MAIN PUMP INLET PRESSURE. THIS ALLOWS THE MAIN (AND KICK) PUMP TO RUN AT HIGHER SPEED FOR THE SAME NPSH MARGIN, AND REDUCES WEIGHT AND SIZE.

THE DRIVES FOR THE BOOST PUMPS SHOWN HERE ARE FULL FLOW HYDRAULIC TURBINES, AND ARE DISCUSSED ON THE NEXT CHART.
BOOST + MAIN + KICK

BOOST + MAIN

MAIN + KICK

MAIN ONLY

CONFIGURATION
HYDRAULIC FLOW CIRCUIT
GROUND RULES FOR PUMP CONFIGURATIONS SIZING

IN-HOUSE STUDIES HAVE SHOWN THAT FULL-FLOW HYDRAULIC TURBINES, IN WHICH ALL OF THE FLOW IS USED TO DRIVE THE BOOST PUMP BEFORE BEING DELIVERED TO THE SYSTEM, HAVE CONSIDERABLE ADVANTAGES OVER RECIRCULATORY FLOW HYDRAULIC TURBINES AND GAS TURBINES. IN THE RECIRCULATORY FLOW SYSTEM, A SMALL FRACTION OF THE FLOW IS TAPPED OFF, USED TO DRIVE THE BOOST PUMP AND THEN RETURNED TO MAIN FLOW AT THE BOOST PUMP DISCHARGE. PREVIOUS STUDIES INDICATED THAT THE BOOST PUMP TURBINES FOR THESE SYSTEMS OPERATED IN AN UNFAVORABLY LOW SPECIFIC SPEED RANGE. GAS TURBINES WERE NOT CONSIDERED FOR THE LOX BOOST PUMP TURBINES DUE TO PURGE SEAL REQUIREMENTS AND WERE LARGE AND OF LOW EFFICIENCY FOR THE FUEL BOOST PUMP DRIVES.

IN THE CONFIGURATION CONTAINING BOOST PUMP, MAIN PUMP AND KICK PUMP THE BOOST PUMP CAN BE DRIVEN BY FLOW FROM THE MAIN PUMP OR KICK PUMP DISCHARGE. THE LATTER WAS NOT CONSIDERED AS PREVIOUS STUDIES HAD SHOWN THAT IT RESULTED IN HIGHER PressURES IN THE BOOST PUMP TURBINE AND CONNECTING DUCTS, WITH NO SIGNIFICANT PERFORMANCE ADVANTAGE.

INDUCER ONLY BOOST PUMPS WERE USED TO MINIMIZE THE POWER REQUIRED BY THE BOOST PUMP AND TO REDUCE COMPLEXITY.

INDUCERS WERE USED UPSTREAM OF THE FIRST STAGE OF ALL MAIN PUMPS TO MAXIMIZE MAIN PUMP SUCTION PERFORMANCE, WHICH MAXIMIZES SPEED (AND HENCE MINIMIZES SIZE AND WEIGHT) AND MINIMIZES BOOST PUMP POWER REQUIREMENT.
MINIMUM SIZE FOR REQUIRED LIFE
OF ALL MAIN PUMPS
INDUCERS UPSTREAM OF THE FIRST STAGE
REDUCED COMPLEXITY
OPTIMUM PERFORMANCE
INDUCER ONLY BOOST PUMPS
DUCTING
HIGH PRESSURE BOOST PUMP TURBINE AND
NO PERFORMANCE ADVANTAGE
NOT INCLUDED
BOOST PUMPS DRIVEN FROM KICK PUMP DISCHARGE
GAS TURBINES
SIZE AND PERFORMANCE ADVANTAGE OVER
FLOW HYDRAULIC TURBINES
PERFORMANCE ADVANTAGE OVER RECYCLATORY
PUMP DRIVES
FULL-FLOW HYDRAULIC TURBINES USED FOR BOOST

CONFIGURATION SIZING
GROUND RULES FOR PUMP
GROUND RULES FOR PUMP SIZING

HYDRODYNAMIC DESIGN PARAMETERS

THE RANGE OF VALUES USED FOR THE HYDRODYNAMIC PUMP DESIGN PARAMETERS REFLECTS ROCKETDYNE'S EXPERIENCE IN DESIGNING HIGH PERFORMANCE, LIGHTWEIGHT, RELIABLE TURBOPUMPS FOR LIQUID ROCKET ENGINE APPLICATIONS.

INDUCER NPSH MARGINS AND IMPELLER MAXIMUM OPERATING SUCTION SPECIFIC SPEED WERE SET TO ENSURE NO PUMP HEAD LOSS AND NO MATERIAL EROSION DUE TO CAVITATION.

INDUCER AND IMPELLER FLOW AND HEAD COEFFICIENT RANGES AND THE IMPELLER EYE-TO-TIP DIAMETER RATIO LIMIT REPRESENT VALUES FOR WHICH GOOD EFFICIENCY AND SUCTION PERFORMANCE HAS BEEN DEMONSTRATED.
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<th>INDUCER HEAD COEFFICIENT</th>
<th>IMPELLER FLOW COEFFICIENT</th>
<th>INDUCER FLOW COEFFICIENT</th>
<th>IMPELLER FOLLOWING INDUCER MAXIMUM SUCTION SPECIFIC SPEED FOR NPSH MARGIN FOR MAIN PUMP FOLLOWING BOOST PUMP NPSH MARGIN FOR BOOST PUMP OR MAIN PUMP ALONE</th>
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RATIONAL

VALUE

GROUNDOIL

HYDRODYNAMIC DESIGN PARAMETERS

GROUNDOILS FOR PUMP SIZING
GROUND RULES FOR PUMP SIZING

STRUCTURAL/MECHANICAL CONSTRAINTS

The structural and mechanical constraints were set by current technology limits and by Rocketdyne's best guess at technology limit improvements available in 1990.

The impeller tip speed limit is set by vane stresses, except in hydrogen where it is set by the disc burst speed.

The inducer tip speed limit is set to ensure that inducer suction performance is not degraded by blade blockage effects.

Bearing size and D-N limits are set to ensure the required bearing life.
### Structural/Mechanical Constraints

Groundrules for Pump Sizing

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<td>Performance</td>
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<td>Structural/Performance</td>
<td>Structural/Performance</td>
<td>2000</td>
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<table>
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<tr>
<th>Maximum Inducer Tip Speed, ft/sec - Lox</th>
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<tr>
<td>LH2</td>
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<tr>
<td>LCH4</td>
<td>LCH4</td>
</tr>
<tr>
<td>LCH8(SC)</td>
<td>LCH8(SC)</td>
</tr>
<tr>
<td>RP-1</td>
<td>RP-1</td>
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</table>
HOT GAS FLOW CIRCUIT OPTIONS

PROPELLANT COOLED ENGINES

FOR THE PROPELLANT COOLED ENGINES, A SINGLE SHAFT CONFIGURATION WAS CONSIDERED, IN WHICH BOTH THE FUEL AND OXIDIZER PUMPS ARE DRIVEN BY THE SAME TURBINE, AND A DUAL SHAFT SERIES CONFIGURATION WAS CONSIDERED IN WHICH THE FUEL AND OXIDIZER PUMPS ARE DRIVEN BY SEPARATE TURBINES IN SERIES. THE DUAL SHAFT PARALLEL CONFIGURATION WILL BE DISCUSSED IN A LATER CHART.
PARALLEL TURBINES

NO ADVANTAGE TO

DUAL SHAFT

SINGLE SHAFT

PROPELLANT COOLED ENGINES

HOT GAS FLOW CIRCUIT OPTIONS
HOT GAS FLOW CIRCUIT OPTIONS
HYDROGEN COOLED ENGINES

THE TURBINE ARRANGEMENTS SHOWN ON THIS CHART WERE ALL CONSIDERED FOR THE
HYDROGEN COOLED ENGINES. THE SINGLE SHAFT + HYDROGEN ARRANGEMENTS HAVE A
TURBINE DRIVING THE HYDROGEN PUMP AND A SINGLE TURBINE DRIVING BOTH FUEL AND
OXIDIZER PUMPS, ARRANGED EITHER IN SERIES OR IN PARALLEL. THE DUAL SHAFT +
HYDROGEN ARRANGEMENTS HAVE SEPARATE TURBINES FOR EACH PUMP (TOTAL OF THREE)
AND CAN BE ARRANGED IN SERIES, PARALLEL OR A COMBINATION.
HOT GAS FLOW CIRCUIT OPTIONS

DUAL SHAFT HYDROGEN + SINGLE SHAFT HYDROGEN

SERIES HYDROGEN COOLED ENGINES

PARALLEL SERIES/PARALLEL
GROUND RULES FOR MAIN TURBINE CONFIGURATION SIZING

IN-HOUSE ENGINE SYSTEM STUDIES INDICATED THAT A SERIES TURBINE ARRANGEMENT REQUIRED CONSIDERABLY LESS FLOW THAN A PARALLEL ARRANGEMENT, AND THUS HAD HIGHER ENGINE SPECIFIC IMPULSE.

IN SERIES ARRANGEMENTS THE TURBINES WERE ARRANGED IN ORDER OF DECREASING SPEED. THIS DECREASES THE TURBINE DIAMETER FOR THE BLADE SPEED REQUIRED FOR THE HIGHEST EFFICIENCY, INCREASING BLADE HEIGHT AND REDUCING THE LIKELIHOOD OF PARTIAL ADMISSION.
Reduced likelihood of partial admission • Smaller diameter for given blade speed • In series configurations • Higher speed turbine placed first • Configuration performance over parallel • System study showed improved • Engines configurations in propellant cooled • Series turbines used for dual shaft • Configuration sizing: Groundrules for main turbine
GROUNDRULES FOR TURBINE SIZING

AERODYNAMIC DESIGN PARAMETERS

TURBINE AERODYNAMIC PARAMETERS ARE SET TO ENSURE HIGH EFFICIENCY OPERATION AND ARE BASED ON ROCKETDYNE'S EXPERIENCE IN DESIGNING COMPACT, HIGH EFFICIENCY, HIGH POWER DENSITY TURBINES FOR LIQUID ROCKET ENGINE APPLICATIONS.

MINIMIZING WHIRL VELOCITY INCREASES PERFORMANCE AND, IN ADDITION, IF THERE IS A SIGNIFICANT WHIRL VELOCITY COMPONENT AT THE TURBINE EXIT, AN ADDITIONAL BLADE ROW, WITH ASSOCIATED LOSSES AND PENALTIES IN TURBINE SIZE, IS REQUIRED TO REMOVE THE WHIRL.

THE PARTIAL ADMISSION LOSSES AND DYNAMIC BLADE LOADING PROBLEMS OFFSET THE BENEFITS OF OPTIMIZING THE DESIGN U/CO BELOW A MINIMUM ARC OF ADMISSION.

TURBINE STAGING IS CHOSEN SO THAT U/CO IS OPTIMIZED WITHIN THE ABOVE AERODYNAMIC CONSTRAINTS, AND THE STRUCTURAL AND MECHANICAL CONSTRAINTS LISTED LATER.
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<tr>
<th>Reason</th>
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<tr>
<td>Efficiency Range</td>
<td>0.40</td>
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<tr>
<td>Demonstrated Optimum</td>
<td>0.25 to 0.3</td>
<td>Target U/Co Values - 2RC</td>
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<tr>
<td>Reduce blade loading</td>
<td>0.2 to 0.25</td>
<td>Minimum arc of admission</td>
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<tr>
<td>Admission losses</td>
<td>10%</td>
<td>Target outlet flow angle</td>
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<td>Minimize partial</td>
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<tr>
<td>Minimize exit whirl</td>
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<tr>
<td>Rational</td>
<td>Value</td>
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<tr>
<td>Aerodynamic design parameters</td>
<td>For Turbine Sizing</td>
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DEFINITION OF TURBINE TYPES

SINGLE STAGE IMPULSE (1S), TWO STAGE PRESSURE COMPOUNDED (2SPC), TWO ROW VELOCITY COMPOUNDED (2RVC) AND TWO STAGE REACTION (2R) STAGING WAS CONSIDERED.

THE FIRST THREE OF THESE USE IMPULSE STAGES, IN WHICH THERE IS NO STATIC PRESSURE DROP ACROSS THE ROTOR. THE FLOW IS ACCELERATED IN THE NOZZLES AND THIS FLUID KINETIC ENERGY CONVERTED TO SHAFT POWER BY THE ROTOR BLADES. IN TWO STAGE PRESSURE COMPOUNDED TURBINES THE FLOW IS REACCELERATED IN A SECOND ROW OF NOZZLES BEFORE THE SECOND ROTOR, WHEREAS IN A TWO STAGE VELOCITY COMPOUNDED TURBINE THE FLOW IS TURNED WITHOUT ACCELERATION IN A STATOR BETWEEN THE TWO ROTORS. IN REACTION STAGES BOTH THE INTERNAL ENERGY OF THE FLUID AND THE KINETIC ENERGY OF THE FLOW IS CONVERTED TO SHAFT POWER IN THE ROTOR. THE STATOR VANES PROVIDE ONLY A SMALL ACCELERATION AND THERE IS A PRESSURE DROP ACROSS THE ROTOR.

REACTION BLADING HAS A HIGHER EFFICIENCY POTENTIAL THAN IMPULSE BLADING, BUT RESULTS IN SIGNIFICANT AXIAL THRUST ON THE ROTOR WHICH MUST BE BALANCED BY THE PUMP.
GROUNDRULES FOR MAIN TURBINE SIZING
MECHANICAL/STRUCTURAL CONSTRAINTS

THE GROUNDRULES WERE SET BY CURRENT TECHNOLOGY LIMITS AND ALSO BY ROCKETDYNE'S
BEST GUESS AT TECHNOLOGY LIMIT IMPROVEMENTS AVAILABLE IN 1990.

THE TEMPERATURE LIMIT IS BASED ON CURRENT SSME PRACTICE AND MATERIAL
STRUCTURAL LIMITATIONS. SUCH LIMITATIONS ALSO SET THE BLADE SPEED LIMITS
WHICH ARE BASED ON DISK TEMPERATURES BELOW 800 °F. N² ANNULUS AREA
LIMITS ARE BASED ON UNCOOLED ROTOR BLADES.
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<th>Security</th>
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**Groundrules for Main Turbine Sizing**

**Mechanical/Structural Constraints**

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<tr>
<td>DIA METER RATIO</td>
<td>BLADE HEIGHT TO MEAN</td>
<td>(RPM-1/2)²</td>
<td>X ANNULUS AREA</td>
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<td>8.0 x 10⁶</td>
<td>9.6 x 10⁶</td>
<td>8.0</td>
<td>1.650</td>
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</table>

**Maximum Speed**

- F/SEC: 1650
- BLADE: 2250
- TEMPERATURE, DEG R: 1990

*Note: Temperature Spikes*
ENGINE 1-LOX/RP-1, COOLED
TURBOMACHINERY CANDIDATES

THE NEXT EIGHT CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 1.
RP-1 COOLED
ENGINE 1 - LOX/RP-1,

TURBOMACHINERY CANDIDATES
PUMPS FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

DUAL SHAFT CONFIGURATIONS

TWO DUAL SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING AS A RESULT OF THE PUMP SCREENING. THESE WERE THE RP-1 MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP CONFIGURATION (SYSTEM 1A), AND THE RP-1 MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP CONFIGURATION (SYSTEM 1B). THE FORMER HAD THE MINIMUM REQUIRED POWER AND LOWEST COMPLEXITY (SINCE THE RP-1 CONFIGURATION OF MAIN PUMP ALONE REQUIRED TWO STAGES) WHILE THE LATTER HAD THE MAXIMUM SPEED.

THE RP-1 CONFIGURATIONS OF MAIN PUMP ALONE AND BOOST PUMP + MAIN PUMP WERE DELETED. THESE CONFIGURATIONS REQUIRED TWO STAGE MAIN PUMPS DUE TO IMPELLER TIP SPEED AND HEAD COEFFICIENT LIMITS, AND CONFIGURATIONS WITH MAIN PUMP + KICK PUMP OFFERED LOWER POWER REQUIREMENT WITH THE SAME COMPLEXITY.

THE RP-1 CONFIGURATION OF BOOST PUMP + MAIN PUMP + KICK PUMP WAS DELETED AS THE SLIGHT DECREASE IN POWER AND SYSTEM WEIGHT WAS OFFSET BY THE INCREASED COMPLEXITY.
### To Offset Increased Complexity
- Performance Improvements Insufficient

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<tr>
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<th>Kick + Main + Boost</th>
<th>Kick + Main</th>
<th>Kick + Main</th>
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<td>Minimum Diameter Carried Forward</td>
<td>MAIN + BOOST</td>
<td>Kick + Main</td>
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<td>Minimum Power Carried Forward</td>
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<td>Two Stage Main Pump Required Deleted</td>
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<tr>
<td>Two Stage Main Pump Required Deleted</td>
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### Conclusions
- Configuration
- LOX Pump
- RP-1 Pump
- Identification System

## Dual Shaft Configurations
- Pumps For Engine 1 - LOX / RP-1, RP-1 Cooled
PUMPS FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

SINGLE SHAFT CONFIGURATIONS

THREE SINGLE SHAFT CONFIGURATIONS WERE CARRIED FORWARD AS A RESULT OF THE PUMP
SCREENING. THESE WERE RP-1 MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP (SYSTEM
1C), RP-1 MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 1D),
AND RP-1 BOOST PUMP + MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP
(SYSTEM 1E). SYSTEM 1C HAD THE MINIMUM POWER, MINIMUM WEIGHT AND LOWEST
COMPLEXITY, WHILE SYSTEM 1E HAD THE MAXIMUM SHAFT SPEED. SYSTEM 1D
REPRESENTED A COMPROMISE, RUNNING AT HIGHER SPEED THAN SYSTEM 1C AND HAVING
LOWER COMPLEXITY THAN SYSTEM 1E. THE SYSTEM 1D MAIN PUMP SPEED WAS SET BY THE
FUEL PUMP SUCTION PERFORMANCE LIMITS AS OPPOSED TO THE MAJORITY OF SINGLE
SHAFT CONFIGURATIONS WHERE IT WAS SET BY THE LOX PUMP SUCTION PERFORMANCE
LIMITS. THERE IS LESS NPSH AVAILABLE TO THE FUEL PUMP INDUCER IN SINGLE SHAFT
CONFIGURATIONS DUE TO LOSSES INCURRED IN THE VOLUTE OR BABYPANTS TYPE INLET
THAT IS REQUIRED WHEN THE FUEL PUMP IS POSITIONED BETWEEN THE LOX PUMP AND THE
TURBINE.

CONFIGURATIONS INVOLVING RP-1 MAIN PUMP ONLY AND RP-1 BOOST PUMP + MAIN PUMP
WERE DELETED FOR THE REASONS STATED ON THE PREVIOUS CHART.

THE CONFIGURATION WITH RP-1 BOOST PUMP + MAIN PUMP + KICK PUMP WITH LOX MAIN
PUMP WAS DELETED AS THE MAIN PUMP SPEED WAS SET BY THE LOX PUMP SUCTION
PERFORMANCE, AND THE RP-1 BOOST PUMP SERVES NO PURPOSE.
<table>
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<th>MAXIMUM SPEED</th>
<th>KICK + MAIN BOOST</th>
<th>KICK + MAIN BOOST</th>
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<tr>
<td>CARRIED FORWARD</td>
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<tr>
<td>SPEED CONTROLLED BY LOX PUMP</td>
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<tr>
<td>NO ADVANTAGE OVER SYSTEM 1A</td>
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<tr>
<td>HIGHER SPEED WITH MEDIUM COMPLEXITY</td>
<td>MAIN + BOOST</td>
<td>KICK + MAIN BOOST</td>
<td>1D</td>
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<td>CARRIAGE FORWARD</td>
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<td>RP PUMP SYSTEM</td>
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**Conclusions**

**Single Shaft Configurations**

**Pumps for Engine 1-Lox/RP-1, RP-1, Lox/Cooled**
TURBOMACHINERY FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

NO FURTHER SYSTEMS WERE DELETED IN THE TURBINE SCREENING PROCESS, AND THUS FIVE SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.

WITH THE EXCEPTION OF THE LOX TURBINE IN CONFIGURATION 1B, WHICH WAS A TWO STAGE REACTION TURBINE, ALL TURBINES WERE TWO ROW VELOCITY COMPOUNDED, WITH A SMALL DEGREE OF REACTION IN THE SECOND ROTOR. THE REACTION IN THE SECOND ROTOR WAS ADDED TO DECREASE THE MAXIMUM FLUID VELOCITIES THERE AND TO REDUCE THE EXIT WHIRL, BOTH OF WHICH INCREASE THE TURBINE EFFICIENCY.

THE EXPECTED TRENDS IN TURBINE FLOWRATE, SYSTEM WEIGHT, MAXIMUM DIAMETER AND SYSTEM COMPLEXITY ARE OBSERVED:

LOWER TURBINE FLOWRATES FOR THE DUAL SHAFT CONFIGURATIONS WHERE BOTH PUMPS ARE OPTIMIZED (SYSTEMS 1A AND 1B).

LOWER WEIGHTS, LARGER DIAMETERS AND LOWER COMPLEXITIES FOR THE SINGLE SHAFT CONFIGURATIONS (SYSTEMS 1C, 1D, 1E) WHERE FEWER TURBOPUMPS ARE REQUIRED, BUT ONE OF THE PUMPS IS NOT OPTIMIZED.

SMALLER DIAMETERS AND HIGHER COMPLEXITIES FOR THE CONFIGURATIONS WITH BOOST PUMPS (SYSTEMS 1B, 1D, 1E) WHERE THE MAIN PUMP SPEED IS INCREASED BUT ANOTHER TURBOPUMP IS REQUIRED.

SYSTEM 1A HAS THE MINIMUM TURBINE FLOWRATE, SYSTEM 1C THE MINIMUM WEIGHT AND COMPLEXITY, AND SYSTEMS 1B AND 1E THE MINIMUM DIAMETER (SET IN ALL CASES BY THE TURBINE TIP DIAMETER)

IT SHOULD BE NOTED THAT, FOR THIS ENGINE, THE ADDITION OF BOOST PUMPS INCREASES THE SYSTEM WEIGHT, THE WEIGHT OF THE BOOST PUMP OFFSETTING THE REDUCTION IN MAIN PUMP WEIGHT DUE TO THE INCREASED MAIN PUMP SPEED.

IF-38
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<th>Number of Pure Seals</th>
<th>Number of Rotors (Blade Rows)</th>
<th>Complexity Factor = Number of Shafts (Turbo Bomppumps)</th>
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<th>Main + Kick + Boost</th>
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**Summary of Candidates**

TURBOMACHINERY FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED
TURBOMACHINERY FOR ENGINE 1-LOX/RP-1, RP-1 COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE FIVE ENGINE 1 TURBOMACHINERY SYSTEMS
RECOMMENDED FOR LIFE CYCLE COST ANALYSIS
TYPICAL TURBOMACHINERY LAYOUT

THIS IS A TYPICAL TURBOPUMP LAYOUT WITH A MAIN PUMP + KICK PUMP AND TWO STAGE TURBINE. THIS TURBOPUMP WOULD BE SUITABLE FOR USE IN A DUAL SHAFT TURBINE ARRANGEMENT.
TURBOMACHINERY CANDIDATES FOR ENGINE 1

- LOX/RP-1, RP-1 COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 1. PUMP ROTATIONAL SPEEDS WERE ALL SET BY SUCTION PERFORMANCE LIMITS.
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<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

**SUMMARY OF PUMP DATA**

**LOX/RP-1, RP-1 Cooled**

**TURBOMACHINERY CANDIDATES FOR ENGINE 1**
TURBOMACHINERY CANDIDATES FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

SUMMARY OF TURBINE DATA

TURBINE DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE RECOMMENDED ENGINE 1 TURBOMACHINERY SYSTEMS. FOR THE LOX/RP-1 DRIVE GASES THE BLADE SPEED IS SET TO OPTIMIZE U/CO WITHIN THE CONSTRAINT OF THE OTHER GROUNDRULES.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>LOX/RP-1</th>
<th>RP-1 Cooled</th>
<th>TURBOMACHINERY CANDIDATES FOR ENGINE I</th>
</tr>
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<tbody>
<tr>
<td>IMPELLER STAGE</td>
<td>OVERALL PRESSURE RATIO</td>
<td>TOTAL TURBINE FLOWRATE, LB/SEC</td>
<td></td>
</tr>
<tr>
<td>0.741</td>
<td>0.21</td>
<td>0.30</td>
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<tr>
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</tr>
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<tr>
<td>0.764</td>
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<td>0.24</td>
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</tbody>
</table>
ENGINE 3 - LOX/METHANE, METHANE COOLED

TURBOMACHINERY CANDIDATES

THE NEXT SEVEN CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 3.
METHANE COOLED
ENGINE 3 - LOX/METHANE,

TURBOMACHINERY CANDIDATES
PUMPS FOR ENGINE 3 - LOX/MEHTANE, METHANE COOLED

DUAL SHAFT CONFIGURATIONS

TWO DUAL SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING AFTER
THE PUMP SCREENING. THESE WERE METHANE MAIN PUMP + KICK PUMP WITH LOX MAIN
PUMP ONLY (SYSTEM 3A), AND METHANE MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP +
MAIN PUMP (SYSTEM 3B). THE FIRST OF THESE WAS THE MINIMUM POWER AND MINIMUM
WEIGHT CONFIGURATION, WHILE THE SECOND SIGNIFICANTLY INCREASED THE LOX PUMP
SPEED WITH ONLY A SLIGHT PENALTY IN REQUIRED POWER AND SYSTEM WEIGHT.

THE METHANE MAIN PUMP ONLY CONFIGURATION WAS DELETED AS IT REQUIRED
SIGNIFICANTLY MORE POWER THAN THE MAIN PUMP + KICK PUMP CONFIGURATION.

THE METHANE CONFIGURATIONS WITH BOOST PUMPS WERE DELETED AS THE INCREASES IN
MAIN PUMP SPEED WERE SMALL DUE TO BEARING ON LIMITS, AND WERE INSUFFICIENT TO
OFFSET INCREASES IN REQUIRED POWER AND COMPLEXITY.
<table>
<thead>
<tr>
<th>AND COMPLEXITY AND COMPLEXITY</th>
<th>KICK +</th>
<th>MAIN +</th>
<th>BOOST +</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFFSET INCREASE IN REQUIRED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POWER • SPEED INCREASE IN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INEFFICIENT TO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELETED</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| MAXIMUM LOX PUMP SPEED       | MAIN + | BOOST |
| CARRIED FORWARD              |        |       |

| MINIMUM POWER, MINIMUM      |        |        |        |
| WEIGHT • CARRIED FORWARD    |        |        |        |

| HIGH POWER REQUIREMENT • DELETED |          |        |        |

| CONCLUSIONS                  | CONFIGURATION LOX PUMP | CONFIGURATION METHANE PUMP | SYSTEM IDENTIFIER |

**DUAL SHAFT CONFIGURATIONS**

**METHANE COOLED**

**PUMPS FOR ENGINE & LOX/METHANE**
PUMPS FOR ENGINE 3 - LOX/METHANE, METHANE COOLED

SINGLE SHAFT CONFIGURATIONS

TWO SINGLE SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING. THESE WERE METHANE MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP (SYSTEM 3C), AND METHANE MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 3D). THE FORMER WAS CARRIED FORWARD AS IT WAS A SIMPLE CONFIGURATION WITH THE SECOND LOWEST POWER REQUIREMENT, WHILE THE LATTER HAD MINIMUM REQUIRED POWER, MINIMUM SYSTEM WEIGHT AND SMALLEST DIAMETER.

CONFIGURATIONS INVOLVING A METHANE MAIN PUMP ALONE WERE DELETED AS THEY HAD THE HIGHEST POWER REQUIREMENT, LARGEST DIAMETERS AND MAXIMUM WEIGHTS. THE METHANE PUMP RUNS AT A SPEED MUCH LOWER THAN OPTIMUM DUE TO THE LOX PUMP SUCTION PERFORMANCE LIMITS, AND THIS SIGNIFICANTLY DEGRADES THE MAIN PUMP PERFORMANCE. IT SHOULD BE NOTED THAT THE SAME TRENDS ARE OBSERVED FOR THE MAIN PUMP + KICK PUMP, BUT THE SPECIFIC SPEEDS OF THESE PUMPS ARE HIGHER THAN FOR THE MAIN PUMP ALONE, AND THUS THE DECREASE IN ROTATIONAL SPEED IN THE SINGLE SHAFT CONFIGURATION DOES NOT REDUCE THE EFFICIENCY AS MUCH.

CONFIGURATIONS INVOLVING METHANE BOOST PUMPS WERE DELETED AS, IN ALL CASES, THE SHAFT SPEED WAS LIMITED BY THE LOX PUMP SUCTION PERFORMANCE AND A METHANE BOOST PUMP SERVES NO PURPOSE.
<table>
<thead>
<tr>
<th>Single Shaft Configuration</th>
<th>Methane Cooled</th>
<th>Pumps for Engine &amp; LOX / Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane Boost Pump Not Required</td>
<td>Speed Controlled by LOX Pump</td>
<td>Kick + Main + Boost</td>
</tr>
<tr>
<td>Methane Boost Pump Not Required</td>
<td>Speed Controlled by LOX Pump</td>
<td>Kick + Main + Boost</td>
</tr>
<tr>
<td>Minimum Power, Diameter, Weight</td>
<td>Carried Forward</td>
<td>Kick + Main + Boost</td>
</tr>
<tr>
<td>Simple Configuration</td>
<td>Carried Forward</td>
<td>Kick + Main + Boost</td>
</tr>
<tr>
<td>High Required Power</td>
<td>Carried Forward</td>
<td>Kick + Main + Boost</td>
</tr>
<tr>
<td>Conclusions</td>
<td>Configuration LOX Pump</td>
<td>Configuration Methane Pump</td>
</tr>
</tbody>
</table>
TURBOMACHINERY FOR ENGINE 3 - LOX/METHANE, METHANE COOLED

NO FURTHER SYSTEMS WERE DELETED IN THE TURBINE SCREENING PROCESS, AND THUS FOUR SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.

BOTH TURBINES IN EACH OF THE DUAL SHAFT CONFIGURATIONS AND THE TURBINE FOR SYSTEM 3D WERE TWO ROW VELOCITY COMPOUNDED TURBINES WITH SLIGHT REACTION IN THE SECOND STAGE. THE TURBINE FOR CONFIGURATION 3C WAS A TWO STAGE PRESSURE COMPOUNDED TURBINE.

THE EXPECTED TRENDS ARE OBSERVED, EXCEPT FOR SYSTEM WEIGHT, WHERE THE SINGLE SHAFT CONFIGURATION WITHOUT BOOST PUMPS (SYSTEM 3C) IS SLIGHTLY HEAVIER THAN THE DUAL SHAFT CONFIGURATION WITHOUT BOOST PUMPS. THIS IS DUE TO THE SIGNIFICANTLY LARGER METHANE IMPELLERS REQUIRED FOR THE LOWER SPEED SINGLE SHAFT CONFIGURATION. FOR THIS ENGINE BOOST PUMPS INCREASE SYSTEM WEIGHT FOR THE DUAL SHAFT CONFIGURATIONS AND DECREASE SYSTEM WEIGHT FOR THE SINGLE SHAFT CONFIGURATIONS.

SYSTEM 3A HAS THE MINIMUM TURBINE FLOWRATE, SYSTEM 3B THE MINIMUM DIAMETER, SYSTEM 3C IS THE SIMPLEST CONFIGURATION, AND SYSTEM 3D HAS THE MINIMUM WEIGHT.
<table>
<thead>
<tr>
<th></th>
<th>3D</th>
<th>3C</th>
<th>3B</th>
<th>3A</th>
</tr>
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<tbody>
<tr>
<td><strong>SYSTEM</strong></td>
<td><strong>IDENTIFIER</strong></td>
<td><strong>LOX PUMP</strong></td>
<td><strong>CONFIG.</strong></td>
<td><strong>B/C</strong></td>
</tr>
<tr>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
</tr>
<tr>
<td><strong>KICK</strong></td>
<td><strong>KICK</strong></td>
<td><strong>KICK</strong></td>
<td><strong>KICK</strong></td>
<td><strong>KICK</strong></td>
</tr>
<tr>
<td><strong>BOOST</strong></td>
<td><strong>BOOST</strong></td>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
<td><strong>MAIN</strong></td>
</tr>
<tr>
<td><strong>SINGLE</strong></td>
<td></td>
<td><strong>SINGLE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>180</strong></td>
<td>176</td>
<td>135</td>
<td>133</td>
<td>2361</td>
</tr>
<tr>
<td><strong>2129</strong></td>
<td>2422</td>
<td>2373</td>
<td>2361</td>
<td></td>
</tr>
<tr>
<td><strong>26.3</strong></td>
<td>30.6</td>
<td>20.7</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td><strong>10</strong></td>
<td>7</td>
<td>13</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**TURBOMACHINERY FOR ENGINE 3 - LOX/METHANE, METHANE COOLED**

**SUMMARY OF CANDIDATES**
TURBOMACHINERY FOR ENGINE 3, LOX/METHANE, METHANE COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE FOUR ENGINE 3 TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.
SCHEMATICS OF CANDIDATES
METHANE COOLED
TURBOMACHINERY FOR ENGINE 3 - LOX/METHANE
TURBOMACHINERY CANDIDATES FOR ENGINE 3-LOX/METHANE,
METHANE COOLED
SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 3. PUMP ROTATIONAL SPEEDS WERE ALL SET BY SUCTION PERFORMANCE LIMITS.
| System | 2.179 | 2.422 | 2.427 | 2.373 | 2.360 | 8.0 | 9.1 | 8.0 | 7.5 | 5.3 | 9.0 | 2.0 | 2.0 | 2.0 | 9.0 | 2.0 | 2.0 | 2.0 |
| Seal Rubbing Speed, Ft/Sec | | | | | | | | | | | | | | | | | | | |
| Bearing Dia., 105 mm Rpm | | | | | | | | | | | | | | | | | | | |
| Number of Stages | | | | | | | | | | | | | | | | | | | |
| Tip Diameter, Inch | | | | | | | | | | | | | | | | | | | |
| Head, Ft | | | | | | | | | | | | | | | | | | | |
| Flow, Gpm | | | | | | | | | | | | | | | | | | | |
| Power, Hp | | | | | | | | | | | | | | | | | | | |
| System Weight | | | | | | | | | | | | | | | | | | | |
| Total System Power | | | | | | | | | | | | | | | | | | | |

**Summery of Pump Data**

**LOX/METHANE, METHANE COOLED**

**TURBOMACHINEY CANDIDATES FOR ENGINE 3**
TURBOMACHINERY CANDIDATES FOR ENGINE 3 - LOX/METHANE, METHANE COOLED

SUMMARY OF TURBINE DATA

TURBINE DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE
RECOMMENDED ENGINE 3 TURBOMACHINERY SYSTEMS. FOR THE LOX/METHANE DRIVE GASES
THE BLADE SPEED IS SET TO OPTIMIZE U/CO WITHIN THE CONSTRAINTS OF THE OTHER
GROUNDRULES
<table>
<thead>
<tr>
<th>System</th>
<th>3D</th>
<th>3B</th>
<th>3A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Arrangement</td>
<td>Lox Pump Configuration</td>
<td>Methane Pump Configuration</td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td>Single</td>
<td>Dual</td>
<td>Single</td>
</tr>
<tr>
<td>B+M</td>
<td>M</td>
<td>B+M</td>
<td>M+K</td>
</tr>
<tr>
<td>M+K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane, Methane</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ENGINE 4-LOX/RP-1, LH$_2$ COOLED

TURBOMACHINERY CANDIDATES

ENGINE 4 - LOX/RP-1,
LH₂ COOLED

TURBOMACHINERY CANDIDATES
PUMPS FOR ENGINE 4 - LOX/RP-1, LH₂ COOLED

DUAL SHAFT + HYDROGEN CONFIGURATIONS

FOUR PUMP CONFIGURATIONS FOR THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENTS WERE CARRIED FORWARD AFTER THE PUMP SCREENING. EVERY CONFIGURATION CARRIED FORWARD USED A MAIN PUMP ONLY FOR THE HYDROGEN PUMP, AND THE RECOMMENDED CONFIGURATIONS WERE COMPRISED OF THE FOUR POSSIBLE COMBINATIONS OF RP-1 MAIN PUMP OR BOOST PUMP + MAIN PUMP, AND LOX MAIN PUMP OR BOOST PUMP + MAIN PUMP. THERE WAS VERY LITTLE DIFFERENCE IN TOTAL REQUIRED POWER FOR THE FOUR SYSTEMS. THE RP-1 MAIN PUMP WITH LOX MAIN PUMP CONFIGURATION (SYSTEM 4A) WAS THE SIMPLEST CONFIGURATION, THE CONFIGURATION WITH JUST THE LOX BOOST PUMP (SYSTEM 4B) HAD HIGH LOX PUMP SPEED, THE CONFIGURATION WITH JUST RP-1 BOOST PUMP (SYSTEM 4C) HAD HIGH RP-1 PUMP SPEED, AND THE CONFIGURATION WITH BOTH BOOST PUMPS (SYSTEM 4D) HAD MINIMUM POWER AND WEIGHT BUT MAXIMUM COMPLEXITY.

THE HYDROGEN PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED, AS THE MAIN PUMP SPEED WAS LIMITED BY BEARING DN RATHER THAN SUCTION PERFORMANCE LIMITS, AND A BOOST PUMP WAS NOT REQUIRED.
<table>
<thead>
<tr>
<th>CARRIED FORWARD</th>
<th>MAIN + BOOST</th>
<th>MAIN + BOOST</th>
<th>MAIN</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Speed</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4C</td>
</tr>
<tr>
<td>Complexity and High RP-1</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4B</td>
</tr>
<tr>
<td>CARRIED FORWARD</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td>MAIN</td>
<td></td>
</tr>
<tr>
<td>Simple Configuration</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td></td>
</tr>
<tr>
<td>CARRIED FORWARD</td>
<td>MAIN + BOOST</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td></td>
</tr>
<tr>
<td>Not Suction Performance</td>
<td>MAIN + BOOST</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion:**

**Dual Shaft + Hydrogen Configuration**

**Pumps for Engine 4 - LOX/RP-1, LH2, Cooled**
PUMPS FOR ENGINE 4 - LOX/RP-1, LH₂ COOLED

SINGLE SHAFT + HYDROGEN CONFIGURATIONS

ONE PUMP CONFIGURATION FOR THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENTS
WAS CARRIED FORWARD FOR TURBINE SIZING. THIS WAS THE HYDROGEN MAIN PUMP ONLY
WITH RP-1 MAIN PUMP ONLY AND LOX BOOST PUMP + MAIN PUMP (SYSTEM 4E). THIS WAS
CLEARLY THE BEST CONFIGURATION HAVING MAXIMUM SHAFT SPEED, MINIMUM REQUIRED
POWER, MINIMUM WEIGHT AND MEDIUM COMPLEXITY.

CONFIGURATIONS INVOLVING THE HYDROGEN BOOST PUMP + MAIN PUMP WERE DELETED FOR
THE REASONS STATED ON THE PREVIOUS CHART.

THE SIMPLEST CONFIGURATION OF THREE MAIN PUMPS WAS NOT CARRIED FORWARD AS IT
HAD A SIGNIFICANTLY HIGHER POWER REQUIREMENT THAN SYSTEM 4E.

THE CONFIGURATIONS WITH RP-1 BOOST PUMPS WERE DELETED AS THE MAIN PUMP SHAFT
SPEEDS WERE SET BY THE LOX PUMP SUCTION PERFORMANCE LIMITS AND THE RP-1 BOOST
PUMPS SERVED NO PURPOSE.
<table>
<thead>
<tr>
<th>Description</th>
<th>Main + Boost</th>
<th>Main + Boost</th>
<th>Main + Boost</th>
<th>Main + Boost</th>
</tr>
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<tbody>
<tr>
<td>Lox Pump Speed Set</td>
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<td>Deleted</td>
<td>Deleted</td>
<td>Deleted</td>
</tr>
<tr>
<td>Low Speed, Max Power</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>High Power, Min Power, Min Min</td>
<td>Main + Boost</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Carried Forward</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Low Speed, High Power</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Not Suction Performance</td>
<td>Main + Boost</td>
<td>Main</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Speed Limited by Bearing DN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conclusions**

**System 3**

**LH2 Pump Configuration**

**RP-1 Pump Configuration**

**LOX Pump Configuration**

**Conclusion**

**Single Shaft + Hydrogen Configuration**

**Pumps for Engine: 4 - LOX/ RP-1, LH2, Cool**
TURBOPUMPS FOR ENGINE 4 - LOX/RP-1, LH₂ COOLED

The next two charts present the results of the turbine screening for engine 4. Six configurations were recommended for life cycle cost analysis. These utilized both a parallel turbine arrangement, or a mixed series/parallel for the dual shaft + hydrogen configurations, and a series turbine arrangement for each of three pump configurations. The pump configurations were three main pumps only with the dual shaft + hydrogen turbine arrangement (system 4A/P and 4A/S), hydrogen main pump with RP-1 main pump and LOX boost pump + main pump with the dual shaft + hydrogen turbine arrangement (systems 4B/P and 4B/S), and hydrogen main pump with RP-1 main pump and LOX boost pump + main pump with the single shaft + hydrogen turbine arrangement.

The 4A systems were the simplest dual shaft + hydrogen systems, with the series turbine arrangement having the minimum flowrate. The 4B systems had small turbine diameters with the series system also having the minimum flowrate. The 4E systems had the minimum weight and the minimum diameter. The parallel configurations were also carried over because there was concern about control of the series systems.

The configurations with RP-1 boost pump + main pump were deleted as the benefits of the increase in RP-1 pump speed were insufficient to offset the increase in complexity.

TE-68
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Turbine Arrangement</th>
<th>LOX Pump Configuration</th>
<th>RP-1 Pump Configuration</th>
<th>LH₂ Pump Configuration</th>
<th>System Identifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Diameter:  Min Turbine Flow Rate, Carried Forward</td>
<td>MAIN + Boost</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
<tr>
<td>Small Diameter:  Low Turbine Flow Rate, Carried Forward</td>
<td>MAIN + Boost</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
<tr>
<td>Min Turbine Flow Rate</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
<tr>
<td>Than System 4AP, Higher Turbine Flow Rate, Deleted</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
<tr>
<td>Simple Configuration</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
<tr>
<td>Highest Turbine Flow Rate, Deleted</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
</tr>
</tbody>
</table>

Türbo pumps for Engine 4 - LOX/RP-1, LH₂ cooled.
TURBOPUMPS FOR ENGINE 4 - LOX/RP-1, LH₂ COOLED (CONT'D)

THE PARALLEL ARRANGEMENT WAS DELETED BECAUSE IT REQUIRED THE HIGHEST TURBINE FLOWRATE FOR ALL PUMP CONFIGURATIONS.

THE COMBINED SERIES/PARALLEL ARRANGEMENT WAS ANALYZED FOR THE PUMP CONFIGURATION WITH THREE MAIN PUMPS, WITH BOTH THE HYDROGEN AND OXYGEN TURBINES ON THE PARALLEL LEG. A LOWER FLOWRATE WAS ACHIEVED WITH THE HYDROGEN TURBINE IN PARALLEL WITH THE SERIES FUEL AND OXIDIZER TURBINES, AND SO THIS ARRANGEMENT WAS USED FOR ALL THE COMBINED SERIES/PARALLEL ARRANGEMENTS.

<table>
<thead>
<tr>
<th>THAN SYSTEM 4/E/P</th>
<th>CARTRIDGE WEIGHT</th>
<th>E/O</th>
<th>MAIN +</th>
<th>MAIN</th>
<th>MAIN</th>
<th>4/E/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWER TURBINE FLOW RATE</td>
<td>CARTRIDGE FORWARD</td>
<td>GC</td>
<td>0</td>
<td>GC</td>
<td>GC</td>
<td>0</td>
</tr>
<tr>
<td>MINIMUM WEIGHT</td>
<td>CARTRIDGE FORWARD</td>
<td>GC</td>
<td>0</td>
<td>GC</td>
<td>GC</td>
<td>0</td>
</tr>
<tr>
<td>TEMS 4/B/P AND 4/B/S</td>
<td>NO ADVANTAGE OVER SYS.</td>
<td>GC</td>
<td>0</td>
<td>GC</td>
<td>GC</td>
<td>0</td>
</tr>
<tr>
<td>Lox Pump Turbine</td>
<td>MAXIMUM DIAMETER SET BY COMPLEXITY</td>
<td>GC</td>
<td>0</td>
<td>GC</td>
<td>GC</td>
<td>0</td>
</tr>
<tr>
<td>OFFSET INCREASED PUMP SPEED INSUFFICIENT TO BENEFITS OF INCREASED RP-1</td>
<td>DELTED</td>
<td>GC</td>
<td>0</td>
<td>GC</td>
<td>GC</td>
<td>0</td>
</tr>
</tbody>
</table>

**Conclusions**

- TURBOPUMPS FOR ENGINE 4 - Lox/RP-1, LH2 COOLED
TURBOMACHINERY FOR ENGINE 4 - LOX/RP-1, LH2 COOLED

SIX TURBOMACHINERY SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS FOR ENGINE 4.

THE EXPECTED TRENDS FOR THE DIFFERENT PUMP CONFIGURATIONS CAN BE SEEN, AS CAN A REDUCTION IN TURBINE FLOWRATE FOR THE SERIES TURBINE ARRANGEMENTS OVER THE COMBINED SERIES/PARALLEL TURBINE ARRANGEMENTS. FOR THIS ENGINE, ADDING A LOX BOOST PUMP DECREASES THE SYSTEM WEIGHT SLIGHTLY.

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Factor</th>
<th>Diameter (lb)</th>
<th>Maximum Weight (lb)</th>
<th>Turbine Flow Rate</th>
<th>Turbine Arrangement</th>
<th>Lox Pump Configuration</th>
<th>Methane Pump Configuration</th>
<th>System Configuration</th>
<th>Report Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>3.2</td>
<td>3188</td>
<td>39.7</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 E/S</td>
<td>86C-9-568</td>
</tr>
<tr>
<td>13</td>
<td>3.0</td>
<td>3188</td>
<td>39.7</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 E/P</td>
<td>86C-9-568</td>
</tr>
<tr>
<td>16</td>
<td>3.4</td>
<td>3488</td>
<td>39.2</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 B/S</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>3.7</td>
<td>3489</td>
<td>39.3</td>
<td>MAIN + BOOST</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 B/P</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3.8</td>
<td>4281</td>
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<td>4 A/S</td>
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</tr>
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<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>MAIN</td>
<td>4 A/P</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY OF CANDIDATES
TURBOMACHINERY FOR ENGINE 4 - LOX/RP-1, LH2 Cooled
TURBOMACHINERY FOR ENGINE 4 - LOX/RP-1, LH₂ COOLED

SCHEMATICS OF CANDIDATES

These are the schematics of the six engine 4 turbomachinery systems recommended for life cycle cost analysis.
Schematics of Candidates
TurboMachiney for Engine 4 - LOX / RP-1, LH₂, COOLED
TURBOMACHINERY CANDIDATES FOR ENGINE 4 -
LOX/RP-1, LH\(_2\) COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 4. PUMP ROTATIONAL SPEEDS FOR THE RP-1 AND LOX PUMPS WERE SET BY SUCITON PERFORMANCE LIMITS, AND FOR THE HYDROGEN PUMPS WERE SET BY BEARING DN LIMITS. IT SHOULD BE NOTED THAT TO BETTER OPTIMIZE THE HYDROGEN PUMP SHAFT SPEED OUTBOARD BEARINGS WERE ASSUMED IN ORDER TO REDUCE THE BEARING DN.
<table>
<thead>
<tr>
<th>System Weight, lb</th>
<th>2489</th>
<th>2541</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>0.9</td>
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<td></td>
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<td>11427</td>
<td>1060</td>
</tr>
<tr>
<td>11140</td>
<td>11140</td>
<td>11140</td>
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<td>44704</td>
<td>44704</td>
<td>44365</td>
</tr>
<tr>
<td>13300</td>
<td>13300</td>
<td>9650</td>
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</table>

<table>
<thead>
<tr>
<th>Seal Rumbling Speed, ft/sec</th>
<th>Bearing DN. 1086 mm, RPM</th>
<th>Number of Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOX</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Weight, lb</th>
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<th>2541</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
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</tr>
<tr>
<td>7.56</td>
<td>7.56</td>
<td>7.56</td>
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<tr>
<td>20518</td>
<td>20518</td>
<td>20518</td>
</tr>
<tr>
<td>3380</td>
<td>3380</td>
<td>3380</td>
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<tr>
<td>17165</td>
<td>17165</td>
<td>17165</td>
</tr>
<tr>
<td>60000</td>
<td>60000</td>
<td>60000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Seal Rumbling Speed, ft/sec</th>
<th>Bearing DN. 1086 mm, RPM</th>
<th>Number of Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Weight, lb</th>
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<th>2541</th>
</tr>
</thead>
<tbody>
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<td>4.6</td>
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<td>4.6</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Turbomachinery Candidates for Engine 4**

**LOX/RP-1/LH2 COoled**

**SUMMARY OF PUMP DATA**
TURBOMACHINERY CANDIDATES FOR ENGINE 4 - LOX/RP-1, LH2 COOLED

SUMMARY OF TURBINE DATA

Design parameters and characteristics are presented for the turbines for the engine 4 turbomachinery candidates. The turbine blade speeds are generally set at the maximum allowable values due to the high available energy of the LOX/hydrogen drive gas and the desire to optimize U/CO. The low flowrates, and large mean diameters combine to necessitate partial admission for the fuel and LOX turbines.
### 1. Multiple Stage 1 Reaction Stage

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>2.5</td>
<td>2.5</td>
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<td>2.5</td>
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<tr>
<td>Admission Percent</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<td>Blade Height, inch</td>
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<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Tip Diameter, inch</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>N2 A/A10_inch</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Mean blade speed, ft/sec</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
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<tr>
<td>Efficiency</td>
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<td>65</td>
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<td>100</td>
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<td>100</td>
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<td>100</td>
</tr>
<tr>
<td>Speed, rpm</td>
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<td>1500</td>
<td>1500</td>
<td>1500</td>
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<tr>
<td>Power, HP</td>
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</tbody>
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### Lox Turbine

<table>
<thead>
<tr>
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<th>2.5</th>
<th>2.5</th>
<th>2.5</th>
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<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admission Percent</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Blade Height, inch</td>
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<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Tip Diameter, inch</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>N2 A/A10_inch</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Mean blade speed, ft/sec</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Efficiency</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
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<td>65</td>
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<tr>
<td>Standing</td>
<td>100</td>
<td>100</td>
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<td>100</td>
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</tr>
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<td>Speed, rpm</td>
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<td>1200</td>
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<td>1200</td>
<td>1200</td>
</tr>
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<td>Power, HP</td>
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<td>30</td>
<td>30</td>
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</tbody>
</table>

### Hydrogen Turbine

<table>
<thead>
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<th>2.5</th>
<th>2.5</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Admission Percent</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Blade Height, inch</td>
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<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Tip Diameter, inch</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>N2 A/A10_inch</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Mean blade speed, ft/sec</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Efficiency</td>
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<tr>
<td>Standing</td>
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<td>100</td>
</tr>
<tr>
<td>Speed, rpm</td>
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<td>1200</td>
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<tr>
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<td>30</td>
<td>30</td>
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</tr>
</tbody>
</table>

### Summary of Turbine Data

**LOX/ RP-1, LH2 COOLED**

**Turbomachinery Candidates for Engine 4**
LH2 COOLED
ENGINE 6 - LOX/METHANE
TURBOMACHINERY CANDIDATES
PUMPS FOR ENGINE 6 - LOX/METHANE, LH₂ COOLED

DUAL SHAFT + HYDROGEN CONFIGURATIONS

TWO PUMP CONFIGURATIONS FOR THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENT WERE CARRIED FORWARD AFTER THE PUMP SCREENING.

BOTH HAD MAIN PUMP ONLY CONFIGURATIONS FOR THE HYDROGEN AND METHANE PUMPS, WITH ONE HAVING A MAIN PUMP ONLY AND THE OTHER A BOOST PUMP + MAIN PUMP FOR THE LOX PUMP CONFIGURATION. THE TWO CONFIGURATIONS HAD ALMOST THE SAME POWER REQUIREMENT, WITH THE CONFIGURATION WITH THE LOX MAIN PUMP BEING SIMPLER, AND THAT WITH THE LOX BOOST PUMP + MAIN PUMP HAVING HIGHER SPEED AND SLIGHTLY LOWER WEIGHT.

THE HYDROGEN PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED, AS THE MAIN PUMP SPEED WAS LIMITED BY BEARING DN RATHER THAN SUCTION PERFORMANCE LIMITS AND A BOOST PUMP WAS NOT REQUIRED.

THE METHANE PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED AS OUTBOARD BEARINGS WERE REQUIRED IN THE MAIN PUMP TO SATISFY BEARING DN LIMITS. THE ADDED COMPLEXITY OF THIS AND THE BOOST PUMP OFFSET THE SIZE AND PERFORMANCE ADVANTAGES OF THE HIGHER MAIN PUMP SPEED.
<table>
<thead>
<tr>
<th>InCREASEd Complexity</th>
<th>INsufficient TO OFFSET Benefits OF Higher Pump Speed</th>
<th>TO REDUCE DN OutBOARD BEARING Required</th>
<th>MAIN + Boost</th>
<th>MAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>pump Speed</td>
<td>Complexity AND High Lox Carried Forward</td>
<td>COMBINES low Power, Medium</td>
<td>MAIN</td>
<td>6B</td>
</tr>
<tr>
<td>simple Configuration</td>
<td>Carried Forward</td>
<td></td>
<td>MAIN</td>
<td>6A</td>
</tr>
<tr>
<td>NOT suction Performance</td>
<td>Sppeed Limited BY Bearing DN</td>
<td></td>
<td>MAIN + Boost</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions

**DUAL SHAFT + HYDROGEN CONFIGURATIONS**

**Pumps FOR ENGINE 6 - LOX/METHANE, LH2 COOLED**
PUMPS FOR ENGINE 6 - LOX/METHANE, LH2 COOLED

SINGLE SHAFT - HYDROGEN CONFIGURATIONS

ONE PUMP CONFIGURATION FOR THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENT WAS CARRIED FORWARD FOR TURBINE SIZING. THE CONFIGURATION WITH HYDROGEN MAIN PUMP, METHANE MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP HAD THE LOWEST POWER REQUIREMENT AS WELL AS THE HIGHEST SPEED AND LOWEST WEIGHT.

CONFIGURATIONS INVOLVING THE HYDROGEN BOOST PUMP + MAIN PUMP WERE DELETED FOR THE REASONS STATED ON THE PREVIOUS CHART.

THE COMBINATION OF THREE MAIN PUMPS WAS DELETED AS THERE WAS A SIGNIFICANT SIZE AND PERFORMANCE PENALTY FOR THE METHANE PUMP WHEN IT WAS CONSTRAINED TO RUN AT THE SAME SPEED AS THE LOX PUMP.

CONFIGURATIONS INVOLVING THE METHANE BOOST PUMP + MAIN PUMP WERE DELETED AS THE MAIN PUMP SPEED IS SET BY THE LOX PUMP SUCTION PERFORMANCE LIMITS AND A METHANE BOOST PUMP IS NOT REQUIRED.
<table>
<thead>
<tr>
<th>Required</th>
<th>Main</th>
<th>Main</th>
<th>Main</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane Boost Pump Not Speed Controlled by LOX Pump Deleted</td>
<td>Main + Boost</td>
<td>Main</td>
<td>6G</td>
</tr>
<tr>
<td>Minimum Power and Weight Carried Forward</td>
<td>Main + Boost</td>
<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Performance Penalty Significant Methane Pump Deleted</td>
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<td>Main</td>
<td>Main</td>
</tr>
<tr>
<td>Not Suction Performance Speed Limited by Bearing DN Deleted</td>
<td>Main + Boost</td>
<td>Main</td>
<td>Main</td>
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<tr>
<td>Conclusions</td>
<td>Configuration LOX Pump</td>
<td>Configuration Methane Pump</td>
<td>Configuration LH2 Pump</td>
</tr>
</tbody>
</table>

**Single Shaft + Hydrogen Configuration**

Pumps for Engine 6 - LOX/Methane, LH2 Coolled
TURBOPUMPS FOR ENGINE 6 - LOX/METHANE, LH2 COOLED

The next two charts present the results of the turbine screening for Engine 6. Six systems were recommended for life cycle cost analysis. These utilized both a parallel turbine arrangement, or a mixed series/parallel for the dual shaft + hydrogen configurations, and a series turbine arrangement for each of three pump configurations. The pump configurations were three main pumps only with the dual shaft + hydrogen turbine arrangement (systems 6A/P and 6A/S), hydrogen main pump with methane main pump and LOX boost pump + main pump with the dual shaft + hydrogen turbine arrangement (systems 6B/P and 6B/S), and hydrogen main pump with methane main pump and LOX boost pump + main pump with the single shaft + hydrogen turbine arrangement (systems 6C/P and 6C/S).

The 6A systems were the simplest dual shaft + hydrogen systems, with the series turbine arrangement having the minimum flowrate. The 6B systems had the minimum diameters and the series turbine arrangement also had the minimum turbine flowrate. The 6C systems had the minimum weight, as would be expected for a single shaft configuration. In common with engine 4 the parallel turbine configurations were carried over partly due to concern about control of the series systems.
**LH₂ COOLED**

**TURBOPUMPS FOR ENGINE 6 - LOX/METHANE**
TURBOPUMPS FOR ENGINE 6, LOX/METHANE, LH2 COOLED (CONT'D)

THE PARALLEL DUAL SHAFT + HYDROGEN ARRANGEMENT AND THE COMBINED
SERIES/PARALLEL ARRANGEMENT WITH THE OXYGEN TURBINE ON THE PARALLEL LEG WERE
DELETED FOR THE REASONS DESCRIBED PREVIOUSLY IN THE DISCUSSION OF THE ENGINE 4
CANDIDATES.

ALL THE TURBINES FOR THESE SYSTEMS WERE TWO ROW VELOCITY COMPOUNDED TURBINES
EXCEPT FOR THE HYDROGEN TURBINES IN THE SERIES ARRANGEMENTS WHICH WERE 2 STAGE
REACTION TURBINES. THE METHANE AND LOX TURBINES WERE PARTIAL ADMISSION DUE TO
LOW TURBINE FLOWRATES.
<table>
<thead>
<tr>
<th>System &amp; Configuration</th>
<th>Main Boost</th>
<th>Main Boost</th>
<th>Main Boost</th>
<th>Main Boost</th>
</tr>
</thead>
<tbody>
<tr>
<td>THXN SYSTEM 6 C/F</td>
<td></td>
<td></td>
<td></td>
<td>6 C/F</td>
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<tr>
<td>Minimum Weight</td>
<td></td>
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<tr>
<td>Carried Forward</td>
<td></td>
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</tbody>
</table>

**Conclusions**
- LH² COOLED
- TURBO PUMPS FOR ENGINE 6 - LOX/METHANE
TURBOMACHINERY FOR ENGINE 6 - LOX/METHANE, LH2 COOLED

SIX CONFIGURATIONS WERE CARRIED FORWARD FOR LIFE CYCLE COST ANALYSIS FOR ENGINE 6.

THE EXPECTED TRENDS FOR BOOST PUMP/NO BOOST PUMP, SINGLE SHAFT/DUAL SHAFT AND PARALLEL TURBINE/SERIES TURBINES ARE OBSERVED. FOR THIS ENGINE THE BOOST PUMPS SIGNIFICANTLY REDUCE THE MAXIMUM DIAMETER AND SLIGHTLY REDUCE THE SYSTEM WEIGHT.

<table>
<thead>
<tr>
<th>Complexity</th>
<th>LOX/METHANE</th>
<th>LH₂ COOLED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkomachinery for Engine 6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complexity</th>
<th>LOX/METHANE</th>
<th>LH₂ COOLED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkomachinery for Engine 6</td>
<td></td>
<td></td>
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</tbody>
</table>
TURBOMACHINERY FOR ENGINE 6, LOX/METHANE, LH2 COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE SIX ENGINE 6 TURBOMACHINERY SYSTEMS
RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.
<table>
<thead>
<tr>
<th>Seal</th>
<th>Purge</th>
<th>Bearing</th>
<th>Seal</th>
<th>Turbine Stage</th>
<th>Pump Kick</th>
<th>Stage Pump</th>
<th>Main Pump</th>
<th>Boost Pump</th>
</tr>
</thead>
</table>

**Legend:**
- Lox
- Methane
- LH2

**Schematics of Candidates:**
- Lox/Methane, LH2, cooled

**TurboMachinery for Engine 6**
TURBOMACHINERY CANDIDATES FOR ENGINE 6 -
LOX/METHANE, LH2 COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS
FOR ENGINE 6. PUMP ROTATIONAL SPEEDS ARE SET BY PUMP SUCTION PERFORMANCE
LIMITS, EXCEPT FOR THE HYDROGEN PUMPS WHICH ARE SET BY BEARING ON LIMITS. IT
SHOULD BE NOTED THAT OUTBOARD BEARINGS WERE ASSUMED FOR THE HYDROGEN PUMPS TO
REDUCE BEARING ON VALUES.
<table>
<thead>
<tr>
<th>Seal</th>
<th>Bearing</th>
<th># Stages</th>
<th>Diameter</th>
<th>Head</th>
<th>Flow</th>
<th>Power</th>
<th>RPM</th>
<th>Speed</th>
<th>Pump</th>
<th>LOX</th>
<th>L I2</th>
<th>CH4</th>
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<tr>
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<td>72</td>
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<td>1.5</td>
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<td>60</td>
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<td>14000</td>
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<td>248</td>
<td>21</td>
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<td>90</td>
<td>60</td>
<td>45729</td>
<td>1150</td>
<td>14000</td>
<td>144</td>
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<tr>
<td>247</td>
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<tr>
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<td>14000</td>
<td>144</td>
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</tbody>
</table>

**Summary of Pump Data**

**LOX/Methylene, LH2 Cooled**

**Turbo machinery candidates for engine 6**
TURBOMACHINERY CANDIDATES FOR ENGINE 6 - LOX/METHANE, LH₂ COOLED

SUMMARY OF TURBINE DATA

DESIGN PARAMETERS AND CHARACTERISTICS FOR THE TURBINES FOR THE TURBOMACHINERY CANDIDATES FOR ENGINE 6 ARE PRESENTED. THE TURBINE BLADE SPEEDS ARE GENERALLY SET CLOSE TO THE MAXIMUM ALLOWABLE VALUES DUE TO THE HIGH AVAILABLE ENERGY OF THE LOX/HYDROGEN DRIVE GAS AND THE DESIRE TO OPTIMIZE U/CO. THE LOW TURBINE FLOWRATES, AND LARGE MEAN DIAMETERS COMBINE TO NECESSITATE PARTIAL ADMISSION FOR THE FUEL AND LOX TURBINES.
## Summary of Turbine Data

**LOX/METHANE, LH₂ COOLED**

**Turbomachinery Candidates for Engine 6**

### Lox Turbine

<table>
<thead>
<tr>
<th>Pressure Ratio</th>
<th>Turbine Flowrate (lb/sec)</th>
<th>Admission Pressure - Max</th>
<th>Bladed Height/Mean Dia. - Min</th>
<th>Tip Diameter Inch</th>
<th>N₂A, 10⁻¹0 Pm² Inch²</th>
<th>Mean Blade Speed, FPM</th>
<th>Efficiency</th>
<th>Stranding</th>
<th>Spool Dia., in.</th>
<th>Spool Dia., FPM</th>
<th>Spool Dia., HP</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

### Methane Turbine

<table>
<thead>
<tr>
<th>Pressure Ratio</th>
<th>Turbine Flowrate (lb/sec)</th>
<th>Admission Pressure - Max</th>
<th>Bladed Height/Mean Dia. - Min</th>
<th>Tip Diameter Inch</th>
<th>N₂A, 10⁻¹0 Pm² Inch²</th>
<th>Mean Blade Speed, FPM</th>
<th>Efficiency</th>
<th>Stranding</th>
<th>Spool Dia., in.</th>
<th>Spool Dia., FPM</th>
<th>Spool Dia., HP</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

### Hydrogen Turbine

<table>
<thead>
<tr>
<th>Pressure Ratio</th>
<th>Turbine Flowrate (lb/sec)</th>
<th>Admission Pressure - Max</th>
<th>Bladed Height/Mean Dia. - Min</th>
<th>Tip Diameter Inch</th>
<th>N₂A, 10⁻¹0 Pm² Inch²</th>
<th>Mean Blade Speed, FPM</th>
<th>Efficiency</th>
<th>Stranding</th>
<th>Spool Dia., in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

### Metaxure Pump Configuration

**System**

- **Dual Shaft**
- **LH² Pump Configuration**

---

**Notes:**

- The data is specific to LOX/METHANE, LH₂ COOLED turbomachinery candidates for engine 6.
- The tables provide a detailed breakdown of pressure ratios, turbine flowrates, admission pressures, and efficiency metrics relevant to the performance of LOX and Methane turbines.
- Additional performance metrics such as tip diameter, N₂A, and mean blade speed are listed to provide a comprehensive overview of the turbine's operational parameters.
TURBOPUMP SCREENING SUMMARY

THIS TABLE SUMMARIZES THE RESULTS OF THE PUMP AND TURBINE SCREENING FOR THE FOUR ENGINES FOR WHICH IT HAS BEEN COMPLETED.

FOR EACH ENGINE IT SHOWS THE TOTAL NUMBER OF TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS, THE TOTAL NUMBER OF EACH PUMP CONFIGURATION USED IN THOSE SYSTEMS, AND HOW MANY UTILIZE DUAL SHAFT AND SINGLE SHAFT TURBINE ARRANGEMENTS WITH SERIES OR PARALLEL HYDROGEN TURBINES (WHEN REQUIRED).
<table>
<thead>
<tr>
<th>Total Number of Candidates</th>
<th>Total Number of Candidates</th>
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<td></td>
</tr>
<tr>
<td>Single</td>
<td>Single</td>
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<tr>
<td>Parallel</td>
<td>Parallel</td>
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<tr>
<td>Series</td>
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<tr>
<td>Fuel</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LH2</td>
<td>LH2</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LOX</td>
<td>LOX</td>
</tr>
</tbody>
</table>
FINAL CONFIGURATION SELECTION LOGIC

For each engine, the candidate turbopumps that survive the screening process must undergo a selection procedure to determine the optimum configuration. This is the flow chart for the selection procedure. The turbine flowrate and turbopump weight for each candidate are translated into vehicle inert weight using engine sensitivity factors from the baseline engine balances and vehicle sensitivity factors from the Space Transportation Architecture Studies (STAS) vehicle analyses. Next, assessments of reliability, complexity, risk, and production and development costs are made for each turbopump candidate. Cost algorithms are then used to translate these assessments and the vehicle inert weight into an overall vehicle life cycle cost impact for each turbopump candidate. This provides a single parameter for running the candidate turbopumps for each engine.
FINAL CONFIGURATION SELECTION LOGIC
THROTTLING REQUIREMENT EVALUATION

THE TURBOMACHINERY SYSTEMS ARE SIZED FOR THE 750K THRUST OPERATING POINT, BUT MUST ALSO OPERATE EFFICIENTLY AND WITH SUFFICIENT MARGIN AT 625K THRUST. THIS THROTTLING REQUIREMENT, HOWEVER, SHOULD NOT AFFECT THE SELECTION PROCESS SIGNIFICANTLY AS THE OFF DESIGN PERFORMANCE OF ALL THE CANDIDATE SYSTEMS FOR AN ENGINE SHOULD BE SIMILAR. THE SELECTED SYSTEM FOR EACH ENGINE WILL BE ANALYZED AT THE 625K THRUST OPERATING POINT TO ENSURE ACCEPTABLE EFFICIENCY, STALL MARGIN AND SUCTION PERFORMANCE AT THAT POINT.
OPERATING POINT TO ENSURE ACCEPTABLE CHARACTERISTICS
SELECTED TURBOMACHINERY SYSTEMS ANALYZED AT 625K
HYDRODYNAMIC AND AERODYNAMIC DESIGN PARAMETERS
COMPONENT OF-FRONT PERFORMANCES SIMILAR FOR

RELATIVE MERT

THROTTLING REQUIREMENTS SHOULD NOT AFFECT SYSTEM
SYSTEMS SIZED FOR 75K BALANCES

THROTTLING REQUIREMENT EVALUATION
AGENDA
SECOND QUARTERLY REVIEW
STBE CONFIGURATION STUDY
STBE COMBUSTION DEVICES

DURING THE TASK 2 STBE STUDIES, FOUR MAJOR COMBUSTION DEVICES COMPONENTS ARE ADDRESSED; THE MAIN INJECTOR, COMBUSTION CHAMBER/NOZZLE, GAS GENERATOR, AND THE IGNITION SYSTEM.
COMBUSTION DEVICES STUDY PLAN

THE PRIMARY OBJECTIVE OF THE COMBUSTION DEVICES PLAN IS TO SELECT OPTIMUM LOX/HC COMBUSTION DEVICES CONFIGURATIONS FOR EACH CANDIDATE.

THE APPROACH IS LISTED ON THIS CHART
Recommended Best Configuration

Technical Risk
- Cost
- Weight
- Performance

Tradeoff Factors

Evaluate Baseline and Alternatives Against

Select Baseline Configuration

Identify Potential Design Concepts

Define Baseline Engine Balance

Use 1986 Technology

Approach

Configuration for Each Candidate

Select Optimum LOX/HC Combustion Devices

Objective

Combustion Devices Study Plan
ENGINE OPERATING CONDITIONS

The basic engine operating conditions for the 6 candidate FOC concepts are listed on this chart, the propellant combination, the chamber coolant and the chamber pressure are key items.
<table>
<thead>
<tr>
<th>Chamber Pressure (psia)</th>
<th>Combustion Characteristic Efficiency (%)</th>
<th>Specific Impulse, sec VAC (s)</th>
<th>Thrust VAC (kips)</th>
<th>Thrust SL (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4200</td>
<td>4170</td>
<td>4165</td>
<td>3495</td>
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<td>361</td>
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<td>750</td>
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<td>750</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>H2</td>
<td>H2</td>
<td>H2</td>
<td>CH4</td>
<td>CH4</td>
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<td>LOX/CH4</td>
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<td>LOX/CH4</td>
<td>LOX/CH4</td>
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<td>6</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Engine Operating Conditions
TYPICAL STBE ENGINE SCHEMATICS

THE FOLLOWING 3 CYCLES ARE THE GAS GENERATOR CYCLE CANDIDATES FOR THE 1995 ENGINES. ALL ARE FUEL COOLED (EITHER HYDROCARBON OR HYDROGEN). THE FIRST (CYCLE TYPE 1) IS A SINGLE SHAFT UNIT FOR LOX/RP-1. EXCEPT FOR THE PARALLEL COOLANT FLOW CIRCUIT, IT IS SIMILAR TO THE SCHEMATIC FOR THE F-1 ENGINE. THE HIGH DENSITY OF RP-1 MAKES THE SINGLE SHAFT TURBOPUMP FEASIBLE.

THE SECOND CYCLE IS THE SAME BASIC FLOW CIRCUIT WITH THE DUAL SHAFT TURBOMACHINERY THAT IS ATTRACTIVE FOR FUELS THAT ARE LOWER IN DENSITY THAN RP-1. THE SERIES TURBINE ARRANGEMENT IMPROVES PERFORMANCE SIGNIFICANTLY.

Typical stobe engine schematics

- Gaseous Methane Injection
- Liquid/Liquid Injection
- Liquid Hydrogen Cooled
- Gas Generator Cycle
- Liquid/Liquid Injection
- Liquid Propane Injection
- Fuel Cooled
- Gas Generator Cycle
- Liquid/Liquid Injection
- Fuel Cooled
- Gas Generator Cycle

(Engines 4, 5, and 6) Cycle Type 3

(Engines 2 and 3) Cycle Type 2

(Engine 1) Cycle Type 1
MAIN INJECTOR DESIGN CONSIDERATIONS

THE MAJOR DESIGN CONSIDERATION FOR THE MAIN INJECTOR ARE LISTED HERE
MAIN INJECTOR DESIGN CONSIDERATIONS

- COMBUSTION STABILITY CONSIDERATIONS
- ARRANGEMENT OF ELEMENTS
- SELECTION OF INJECTION ELEMENT
- INJECTOR OPERATIONS CONDITIONS
MAIN INJECTOR OPERATING CONDITIONS

THE MAIN INJECTOR OPERATING CONDITIONS AND SIZES ARE TABULATED ON THIS CHART. PERFORMANCE, Pc, AND FUEL INJECTION STATE ARE HIGHLIGHTED
<table>
<thead>
<tr>
<th>INJECTOR DIAMETER, in.</th>
<th>18.6</th>
<th>18.6</th>
<th>18.7</th>
<th>20.4</th>
<th>20.7</th>
<th>25.3</th>
</tr>
</thead>
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<tr>
<td>FUEL INJ. STATE</td>
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<td>L10</td>
<td>L10</td>
<td>GAS</td>
<td>L10</td>
<td>L10</td>
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<tr>
<td>TR INJ. F.° R.</td>
<td>210</td>
<td>160</td>
<td>520</td>
<td>341</td>
<td>611</td>
<td>969</td>
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<td>TR INJ. OX. F. P.sia</td>
<td>5040</td>
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<td>4998</td>
<td>4194</td>
<td>4089</td>
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<td>PR INJ. OX. F. P.sia</td>
<td>163</td>
<td>163</td>
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<tr>
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<td>4998</td>
<td>4194</td>
<td>4089</td>
<td>2850</td>
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<tr>
<td>MR. O/F</td>
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<tr>
<td>W FL. lb/s</td>
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<td>567</td>
<td>628</td>
<td>572</td>
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<td>97</td>
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<tr>
<td>PROPELLANT COMBINATION</td>
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<td>LOX/CH₄</td>
<td>LOX/CH₄</td>
<td>LOX/CH₄</td>
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</tr>
</tbody>
</table>

MAIN INJECTOR OPERATING CONDITIONS
NONIMPINGING 
IMPINGING 
GAS/LIQUID 
NONIMPINGING 
UNLIKE IMPINGING 
LIKE IMPINGING 
LIQUID/LIQUID 

CANDIDATE ELEMENTS • 
EXPERIENCE • 
DURABILITY • 
PRODUCIBILITY • 
SOFTWARE COMPATIBILITY • 
STABILITY • 
PERFORMANCE • 

CONSIDERATIONS • 

INJECTOR ELEMENT DESIGN
CANDIDATE INJECTOR ELEMENTS

THIS CHART PRESENTS A LIST OF CANDIDATE MAIN INJECTOR ELEMENTS SUBJECTED TO INITIAL SCREENING FOR THE STBE. THE ELEMENTS ARE DIVIDED INTO LIQUID/LIQUID AND GAS/LIQUID CATEGORIES.
INJECTOR ELEMENT SELECTION TRADES

THE KEY TRADE FACTORS OR CONSIDERATIONS USED FOR INJECTOR ELEMENT ASSESSMENT AND THE MAIN INJECTOR ELEMENT CANDIDATES ARE EVALUATED FOR BOTH LIQUID/LIQUID AND GAS/LIQUID PROPELLANT COMBINATIONS. EACH OF THESE INJECTOR ELEMENT TYPES WERE RATED ON A SCALE FROM 1 TO 3 (LOW TO HIGH) WITH REGARD TO POTENTIAL PERFORMANCE (ATOMIZATION, MIXING, AND THROTTLEABLE), STABILITY, COMPATIBILITY, PRODUCIBILITY, AND EXPERIENCE ADVANTAGES. THE ELEMENTS WITH THE HIGHEST COMBINED TOTALS ARE JUDGED TO BE THE BEST.
## Trade Factor

<table>
<thead>
<tr>
<th>Trade Factor</th>
<th>Gas/Lhr</th>
<th>Gas/Lhr</th>
<th>Gas/Lhr</th>
<th>Gas/Lhr</th>
<th>Coal/Slag</th>
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</thead>
<tbody>
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<tr>
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</tbody>
</table>

### Element Configurations

<table>
<thead>
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<tr>
<td></td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Total

- Experience
- Productivity
- Compatibility
- Stability
- Throttleable
- Mixing
- Atomization
LIQUID/LIQUID INJECTOR ELEMENT SELECTION

THE LIKE DOUBLET ELEMENT IS SELECTED AS THE BASELINE FOR THE LIQUID/LIQUID INJECTOR CONCEPTS FOR FIVE ENGINES; #1, 2, 4, 5 & 6.
ELEMENT SELECTION

- ENGINE 6 - LOX/METHANE, H₂ COOLED
- ENGINE 5 - LOX/PROPANE, H₂ COOLED
- ENGINE 4 - LOX/RP-1, H₂ COOLED
- ENGINE 2 - LOX/PROPANE
- ENGINE 1 - LOX/RP-1

ENGINE CONFIGURATION

LIQUID/LIQUID INJECTOR ELEMENT SELECTION
GAS/LIQUID INJECTOR ELEMENT SELECTION

THE COAXIAL INJECTOR ELEMENT CONCEPT IS SELECTED AS THE BASELINE FOR ENGINE #3.
PRODUCIBILITY • CHAMBER COMPATIBILITY • PERFORMANCE • STABLE • PROVEN/EXPERIENCE

COAXIAL • ELEMENT SELECTION • ENGINE 3 – LOX/METHANE • ENGINE CONFIGURATION •

GAS/LIQUID INJECTOR ELEMENT SELECTION
ELEMENT ARRANGEMENT REQUIREMENTS

ELEMENT ARRANGEMENT REQUIREMENTS ARE IDENTIFIED HERE. KEY ELEMENT PATTERN AND ELEMENT ORIENTATION CONSIDERATIONS ARE LISTED.
ELEMENT ARRANGEMENT REQUIREMENTS

- Baffles
- Chamber Wall
- Hardware Compatibility
- Heat Transfer Rate
- Orientation
  InterElement Mixing (Impinging)
  Mixture Ratio Uniformity
  Mass Flux Uniformity
- Pattern
ELEMENT ARRANGEMENT SELECTION

SELECTION OF THE ELEMENT ARRANGEMENTS FOR THE LIQUID/LIQUID AND THE GAS/LIQUID INJECTORS ARE PRESENTED. A "BOX" PATTERN IS SELECTED FOR THE LIKE DOUBLET LIQUID/LIQUID CONCEPTS AND A SYMMETRICAL PATTERN IS SELECTION FOR THE COAXIAL GAS/LIQUID CONCEPT. PRIMARY REASONS FOR THESE SELECTIONS ARE GIVEN.
Fuel Rich Boundary •
Chamber Wall Compatibility •
Experience Base •
Stability •
Uniform Mixture Ratio •
Uniform Mass Flux •
Performance •
Symmetrical Pattern •
Gas/Liquid •
Liquid/Liquid •

Element Arrangement Selection
BASELINE LIQUID/LIQUID INJECTOR

THIS CHART GRAPHICALLY SHOWS THE LIKE DOUBLET INJECTOR ELEMENT AND THE BOX PATTERN ARRANGEMENT OF INJECTOR ELEMENTS FOR THE LIQUID/LIQUID INJECTOR CONCEPTS.
BASELINE GAS/LIQUID INJECTOR

THE GAS/LIQUID COAXIAL INJECTOR ELEMENT AND A TYPICAL SYMMETRICAL COAXIAL INJECTOR ELEMENT ARRANGEMENT ARE GRAPHICALLY SHOWN HERE.
COMBUSTION STABILITY CONSIDERATIONS

PRIMARY COMBUSTION STABILITY CONSIDERATIONS FOR THIS STBE STUDY ARE PRIOR EXPERIENCE, OPERATING CONDITIONS OF THE CHAMBER, INJECTOR/COMBUSTOR GEOMETRY FEATURES AND STABILITY AIDS. KEY PARAMETERS ARE LISTED UNDER EACH OF THE MAIN CONSIDERATION TOPICS.
COMBUSTION STABILITY CONSIDERATIONS

- Lines
- Orientation
- Absorbers/Cavities - Open Area and Length
- Baffles - Length

STABILITY DEVICES

- Element Orifice Diameter
- Injection Element Type/Spacing/Orientation
- Chamber Length
- Chamber Diameter

GEOMETRY

- Mixing/Burning Rate
- Concentration
- Stream and Drop Size/Automatization Rate
- Mass Distribution
- Chamber Pressure
- Propellants/Temperature

OPERATING CONDITIONS

EXPERIENCE
COMBUSTION STABILITY ANALYSES

THIS CHART PRESENTS THE PRIMARY STABILITY THEORIES (TOOLS) USED TO ANALYZE COMBUSTION STABILITY. THE PRIEM ANALYSIS AND THE ROCKETDYNE STREAM BREAKUP CORRELATION WILL BE MAINLY USED FOR THE STBE STUDIES.
INCORPORATES STEAM BREAKUP PROCESS MODEL
ASSUMES STEAM BREAKUP CONTROLS
FULL SIZE STABILITY DATA CORRELATION
STABILITY OF INJECTOR DESIGNS

ROCKETDyne STEAM BREAKUP CORRELATION
CSU EFFORT TO ANCHOR TO H-1 DATA
MODEL IMPLIED FROM AVAILABLE STABILITY DATA
HEURISTIC COMBUSTION RESPONSE MODEL
DETAILED CHAMBER ACOUSTIC TREATMENT
WIDE APPLICATION
STABILITY OF INJECTOR/CAVITY DESIGNS

SENSITIVE TIME LAG (N-\(\tau\))
DEPENS ON ACCURATE DROPLET SIZE DATA
MODELS PHYSICAL EVAPORATION PROCESSES
ASSUMES DROPLET EVAPORATION CONTROLS
RELATIVE STABILITY OF INJECTOR

PRiM

COMBUSTION STABILITY ANALYSES
LIQUID/LIQUID INJECTOR STABILITY

STABILITY CONSIDERATIONS ARE IDENTIFIED FOR THE LIQUID/LIQUID INJECTORS. THE ELEMENT BY ITSELF, THE ELEMENT ARRANGEMENT, AND THE STABILITY AIDS ARE KEY TO ENHANCING STABILITY. BAFFLE/STABILITY AID SELECTION HAS NOT BEEN COMPLETED FOR THE BASELINE CONFIGURATION, HOWEVER, A 19 COMPARTMENT BAFFLE ARRANGEMENT IS TENTATIVELY SELECTED. AN ALTERNATE APPROACH IS TO DECREASE THE NUMBER OF COMPARTMENTS (BAFFLES).
LIQUID/ LIQUID INJECTOR STABILITY

- STABILITY CONSIDERATIONS
  - BAFFLE CONFIGURATION
    - BOX "PATTERN WITH COAX COMBUSTION" ELEMENT
  - ACTIVE INJECTION BAFFLE
  - BIPROPELLANT COOLED BAFFLE
- LENGTH
GAS/LIQUID INJECTOR STABILITY

KEY CONSIDERATIONS FOR ENSURING THE STABILITY OF THE GAS/LIQUID INJECTOR ARE THE LOX/H₂ AND LOX/CH₄ EXPERIENCES, THE STABLE COAXIAL INJECTOR ELEMENT ITSELF AND BAFFLES. TENTATIVELY THE BASELINE CONFIGURATION WILL UTILIZE A BAFFLE ARRANGEMENT SIMILAR TO THE SSME. THE ALTERNATE APPROACH WILL BE TO ELIMINATE THE BAFFLES
GAS/LIQUID INJECTOR STABILITY

- BIPROPellant COOLANT Baffle
- Active INJECTION Baffle
- Alternative Configuration
- Stable COAXIAL ELEMENT
- EXPERIENCE

(No Baffles)

Baseline
COMBUSTION CHAMBER AND NOZZLE
COMBUSTION CHAMBER/NOZZLE DESIGN CONSIDERATIONS

Design Considerations
Combustion Chamber/Nozzle

- Epsilon
- Length
- Shape
- Nozzle Sizing
- Nozzle Attachment Point
- Contraction Ratio
- Convergence Angle
- Length
- Combustor contour
- Tubes
- Channel
- Coolant Passages
- Configuration
- Film - BLI
- Dual Propellant Regenerative
- Single Propellant Regenerative (Series or Parallel)
- Coolant Flow Circuit
- Life Requirements
- Heat Loads
- Pressures
- Coolant Type and Flow
- Operating Conditions
CHAMBER/NOZZLE OPERATING CONDITIONS

These chamber and nozzle operating conditions play a major role in the design. Type of coolant, coolant delta-p and coolant outlet temperature are some of the more important parameters.
<table>
<thead>
<tr>
<th>Engine Configuration Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber/Nozzle Operating Conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAMBER/NOZZLE GEOMETRY

BASELINE CHAMBER AND NOZZLE GEOMETRY ARE LISTED. CHAMBER DIAMETER AND LENGTH PARAMETERS CAN SIGNIFICANTLY EFFECT PERFORMANCE, STABILITY AND HEAT TRANSFER.
<table>
<thead>
<tr>
<th>RPM</th>
<th>64.6</th>
<th>64.9</th>
<th>64.3</th>
<th>57.9</th>
<th>56.9</th>
<th>42.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1160</td>
<td>1170.0</td>
<td>117.0</td>
<td>117.0</td>
<td>117.9</td>
<td>119.5</td>
<td>123.2</td>
</tr>
<tr>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>132</td>
<td>132</td>
<td>142</td>
<td>144</td>
<td>169</td>
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<td>113</td>
<td>113</td>
<td>114</td>
<td>124</td>
<td>126</td>
<td>154</td>
<td>154</td>
</tr>
<tr>
<td>H₂</td>
<td>H₂</td>
<td>H₂</td>
<td>H₂</td>
<td>CH₄</td>
<td>CH₄</td>
<td>C₂H₆</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Chamber/Nozzle Geometry**
COMBUSTION CHAMBER/NOZZLE DESIGN GROUNDRULES

THIS TABLE PRESENTS THE GROUNDRULES AND CONSTRAINTS THAT HAVE BEEN SELECTED AND INCORPORATED INTO THE ENGINE BALANCE PROGRAM. THE PRIMARY ADVANTAGE OR REASONS FOR THESE GROUNDRULES ARE ALSO PRESENTED.

PM-50
<table>
<thead>
<tr>
<th>Performance</th>
<th>Weight</th>
<th>Coolant Passage Geometry -- Tube</th>
<th>Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Weight</td>
<td>Coolant Passage Material -- A286</td>
<td></td>
</tr>
<tr>
<td>Fabrication</td>
<td>Heat Transfer</td>
<td>Expansion Ratio -- 70</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Contraction Ratio -- 2.7</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Convergence Angle -- 25.4 deg</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Cylindrical Length -- 3 ( \text{in} )</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Contour Geometry</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Depth/Width -- ( \geq 5 )</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>CHannels -- Slotted</td>
<td></td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Heat Transfer</td>
<td>Coolant Passage Geometry</td>
<td></td>
</tr>
<tr>
<td>Life</td>
<td>Life</td>
<td>Coolant Jacket</td>
<td>Component</td>
</tr>
<tr>
<td>Avoid Corrosion</td>
<td>Life</td>
<td>Coolant Bulk Temp Limit (( ^\circ \text{F} )) -- 1060-1200</td>
<td>Component</td>
</tr>
</tbody>
</table>

**Combustion Chamber/Nozzle Design Ground Rules**

- Exit Pressure -- 6 psia (DE)
- Length -- 80% Bell
- Contour Geometry
TYPICAL MAIN COMBUSTION CHAMBER

THIS IS A TYPICAL MAIN COMBUSTION CHAMBER CANDIDATE WITH CHANNEL WALL CONSTRUCTION.
Typical Nozzle
CHAMBER ASSEMBLY TRADE STUDIES TO BE CONDUCTED ARE DIAGRAMMED HERE. THE FIRST TWO STEPS HAVE BEEN ACCOMPLISHED. THE NEXT STEP IS TO SELECT THE INJECTOR ELEMENT SIZES AND STABILITY AIDS USING THE BASELINE CHAMBER SIZE. COST, WEIGHT AND RISK FACTORS ARE THEN ESTABLISHED FOR THIS BASELINE INJECTOR AND CHAMBER. THE NEXT STEP IS TO CHANGE THE CHAMBER GEOMETRY; ESTABLISH NEW INJECTOR SIZES AND STABILITY AIDS; DETERMINE ENGINE IMPACT; ESTABLISH NEW COST, WEIGHT AND RISK VALUES OR "DELTAS"; AND THEN ESTABLISH ENGINE AND VEHICLE LCC COMPARISONS. THESE COMPARISONS ARE THEN USED TO HELP SELECT THE OPTIMUM CHAMBER ASSEMBLY FOR EACH ENGINE AND TO HELP SELECT THE BEST ENGINE CONCEPT.
CHAMBER ASSEMBLY TRADE STUDY RESULTS

THE CHAMBER ASSEMBLY TRADE STUDY RESULTS WILL BE FORMATTED AS SHOWN BY THIS TABLE. CHAMBER ASSEMBLY COST, WEIGHT, AND RISK IMPACTS WILL BE ASSESSED AS WELL AS ENGINE AND VEHICLE LIFE CYCLE COSTS.
<table>
<thead>
<tr>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
<th>ACCEPTECH</th>
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</thead>
<tbody>
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<td>27/11.2</td>
<td>27/13.6</td>
<td>27/14.4</td>
<td>27/13.2</td>
<td>27/13.2</td>
<td>27/14.4</td>
<td>27/16.9</td>
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<tr>
<td>18</td>
<td>12</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

**RESULTS**

**CHAMBER/INJECTOR ASSEMBLY TRADE STUDY**
GAS GENERATOR INJECTOR DESIGN CONSIDERATIONS

KEY GG INJECTOR DESIGN CONSIDERATIONS ARE LISTED; NAMELY THE OPERATING CONDITIONS, INJECTION ELEMENT/ARRANGEMENT SELECTION, COMBUSTION STABILITY, AND COMBUSTOR SIZE.
DESIGN CONSIDERATIONS
CANNISTER INSTALLATION

COMBUSTOR STABILITY

COMBUSTOR SIZING

INJECTION ELEMENT/ARRANGEMENT SELECTION

OPERATING CONDITIONS

GAS GENERATOR INJECTOR
GAS GENERATOR OPERATING CONDITIONS

THESE PARAMETERS ARE THE PRIMARY GG OPERATING CONDITIONS FOR THE SIX STBE (1995 IOC) ENGINES. TYPE OF FUEL, OPERATING CHAMBER PRESSURE, FUEL INJECTION STATE, AND HOT GAS TEMPERATURE REQUIREMENTS ARE SOME OF THE MORE SIGNIFICANT ITEMS FOR THIS STUDY.
| G6 | G6S | 1175 | 5040 | 0.46 | 32 | 10 | 0.32 | 0.030 | 5.0 | 44.8 | 1.65 | 5.34 | 2.34 | 41.94 | 4.998 | 2820 | 0.272 | 1.11 | 46 | 29 | 38 | 96 | 5 | 3 | 6 | 1 | 2 | 4 | 3 |
|----|-----|------|------|------|----|----|------|-------|----|------|-----|-----|-----|-------|------|------|-------|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

**Engine Configuration Number**

**T/C Propellant Combination**

**G6 Fuel Propellant**

**G6 Oxidizer Propellant**

**FUEL INJ STATE**

- T INJ Fl. *R*
- P INJ Fl. *Psia*
- T INJ Ox. *R*
- P INJ Ox. *Psia*
- MR O/F
- W FL lbs/s
- W Ox lbs/s

**PC. Psia**

**EXHAUST TEMP. °R**

**GAS GENERATOR OPERATING CONDITIONS**
GAS GENERATOR INJECTION ELEMENT SELECTION

THIS CHART PRESENTS THE TYPE OF INJECTION ELEMENT SELECTED AS BASELINE FOR EACH OF THE 6 ENGINES. A LIKE IMPINGING DOUBLET IS SHOWN FOR THE TWO LIQUID/LIQUID GG INJECTORS AND A COAXIAL ELEMENT SELECTED FOR THE GAS/LIQUID INJECTORS.
<table>
<thead>
<tr>
<th>ENGINE NUMBER</th>
<th>MAIN FUEL</th>
<th>NOZZLE/CHAMBER COOLANT</th>
<th>GG FUEL</th>
<th>PROPellant INJECTION STATE</th>
<th>GG INJECTOR ELEMENT TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RP-1</td>
<td>RP-1</td>
<td>RP-1</td>
<td>LIQ/LIQ</td>
<td>LIKE MP</td>
</tr>
<tr>
<td>2</td>
<td>CH₄</td>
<td>H₂</td>
<td>CH₄</td>
<td>LIQ/GAS</td>
<td>COAX</td>
</tr>
<tr>
<td>3</td>
<td>CH₄</td>
<td>H₂</td>
<td>CH₄</td>
<td>LIQ/GAS</td>
<td>COAX</td>
</tr>
<tr>
<td>4</td>
<td>C₂H₂</td>
<td>H₂</td>
<td>C₂H₂</td>
<td>LIQ/LIQUID</td>
<td>LIQ/GAS</td>
</tr>
<tr>
<td>5</td>
<td>H₂</td>
<td>H₂</td>
<td>H₂</td>
<td>LIQ/LIQUID</td>
<td>LIQ/GAS</td>
</tr>
<tr>
<td>6</td>
<td>CH₄</td>
<td>H₂</td>
<td>CH₄</td>
<td>LIQ/LIQUID</td>
<td>LIQ/GAS</td>
</tr>
</tbody>
</table>
BASELINE ELEMENT SELECTION RATIONALE

RATIONAL FOR SELECTING THE BASELINE GG INJECTOR ELEMENTS ARE PRESENTED. THE LIKE DOUBLETS ARE SELECTED BECAUSE OF FAVORABLE PRIOR EXPERIENCE, WALL COMPATIBILITY, GOOD STABILITY HISTORY, AND POTENTIALLY GOOD ATOMIZATION AND MIXING. THE COAXIAL ELEMENTS ARE SELECTED FOR BASICALLY THE SAME REASONS BUT WITH GAS/LIQUID PROPELLANTS.
AND SMALL ELEMENTS
ATOMIZATION AND MIXING VERY GOOD WITH HIGH AV
STABILITY
VERY GOOD WALL CAPABILITY
EXPERIENCE

COAXIAL - GAS/LIQUID

WITH SIZING AND FAN ORIENTATION
GOOD ATOMIZATION AND MIXING CAN BE ACHIEVED
STABILITY
GOOD WALL COMPATIBILITY
EXPERIENCE

LIKE DOUBLETS - LIQUID/LIQUID

RATIONALE
BASELINE CG ELEMENT SELECTION
LIQUID/LIQUID G6 INJECTOR BASELINE PATTERN

THE LIQUID DOUBLE ELEMENT AND A TYPICAL ELEMENT ARRANGEMENT ARE SHOWN BY THESE SKETCHES.
ELEMENT

FUEL

OX

OR

DOUBLET LIKE

(1 ON I)

ENGINES 1 AND 2

LIQUID/LIQUID CG INJECTOR BASELINE PATTERN
The coaxial element and a typical coaxial element arrangement are pictured for the gas/liquid GG injectors.
ENGINE 3, 4, 5, AND 6
GAS/LIQUID CG INJECTOR BASELINE PATTERN
GAS GENERATOR COMBUSTOR DESIGN CONSIDERATIONS

PRIMARY GG COMBUSTOR DESIGN CONSIDERATIONS ARE PRESENTED FOR THE STBE STUDY. THESE INCLUDE THE OPERATING REQUIREMENTS AND CONFIGURATION FEATURES SUCH AS SIZE, SHAPE, AND MIXING ENHANCEMENT FEATURES TO OBTAIN A UNIFORM GAS TEMPERATURE
FLOW DIRECTION CHANGE
TURBULENCE RING
MIXING ENHANCEMENT DEVICES
DIMENSION — INJECTION ELEMENT PATTERN
LENGTH/VOLUME — STAY TIME
SIZE — ALLOW FOR COMPLETE COMBUSTION
AXIAL/SIDE OUTLET
REVERSE FLOW
AXIAL FLOW
SHAPE — MAXIMIZE MIXING/MINIMIZE HOT SPOTS

CONFIGURATION

INTERFACE WITH TURBINE
TURBINE DELIVER UNIFORM HOT-GAS (COMPLETE COMBUSTION)
FORCE MIXING OF FUEL RICH PROPELLANTS
FACILITATE AUTOMATION BY CONTROLLING VELOCITIES

OPERATING REQUIREMENTS

DESIGN CONSIDERATIONS
GAS GENERATOR COMBUSTOR
CANDIDATE GAS GENERATOR COMBUSTORS

SOME TYPICAL GAS GENERATOR COMBUSTORS ARE SHOWN. THE ACTUAL COMBUSTOR SELECTION WILL BE ACCOMPLISHED AFTER THE TURBINE AND ENGINE INTERFACES HAVE BEEN DEFINED.
GAS GENERATOR ASSEMBLY TRADE STUDIES

This flow diagram shows the sequence of events to be used during the gas generator assembly trade studies. Injector element type and arrangement have been completed. Injector element sizes, combustor sizes, and stability aids are established next. The tradeoff is to vary the combustor sizes and the injector element sizes to optimize the assembly. Cost, weight, and risk factors are assessed relative to the combustor/injector size changes. Also, engine and vehicle life cycle costs are compared. The end results will be to select the optimum GG assembly for each engine configuration.
GAS GENERATOR ASSEMBLY TRADE STUDY
IGNITION SYSTEMS CONSIDERED

A LIST OF 6 CANDIDATE IGNITION SYSTEMS WERE SELECTED FOR STBE CONSIDERATION AS FOLLOWS.
IGNITION SYSTEMS CONSIDERED

HYPERGOLIC OXIDIZER •

COMBUSTION WAVE •

DIRECT SPARK •

PYROTECHNIC •

SPARK TORCH •

HYPERGOLIC FUEL •
IGNITION SYSTEM TRADE FACTORS

KEY TRADE FACTORS THAT WERE USED FOR THE IGNITION SYSTEM STUDIES ARE LISTED ON THIS CHART.
SAFETY

HEALTH MONITORING (IGNITION DETECT)

RELIABILITY

COMPLEXITY

EXTERNAL POWER

WEIGHT

COST

DEVELOPMENT MATURITY

IGNITION SYSTEM TRADE FACTORS
MAIN CHAMBER IGNITION SYSTEM SELECTION

THE FOLLOWING CHART PRESENTS THE MAIN CHAMBER IGNITION SYSTEM STUDY CONCLUSIONS FOR THE CANDIDATE ENGINE CONCEPTS. THE CONCLUSIONS ARE PRESENTED RELATIVE TO EACH OF THE TRADE FACTORS. LOX/C₃H₈ AND LOX/CH₄ FOR ENGINES 2, 5 & 6 WERE ASSUMED TO BE SIMILAR TO LOX/RP-1. AS A RESULT OF THIS STUDY IT WAS CONCLUDED THAT A HYPERGOLIC FUEL SYSTEM IS BEST FOR THE LOX/RP-1, LOX/C₃H₈, AND LOX/CH₄ MAIN CHAMBERS FOR ENGINE #1, 2, 4, 5 & 6. A SPARK TORCH SYSTEM BEST FOR THE LOX/CH₄ MAIN CHAMBER FOR ENGINE #3.
HYPERGOLUM SYSTEM CAN BE DEVELOPED TO WORK WITH CRYSOFICE FUELS (C²H₆ AND C₃H₆)

<table>
<thead>
<tr>
<th>LOX/CH₄</th>
<th>LOX/C²H₆ AND LOX/CH₄</th>
<th>LOX/CH₄</th>
<th>Engine 3</th>
<th>Engine 2</th>
<th>Engine 1 AND 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>DETECTOR SWITCH</td>
<td>LOX</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>THROUGH ANALYSIS</td>
</tr>
<tr>
<td>HIGH</td>
<td>EX REORDER SWITCH</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>HYPERGOLUM FUEL</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
</tr>
</tbody>
</table>

RECOMMENDED SYSTEM

MAIN CHAMBER IGNITION SYSTEM SELECTION
GAS GENERATOR IGNITION SYSTEM SELECTION

THIS CHART PRESENTS THE GAS GENERATOR IGNITION SYSTEM STUDY CONCLUSIONS RELATIVE TO EACH OF THE TRADE FACTORS. CONCLUSIONS FROM THESE STUDIES SUGGESTS THAT PYROTECHNIC IGNITION IS BEST FOR ENGINES #1 AND 2 AND SPARK TORCH BEST FOR ENGINES #3 - 6.
<table>
<thead>
<tr>
<th>ENGINE</th>
<th>RECOMMENDED SYSTEM</th>
<th>PYROTECHNIC DEVELOPMENT</th>
<th>SPARK TORCH DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TO BE SIMILAR TO LOX/RP-1</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>2</td>
<td>LOW</td>
<td>MODERATE</td>
<td>TIP*</td>
</tr>
<tr>
<td>3</td>
<td>LOW</td>
<td>MODERATE</td>
<td>TIP*</td>
</tr>
<tr>
<td>4, 5, 6</td>
<td>LOW</td>
<td>MODERATE</td>
<td>INHERENT</td>
</tr>
</tbody>
</table>

* LOX/CH₄, GG IGNITION ASSUMED TO BE SIMILAR TO LOX/RP-1, LOX/CH₄, GG IGNITION ASSUMED.
SUMMARY
CONTROL SYSTEM AND HEALTH MONITOR STUDIES
R. BREWSTER
D. NGUYEN
W. BISSELL
J. THORNTON ON-DESIGN/OFF-DESIGN STUDY
P. MEGHAN
COMBUSTION DEVICES STUDIES
A. EASTLAND
TURBOMACHINERY STUDIES
A. WEISS
SUBSYSTEM OPTIMIZATION APPROACH
A. WEISS

TASK 1 SUMMARY
A. WEISS
F. KIRBY

TASK 2 STATUS REVIEW
A. WEISS

AGENDA
SECOND QUARTERLY REVIEW
STBE CONFIGURATION STUDY
TASK 2 - SYSTEM ANALYSES
FLOW DIAGRAM

IN THE THROTTLING ENGINE ANALYSIS BRANCH OF THE TASK 2 FLOW DIAGRAM, THE DESIGN POINT ANALYSIS PROVIDES DATA TO THE OFF-DESIGN ANALYSIS WHICH, IN TURN, PROVIDES THE REQUIREMENTS FOR THE CONTROLS ANALYSIS. THE LATTER PROVIDES COMPONENT OPTIONS TO THE LIFE CYCLE ANALYSIS, WHERE THOSE OPTIONS ARE EVALUATED AND FINAL COMPONENT SELECTIONS ARE MADE. NOTE THAT THE CONTROL ANALYSIS HAS 2 BRANCHES; ONE IN WHICH THE CONTROLS ARE SELECTED FOR EACH INDIVIDUAL ENGINE, AND ONE IN WHICH THE GENERAL CONTROL SYSTEM COMPLEXITY (APPLICABLE TO ALL ENGINES) IS EXPLORED.
TASK 2 — SYSTEM ANALYSES FLOW DIAGRAM
THROTTLING ENGINE COMPONENT SELECTION

THE PRELIMINARY COMPONENT SELECTIONS FOR THE THROTTLEABLE ENGINES ARE SHOWN. THESE WERE USED TO GENERATE THE THROTTLEABLE ENGINE DESIGN POINT BALANCES. THE ONLY ISSUE THAT IS SOMewhat IN QUESTION IS THE CHAMBER PRESSURE DESIGN CRITERION. THE RESOLUTION OF THIS ISSUE IS DISCUSSED ON THE NEXT FEW CHARTS.
<table>
<thead>
<tr>
<th>Reason</th>
<th>Type/Value</th>
<th>Component/Parameter</th>
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</thead>
<tbody>
<tr>
<td>Performance related criteria, all component weights reflect 760K stresses</td>
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<tr>
<td>High performance, high performance, high performance</td>
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<tr>
<td>Tip speed limit at 760K</td>
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<tr>
<td>3 stage LH2 pump</td>
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<tr>
<td>Maximum Isopac AT 760K</td>
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<tr>
<td>g psia at 625K</td>
<td>g at 625K</td>
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<td>0.2 AT 625K</td>
<td>0.1 AT 760K</td>
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<td>T/C MR control</td>
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<td>Cooling Jacket 100 million life</td>
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<td>Minimum injector AP/PP</td>
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<td>Minimum value AP/PP</td>
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<td>Chamber pressure design</td>
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<tr>
<td>LH2-cooled</td>
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</table>

For LOX/RP-1 and LOX/CH4 engines

Throttling Engine component selection
GG CYCLE PERFORMANCE OPTIMIZATION

For LH₂-cooled GG cycle engines, performance increases steadily with chamber pressure until the LH₂ pump tip speed limit is reached. Because that tip speed is highest at the 750K operating condition, that point is the 750K operating point, and the 625K operating condition is obtained by throttling the engine to a lower chamber pressure.

For fuel-cooled GG cycle engines, the trend is not as obvious because the peak performance occurs at the peak of a very flat curve. At this optimum chamber pressure, engine weight is increasing and propellant bulk density is decreasing. Both of these could significantly effect the engine chamber pressure selection because the performance curve is so flat. Also, for an engine with two operating points, there is a question as to the operating point at which to optimize the performance.
EFFECT OF FUEL-COOLED ENGINE CHAMBER PRESSURE
ON SPECIFIC IMPULSE

TO DETERMINE THE APPROPRIATE APPROACH FOR SETTING THE CHAMBER PRESSURE FOR FUEL-COOLED ENGINES, 750K FUEL-COOLED LOX/RP-1 DESIGNS WERE ESTABLISHED AS A FUNCTION OF PC, AND EACH WAS THROTTLED DOWN TO 625K. THE RESULTING PERFORMANCES ARE SHOWN HERE. EACH DASHED LINE CONNECTS A 750K OPERATING POINT TO THE 625K OPERATING POINT FOR THAT SAME ENGINE. THIS FIGURE SHOWS THAT THROTTLING IMPROVES VACUUM PERFORMANCE SLIGHTLY, AND SIGNIFICANTLY DECREASES SEA LEVEL PERFORMANCE.
EFFECT OF FUEL-COOLED ENGINE CHAMBER PRESSURE ON SPECIFIC IMPULSE
ENGINE PERFORMANCE FOR VEHICLE DESIGN CONDITION

THE VEHICLE DESIGN CONDITION OCCURS AT THE ENGINE OPERATING CONDITION THAT YIELDS THE WORST OVERALL PERFORMANCE. FOR A VEHICLE WITH AN ENGINE OUT CAPABILITY, THIS CONDITION OCCURS WHEN THE ENGINE GOES OUT AT THAT ALTITUDE AT WHICH THE PERFORMANCE FOR ALL ENGINES OPERATING EQUALS THAT FOR ONE ENGINE OUT. THIS RESULTS IN OPERATION AT THE LOWEST OF THE PERFORMANCE CURVES OVER THE ENTIRE FLIGHT TRAJECTORY.
THESE ARE THE ANALYTICAL RELATIONSHIPS THAT WERE USED TO EVALUATE THE IMPACT OF FUEL-COOLED ENGINE CHAMBER PRESSURE ON THE VEHICLE. THE FIRST IS AN APPROXIMATION OF THE AVERAGE ENGINE SPECIFIC IMPULSE THAT OCCURS AS THE ENGINE PASSES FROM SEA LEVEL TO ALTITUDE AT THE PREVIOUSLY DESCRIBED VEHICLE DESIGN CONDITION. THE SECOND IS THE EXPRESSION FOR THE PROPELLANT BULK DENSITY FOR ENGINES THAT ARE NOT HYDROGEN COOLED. THE THIRD IS THE RELATIVE VEHICLE INERT WEIGHT EXPRESSION THAT TRANSLATES THE ENGINE PARAMETERS INTO VEHICLE INERT WEIGHT WHICH, IN TURN, IS AN INDICATOR OF RELATIVE VEHICLE COST.
VEHICLE EXCHANGE FACTOR FROM STAS CONTRACTORS

\[
\frac{d_e}{\text{MRE} + 1} = \frac{d_o}{\text{MRE} + 1} \cdot \left(15\text{ps/lmin} + 0.75(\text{ispavcmin} - 15\text{ps/lmin})\right)
\]

\[
\text{VEHICLE AV\text{INF}_{EF} = -6.38(\text{ispavc} - \text{ispavc\text{AVG}}) + 1.61(6)\text{W} - \text{REF} - 8.48(d_b - \text{REF})}
\]

ANALYTICAL RELATIONSHIPS
EFFECT OF DESIGN CHAMBER PRESSURE ON VEHICLE INERT WEIGHT FOR FUEL-COOLED, LOX/RP-1, GG CYCLE ENGINES

This curve shows how the vehicle inert weight at the vehicle design condition varies with design chamber pressure when the engines are operating at 750k. It also shows that the engine design chamber pressure at which optimum vacuum specific impulse ($I_{sp_{vac}}$) occurs also yields very close to the minimum vehicle inert weight. It may then be concluded that optimizing $I_{sp_{vac}}$ at 750k is a satisfactory design chamber pressure selection criterion for fuel-cooled GG cycle engines.
Design Chamber Pressure at 750k Operating Condition, psia

Isp VAC at 750k
Optimum

Vehicle Inert Weight
Yields Closest to Minimum
for Vacuum Isp at 750k
The Fue1-cooled Engine Optimized
Conclusion:

LOX/Rp-1, Rp-1 cooled
Inert Weight for Engine
Effect of Design Chamber Pressure on Vehicle
FUEL-COOLED THROTTLING ENGINE BALANCE SUMMARY

THIS IS THE RESULTING THROTTLING ENGINE BALANCE SUMMARY, AT 750K SEA LEVEL THRUST, FOR ENGINES 1 AND 3, WHICH ARE RP-1-COOLED LOX/RP-1 AND CH₄-COOLED LOX/CH₄ GAS GENERATOR CYCLES, RESPECTIVELY. OF THE SIMPLE GG CYCLE ENGINES, THESE REPRESENT THE HIGHEST AND THE LOWEST FUEL (AND COOLANT) DENSITIES.
<table>
<thead>
<tr>
<th>ENGINE (C-G)</th>
<th>ENGINE (C-RP-1)</th>
<th>ENGINE PARTNER DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2000</td>
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<tr>
<td>607</td>
<td>607</td>
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<td>450</td>
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<td>136.7</td>
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<tr>
<td>750.9</td>
<td>750.9</td>
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</tr>
<tr>
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<td>641.2</td>
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</tr>
<tr>
<td>1845.2</td>
<td>1845.2</td>
<td></td>
</tr>
<tr>
<td>762.2</td>
<td>762.2</td>
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<tr>
<td>0.315</td>
<td>0.315</td>
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<td>160.71</td>
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<td>358.10</td>
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<td>310.21</td>
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**Balance Summary**

Fuel-Coolled Throttling Engine
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LOX/CH4</th>
<th>LOX/RP-1</th>
<th>Engine Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Weight (lb)</td>
<td>7713</td>
<td>7354</td>
<td>7713</td>
</tr>
<tr>
<td>Hot Horsepower (hp)</td>
<td>39,218</td>
<td>60,315</td>
<td>39.218</td>
</tr>
<tr>
<td>Hot Horsepower (%)</td>
<td>76.94</td>
<td>60,315</td>
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<tr>
<td>Hot Efficiency (%)</td>
<td>N/A</td>
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<td>N/A</td>
</tr>
<tr>
<td>Hot Efficiency (%)</td>
<td>72.19</td>
<td>62.82</td>
<td>72.19</td>
</tr>
<tr>
<td>Hot Efficiency (%)</td>
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<td>62.82</td>
<td>71.99</td>
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<td>Hot Efficiency (%)</td>
<td>68.39</td>
<td>62.82</td>
<td>68.39</td>
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<tr>
<td>Hot Efficiency (%)</td>
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<td>Hot Efficiency (%)</td>
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<td>Hot Efficiency (%)</td>
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<tr>
<td>Hot Efficiency (%)</td>
<td>18.62</td>
<td>62.82</td>
<td>18.62</td>
</tr>
<tr>
<td>Fuel Pump Speed (rpm)</td>
<td>8.0/7.4</td>
<td>12.6/3.2</td>
<td>8.0/7.4</td>
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<tr>
<td>GG OXIDIZER INJECTOR AP (psid/%P)</td>
<td>59/2.4</td>
<td>59/2.4</td>
<td>GG OXIDIZER INJECTOR AP (psid/%P)</td>
</tr>
<tr>
<td>GG FUEL INJECTOR AP (psid/%P)</td>
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<td>59/2.4</td>
<td>GG FUEL INJECTOR AP (psid/%P)</td>
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<tr>
<td>MAIN OXIDIZER INJECTOR AP (psid/%P)</td>
<td>59/2.4</td>
<td>59/2.4</td>
<td>MAIN OXIDIZER INJECTOR AP (psid/%P)</td>
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<tr>
<td>MAIN FUEL INJECTOR AP (psid/%P)</td>
<td>59/2.4</td>
<td>59/2.4</td>
<td>MAIN FUEL INJECTOR AP (psid/%P)</td>
</tr>
</tbody>
</table>

_Fuel-Cooled Thrustling Engine (Continued)_

Balance Summary
LH₂-COOLED THROTTLING ENGINE BALANCE SUMMARY

These are the corresponding balances for the corresponding hydrogen cooled engines, which are engines 4 and 6 (LOX/RP-1 and LOX/CH₄, respectively). Of the hydrogen-cooled GG cycle engines, these have the highest and the lowest thrust chamber fuel densities.

The component selection and selection procedures are similar to those for the previous fuel-cooled engines. As discussed earlier, the procedure for optimizing the 750K engine for vacuum performance is different. For hydrogen-cooled engines, the maximum performance occurs at the hydrogen pump tip speed limit which, in turn, occurs at the maximum thrust operating point, which is 750K.
<table>
<thead>
<tr>
<th>Engine Parameter Description</th>
<th>LOX/CH4/LH2</th>
<th>LOX/RP-1/LH2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Balance Summary</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH-2 COOLED THRUSTING ENGINE</td>
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</table>

### Engine Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LOX/CH4/LH2</th>
<th>LOX/RP-1/LH2</th>
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</thead>
<tbody>
<tr>
<td>GG Temperature (°F)</td>
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<tr>
<td>Nozzle Jacket Discharge Temperature (°F)</td>
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<tr>
<td>Combustor Jacket Discharge Temperature (°F)</td>
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</tr>
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<td>GG Gas Flow Rate (lb/s)</td>
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<tr>
<td>LH2 Flow Rate (lb/s)</td>
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<td>GG Mixture Ratio (o/F)</td>
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<table>
<thead>
<tr>
<th>(ENGINE 6)</th>
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<td>LOX/CH4/LH2</td>
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</table>

<table>
<thead>
<tr>
<th>Engine Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOX/CH4/LH2</td>
</tr>
</tbody>
</table>

**LH2-Cooled Throttling Engine**

**Balance Summary**

(continued)
PRELIMINARY STEADY-STATE OFF-DESIGN STUDY
FOR LOX/RP-1 AND LOX/CH₄
FUEL-COOLED GAS GENERATOR CYCLES

THIS SECTION PRESENTS THE PRELIMINARY STEADY-STATE OFF-DESIGN STUDY
CONDUCTED FOR THE FUEL-COOLED LOX/RP-1 (ENGINE 1) AND LOX/CH₄ (ENGINE 3)
ENGINES.
ENGINE 3 - LOX/CH₄, CH₄ COOLED

ENGINE 1 - LOX/RP-1, RP-1 COOLED

Preliminary state
OBJECTIVE AND ANALYTICAL APPROACH

These are the objective, criteria and analytical approach which were used in the preliminary steady-state off-design study for the fuel-cooled LOX/RP-1 and LOX/CH₄ engines.
DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS

PERFORM ENGINE THROTTLING PERFORMANCE ANALYSIS WITH

CONDUCT SENSITIVITY STUDY ON CONTROL VALUES

ENGINES

MODEL DETAILED STEADY-STATE OPERATION OF THE LOX/H2

UPGRADE EXISTING BOOSTER ENGINE OF DESIGN CODE TO

ANALYTICAL APPROACH

START/CUTOFF REQUIREMENTS

ENGINE SENSITIVITIES

MAXIMUM VALUE & MARGINS

MINIMUM PROPELLANT CONSUMPTION

MINIMUM VEHICLE INERT WEIGHT

ON:

SELECT THRUST AND MIXTURE RATIO CONTROL VALUES BASED

OBJECTIVE

OBJECTIVE AND ANALYTICAL APPROACH
ENGINE 1 FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE FUEL-COOLED LOX/RP-1 (ENGINE 1) ENGINE BEING STUDIED.
ENGINE 3 FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE FUEL-COOLED LOX/CH₄ (ENGINE 3) ENGINES BEING STUDIED. IT ALSO REPRESENTS THE LOX/C₃H₈ (ENGINE 2) ENGINE.
LH$_2$-COOLED ENGINE FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE LH$_2$-COOLED LOX/RP-1 (ENGINE 4), LOX/CH$_4$ (ENGINE 6) AND LOX/C$_3$H$_8$ (ENGINE 5) ENGINES BEING STUDIED.
LH2-COOLED ENGINE FLOW SCHEMATIC

ENGINES 4, 5, AND 6
OVERALL GROUND RULES/ASSUMPTIONS

These are the general ground rules and assumptions used in the preliminary steady-state off-design study for the fuel-cooled LOX/RP-1 and LOX/CH₄ engines.
ON-DESIGN OPERATING CONDITION

- CONSTANT BOOSTER ENGINE BURN TIME OF 160 s
- MINIMUM THRUST/MP THRUST VALVE ADP = 10% OF OPERATING PC
- MAINTAIN COOLANT FLOW SPLIT AT 50/50 OF ENGINE FLOW RATE
- KEEP CG TEMPERATURE LESS THAN OR EQUAL TO 200°F
- CG MIXTURE RATIO
- COOLANT FLOW SPLIT
- ENGINE OR T/C MIXTURE RATIO
- ENGINE THRUST

ENGINE PARAMETERS TO BE CONTROLLED:
- MUST COMPLETE THE MISSION WITH EITHER SIX OR FIVE ENGINES

OVERALL GROUNDRULES/ASSUMPTIONS
SENSITIVITY STUDY
GROUNDRULES/ASSUMPTIONS

THESE ARE THE GROUNDRULES AND ASSUMPTIONS USED ONLY IN THE SENSITIVITY STUDY FOR THE FUEL-COOLED LOX/RP-1 ENGINE.
COOLED LOX/CH4

LOX/RP-1, RP-1 COOLED

COOLED C3H8, C3H8 COOLED AND ENGINE 3 - LOX/CH4

EXPECT SIMILAR SENSITIVITIES FOR ENGINE 2

ONLY CONDUCT SENSITIVITY STUDY FOR ENGINE 1

NO CONSTRAINT ON T/L TEMPERATURE

VARY ONE VALUE AT A TIME AND REBALANCE THE ENGINE

GROUNDRULES/ASSUMPTIONS

SENSITIVITY STUDY
<table>
<thead>
<tr>
<th>DEPENDENT VARIABLES</th>
<th>INDEPENDENT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>GG TEMPERATURE</td>
<td>GG CHAMBER PRESSURE</td>
</tr>
<tr>
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<tr>
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<td>0.009</td>
<td>0.008</td>
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<td>GG Mixture RATIO</td>
<td>ENGINE Mixture RATIO</td>
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<tr>
<td>-0.076</td>
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<tr>
<td>GG GGOV</td>
<td>GG GGOV</td>
</tr>
<tr>
<td>0.443</td>
<td>0.290</td>
</tr>
</tbody>
</table>

*INFLUENCE COEFFICIENT = PERCENTAGE CHANGE IN DEPENDENT VARIABLE PER ONE PERCENTAGE CHANGE IN THE INDEPENDENT VARIABLE
ENGINE THRUST SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON ENGINE SEA LEVEL THRUST FOR THE FUEL-COOLED LOX/RP-1 ENGINE.
PERCENTAGE CHANGES IN S.L. THRUST

ENGINE THRUST SENSITIVITIES
T/C MIXTURE RATIO SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON T/C MIXTURE RATIO FOR THE FUEL-COOLED LOX/RP-1 ENGINE.
ENGINE MIXTURE RATIO SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON ENGINE MIXTURE RATIO FOR THE FUEL-COOLED LOX/RP-1 ENGINE.
PERCENTAGE CHANGES IN ENGINE MIXTURE RATIO

ENGINE MIXTURE RATIO SENSITIVITIES
THESE ARE THE EFFECTS OF THROTTLING VALVES ON GG TEMPERATURE FOR THE FUEL-COOLED LOX/JP-1 ENGINE.

GG TEMPERATURE SENSITIVITIES
PERCENTAGE CHANGES IN VALVE EFFECTIVE FLOW AREA

GGVYE

MOV, MIV-1/2

GGVYE

PERCENTAGE CHANGES IN GG TEMPERATURE

CG TEMPERATURE SENSITIVITIES
MAIN CHAMBER PRESSURE SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON MAIN CHAMBER PRESSURE FOR THE FUEL-COOLED LOX/RP-1 ENGINE.
PERCENTAGE CHANGES IN MAIN CHAMBER
PRESSURE

PERCENTAGE CHANGES IN MAIN CHAMBER
EFFECTIVE FLOW AREA

MAIN CHAMBER PRESSURE SENSITIVITIES
PERCENTAGE CHANGES IN GG CHAMBER PRESSURE vs. effective flow area

GGV
MFE-1/2
MOV
GGV

PERCENTAGE CHANGES IN GG CHAMBER PRESSURE SENSITIVITIES
PERFORMANCE SENSITIVITIES

These are the effects of throttling valves on average specific impulse for the fuel-cooled LOX/RP-1 engine.
PERCENTAGE CHANGES IN AVERAGE ISP

PERCENTAGE CHANGES IN VALVE EFFECTIVE FLOW AREA

GGFV, MPV-1, MOV, GGOV
SENSITIVITY STUDY
RESULTS/CONCLUSIONS

These are the results and conclusions from the preliminary sensitivity study conducted for the fuel-cooled LOX/RP-1 engine.
CONTROL
USE MFE-1 OR MFE-2 FOR COOLANT FLOW SPLIT

MIXTURE RATIO CONTROL
USE GGOV AND/OR GFFY FOR THRUST AND/OR GG

TRUE RATIO CONTROL
USE MFOV, MFE-1, OR MFE-2 FOR T/C OR ENGINE MIX.

AND GFFY THAN OTHER VALUES

AND GGOV THAN OTHER VALUES

GG TEMPERATURE IS MUCH MORE SENSITIVE TO GGOV

ENGINE THRUST IS MUCH MORE SENSITIVE TO GGOV

VALUES

SENSITIVE TO MFE-1, MFE-2, AND MOV THAN OTHER
T/C AND ENGINE MIXTURE RATIOS ARE MUCH MORE

RESULTS/CONCLUSIONS

SENSITIVITY STUDY
ENGINE THROTTLING PERFORMANCE ANALYSIS
GROUNDRULES/ASSUMPTIONS

THESE ARE THE GROUNDRULES AND ASSUMPTIONS USED IN THE ENGINE THROTTLING PERFORMANCE ANALYSIS FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH₄ ENGINES.
ON-DESIGN OPERATING CONDITION

625K NOZZLE AS "ON-DESIGN"
USE LOX/RP-1 ENGINE 1 AND LOX/CH4 ENGINE 3 WITH
CONSTANT BOOSTER ENGINE BURN TIME OF 160 S
ING PC
MINIMUM THRUST/MAJOR CONTROL VALVE ADP = 10% OF OPERAT.
RATE
MAINTAIN COOLANT FLOW SPLIT AT 50/50 OF ENGINE FLOW
KEEP GG TEMPERATURE LESS THAN OR EQUAL TO 200°F
FIXED THROTTLED THRUST = 625 KIU AT SEA LEVEL
ENGINES
MUST COMPLETE THE MISSION WITH EITHER SIX OR FIVE
GROUNDRULES/ASSUMPTIONS

ENGINE THROTTLING PERFORMANCE ANALYSIS
THrust And MIXture ratio CoNTrol oPtions For Throttling

These are the various thrust and mixture ratio control options being investigated for the fuel-cooled LOX/RP-1 and LOX/CH₄ engines at throttling condition.
# Thrust and Mixture Ratio Control Options

<table>
<thead>
<tr>
<th><strong>T/C or Engine Control</strong></th>
<th><strong>GG Mixture Ratio Used</strong></th>
<th><strong>MR Control</strong></th>
<th><strong>Engine Thrust Control</strong></th>
<th><strong>GGOV/GGFV Used</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option I:</strong></td>
<td>MOV used</td>
<td><strong>GGOV/GGFV</strong></td>
<td><strong>GG Mixture</strong></td>
<td><strong>GG Mixture</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>used</td>
<td>ratio controlled</td>
<td>ratio controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>GG Mixture</strong></td>
<td>NO. OF CONTROL VALVES</td>
<td>NO. OF CONTROL VALVES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ratio controlled</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ratio controlled</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ratio controlled</td>
<td>3</td>
<td>ratio controlled</td>
</tr>
</tbody>
</table>

*GG mixture ratio is controlled.*

**GG mixture ratio is not controlled.**

---

**Note:**

- Option I: MOV used, GGOV = Thrust Control, 2. MOV = MR Control, 3. MFV = COOLANT, 4. GGFV = GG MR Control.
- Option II: NO. OF CONTROL VALVES = 4.

**GGOV/GGFV** used for throttling.
LOX/RP-1 ENGINE 1 BALANCE SUMMARY
WITH T/C MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COoled LOX/RP-1 ENGINE WITH T/C MIXTURE RATIO CONTROL; I.E., CONSTANT T/C MIXTURE RATIO.
<table>
<thead>
<tr>
<th>Design</th>
<th>ON</th>
<th>THRUST AND MR CONTROL OPTION</th>
<th>WITH T/C MIXTURE RATIO CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>LOX/RP-1 ENGINES</td>
</tr>
<tr>
<td>Engine Parameter Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE FUEL FLOW RATE (lbs)</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE OXIDIZER FLOW RATE (lbs)</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GG TEMPERATURE (°F)</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T/C MIXTURE RATIO (O/F)</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE MIXTURE RATIO (O/F)</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GG CHAMBER PRESSURE (psia)</td>
<td>2468</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAIN CHAMBER PRESSURE (psia)</td>
<td>2468</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE SEA LEVEL Isp (sec)</td>
<td>316.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE Isp (sec)</td>
<td>316.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE VACUUM Isp (sec)</td>
<td>316.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENGINE VACUUM THUST (kN)</td>
<td>750.0</td>
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<td></td>
</tr>
<tr>
<td>ENGINE SEA LEVEL THRUST (kN)</td>
<td>750.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table includes various parameters such as fuel and oxidizer flow rates, engine temperatures, mixture ratios, chamber pressures, and sea level thrust, among others, for different designs.
LOX/RP-1 ENGINE 1 BALANCE SUMMARY
WITH ENGINE MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS
AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/RP-1 ENGINE
WITH ENGINE MIXTURE RATIO CONTROL; I.E., CONSTANT ENGINE MIXTURE RATIO.
<table>
<thead>
<tr>
<th>Number of Throttle Valve Used</th>
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</thead>
</table>

**Engine Oxidizer Flow Rate (lb/s):**

<table>
<thead>
<tr>
<th>Design</th>
<th>One</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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<td>1</td>
<td>1</td>
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</tbody>
</table>

**Engine Parameter Description**

**Engine Fuel Flow Rate (lb/s):**

<table>
<thead>
<tr>
<th>Design</th>
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<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Engine Temperature (°R):**

<table>
<thead>
<tr>
<th>Design</th>
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<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Engine Mixture Ratio (O/F):**

<table>
<thead>
<tr>
<th>Design</th>
<th>One</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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<td>1</td>
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</tbody>
</table>

**Engine Mixture Ratio (O/F):**

<table>
<thead>
<tr>
<th>Design</th>
<th>One</th>
<th>II</th>
<th>III</th>
<th>IV</th>
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<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Engine Chamber Pressure (psia):**

<table>
<thead>
<tr>
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<th>One</th>
<th>II</th>
<th>III</th>
<th>IV</th>
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<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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</tbody>
</table>

**Main Chamber Pressure (psia):**

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<tr>
<td>Thrust and MR Control Option</td>
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</tbody>
</table>

**Engine Sea Level ISP (s):**

<table>
<thead>
<tr>
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<th>III</th>
<th>IV</th>
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<tbody>
<tr>
<td>Thrust and MR Control Option</td>
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**Engine Vacuum ISP (s):**

<table>
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<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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<td>1</td>
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</table>

**Average ISP (s):**

<table>
<thead>
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<th>III</th>
<th>IV</th>
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<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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</table>

**Engine Vacuum Thrust (lbf):**

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<tr>
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<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
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<td>1</td>
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</tbody>
</table>

**Engine Sea Level Thrust (lbf):**

<table>
<thead>
<tr>
<th>Design</th>
<th>One</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust and MR Control Option</td>
<td>LOX/RP-1 Engine</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tbody>
</table>
LOX/CH$_4$ ENGINE 3 BALANCE SUMMARY
WITH T/C MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS
AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/CH$_4$ ENGINE
WITH T/C MIXTURE RATIO CONTROL; I.E., CONSTANT T/C MIXTURE RATIO.
<table>
<thead>
<tr>
<th>ENGINE PARAMETER DESCRIPTION</th>
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<tbody>
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<td>THRUST AND MR CONTROL OPTION</td>
<td>III</td>
</tr>
<tr>
<td>WITH T/C MIXTURE RATIO CONTROL</td>
<td>I</td>
</tr>
<tr>
<td>LOX/CH4 ENGINE 3 BALANCE SUMMARY</td>
<td>II</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Engine Parameter Description</th>
<th>Design On</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/C Mixture Ratio (O/F)</td>
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<tr>
<td>Engine Chamber Pressure (psia)</td>
<td>2941</td>
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<tr>
<td>Main Chamber Pressure (psia)</td>
<td>4517</td>
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<tr>
<td>Engine Sea Level ISP (s)</td>
<td>310.21</td>
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<td>Engine Vacuum ISP (s)</td>
<td>346.8</td>
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<tr>
<td>Average ISP (s)</td>
<td>337.75</td>
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<tr>
<td>Engine Vacuum Thrust (lbf)</td>
<td>383.66</td>
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<tr>
<td>Engine Sea Level Thrust (lbf)</td>
<td>750.00</td>
</tr>
</tbody>
</table>

Number of Thrustline Values Used (None)
LOX/CH$_4$ ENGINE 3 BALANCE SUMMARY
WITH ENGINE MIXTURE MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS
AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/CH$_4$ ENGINE
WITH ENGINE MIXTURE RATIO CONTROL; I.E., CONSTANT ENGINE MIXTURE RATIO.
<table>
<thead>
<tr>
<th>Number of Throttling Valves Used (None)</th>
<th>Engine Oxidizer Flow Rate (lb/s)</th>
<th>Engine Fuel Flow Rate (lb/s)</th>
<th>Engine Temperature (°F)</th>
<th>Engine Mixture Ratio (O/F)</th>
<th>Engine Mixture Ratio (O/F)</th>
<th>Main Chamber Pressure (psia)</th>
<th>GG Chamber Pressure (psia)</th>
<th>GG Temperature (°F)</th>
<th>Engine Sea Level ISP (s)</th>
<th>Engine Vacuum ISP (s)</th>
<th>Average ISP (s)</th>
<th>Engine Vacuum Thrust (kips)</th>
<th>Engine Sea Level Thrust (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>
EFFECT OF CONTROL OPTIONS ON ENGINE 1, LOX/RP-1, RP-1 COOLED WITH T/C MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/RP-1 ENGINE AT THROTTLING CONDITION WITH CONSTANT T/C MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE ΔP/Pc RATIO, T/C MIXTURE RATIO CONTROL VALVE ΔP/Pc, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND T/C MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION 1 WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/RP-1 ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.
EFFECT OF CONTROL OPTIONS ON ENGINE 1

LOX/RP-1, RP-1 COOLED T/C MIXTURE RATIO CONTROL

\[ \Delta W_{\text{INERT}} \text{ (lb)} \]

CONTROL OPTION

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (REF)</td>
<td>120</td>
<td>2250</td>
<td>2300</td>
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</tbody>
</table>

\[ \Delta W_p \text{ (lb)} \]

CONTROL OPTION

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<thead>
<tr>
<th>I</th>
<th>II</th>
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<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (REF)</td>
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<td>22470</td>
<td>23100</td>
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AVERAGE ISP (s)

CONTROL OPTION

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>316.1</td>
<td>315.9</td>
<td>312.8</td>
<td>312.7</td>
</tr>
</tbody>
</table>

BULK DENSITY (lb/ft³)

CONTROL OPTION

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.4</td>
<td>63.4</td>
<td>63.2</td>
<td>63.2</td>
</tr>
</tbody>
</table>

T/C MIXTURE RATIO

CONTROL VALVE \( \Delta P/P_c \) (%)

CONTROL OPTION

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>11</td>
<td>15</td>
<td>11</td>
</tr>
</tbody>
</table>

THRUSt CONTROL VALVE

\( \Delta P/P_c \) (%)

CONTROL OPTION

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>24</td>
<td>19</td>
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</tbody>
</table>
EFFECT OF CONTROL OPTIONS ON ENGINE 1
RP-1 COOLED WITH ENGINE MIXTURE RATIO CONTROL

This chart illustrates the effect of different thrust and mixture ratio control options on the fuel-cooled LOX/RP-1 engine at throttling condition with constant engine mixture ratio. It shows (clock-wise from top left) the average specific impulse, propellant bulk density, thrust control valve ΔP/Pc ratio, engine mixture ratio control valve ΔP/Pc, total propellant consumption and vehicle inert weight differentials vs. thrust and engine mixture ratio control options.

Control option 1 which results in minimum vehicle inert weight differential with adequate valve ΔP margins is selected for the fuel-cooled LOX/RP-1 engine. In addition, GG mixture ratio control is recommended for high engine performance.
ENGINE MIXTURE RATIO CONTROL VALVE

ENGINE MIXTURE RATIO CONTROL VALVE

ENGINE MIXTURE RATIO CONTROL VALVE

ENGINE MIXTURE RATIO CONTROL VALVE

THRUST CONTROL VALVE

THRUST CONTROL VALVE

THRUST CONTROL VALVE

THRUST CONTROL VALVE

BULK DENSITY (lb/ft³)

BULK DENSITY (lb/ft³)

BULK DENSITY (lb/ft³)

BULK DENSITY (lb/ft³)

AVERAGE ISP (s)

AVERAGE ISP (s)

AVERAGE ISP (s)

AVERAGE ISP (s)

LOX/RP-1', RP-1 COOLED

LOX/RP-1', RP-1 COOLED

LOX/RP-1', RP-1 COOLED

LOX/RP-1', RP-1 COOLED

EFFECT OF CONTROL OPTIONS ON ENGINE 1
EFFECT OF T/C AND ENGINE MIXTURE RATIO CONTROL ON ENGINE 1
AT NOMINAL/OFF-NOMINAL CONDITIONS WITH
SELECTED CONTROL OPTION I

THIS CHART ILLUSTRATES THE EFFECT OF T/C AND MIXTURE RATIO CONTROLS ON THE
FUEL-COOLED LOX/RP-1 ENGINE AT NOMINAL AND OFF-NOMINAL OPERATING
CONDITIONS. IT SHOWS (CLOCK-WISE FROM TOP LEFT) ENGINE MIXTURE RATIO,
AVERAGE SPECIFIC IMPULSE, VEHICLE INERT WEIGHT DIFFERENTIAL, TOTAL
PROPELLANT, LOX AND RP-1 CONSUMPTION DIFFERENTIALS VS. ENGINE OPERATING
CONDITIONS AND MIXTURE RATIO CONTROLS. THE CONTROL OPTION I SELECTED
PREVIOUSLY IS USED FOR THROTTLING; I.E., NOMINAL OPERATING CONDITION.
EFFECT OF T/C AND ENGINE MR CONTROL ON ENGINE 1 AT NOMINAL/OFF-NOMINAL CONDITIONS

ΔW_{FUEL} (lb)

ENGINE Mixture RATIO (O/F)

ΔW_{OXIDIZER} (lb)

AVERAGE ISP (s)

ΔW_{P} (lb)

ΔW_{INERT} (lb)

0 (REF)

1000

-1800

-34.530

-30.120

-40.190

0 (REF)

N/A

0

2.42

316.1

180
EFFECT OF CONTROL OPTIONS ON ENGINE 3, LOX/CH₄, CH₄ COOLED WITH T/C MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/CH₄ ENGINES AT THROTTLING CONDITION WITH CONSTANT T/C MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE ΔP/PC RATIO, T/C MIXTURE RATIO CONTROL VALVE ΔP/PC, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND T/C MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION II WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/CH₄ ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.
Effect of Control Options on Engine 3

LOX/CH₄, CH₄ COOLED

T/C MIXTURE RATIO CONTROL

CONTROL OPTION

Thrust Control Valve

Bulk Density (lb/ft³)

Average ISP (s)
EFFECT OF CONTROL OPTIONS ON ENGINE 3, LOX/CH₄,
CH₄ COOLED WITH ENGINE MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO
CONTROL OPTIONS ON THE FUEL-COOLED LOX/CH₄ ENGINE AT THROTTLING
CONDITION WITH CONSTANT ENGINE MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM
TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST
CONTROL VALVE ΔP/Pc RATIO, ENGINE MIXTURE RATIO CONTROL VALVE ΔP/Pc,
TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS.
THRUST AND ENGINE MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION II WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT
DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE
FUEL-COOLED LOX/CH₄ ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS
RECOMMENDED FOR HIGH ENGINE PERFORMANCE.
EFFECT OF CONTROL OPTIONS ON ENGINE 3

LOX/CH4, CH4 COOLED
ENGINE MIXTURE RATIO CONTROL

ENGINE MIXTURE RATIO CONTROL VALVE \( \Delta P/P_c \) (%)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 0
- 10
- 16

THRUST CONTROL VALVE \( \Delta P/P_c \) (%)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 10
- 16
- 31
- 31
- 34
- 34
- 31
- 31

AVERAGE ISP (s)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 327.3
- 328.8
- 334.8
- 334.3

BULK DENSITY (lb/ft³)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 48.9
- 48.9
- 48.9
- 48.9

\( \Delta W_{\text{INERT}} \) (lb)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 2130
- 1910

\( \Delta W_p \) (lb)

- CONTROL OPTION
  - I
  - II
  - III
  - IV

- (Ref)
- 18460
- 17570

86D-9-1877

Rockwell International
Rockford, Illinois

DI-53
EFFECT OF T/C AND ENGINE MIXTURE RATIO CONTROL
ON ENGINE 3 AT NOMINAL/OFF-NOMINAL CONDITIONS
WITH SELECTED CONTROL OPTION II

THIS CHART ILLUSTRATES THE EFFECT OF T/C AND MIXTURE RATIO CONTROLS ON THE
FUEL-COOLED LOX/CH₄ ENGINE AT NOMINAL AND OFF-NOMINAL OPERATING
CONDITIONS. IT SHOWS (CLOCK-WISE FROM TOP LEFT) ENGINE MIXTURE RATIO,
AVERAGE SPECIFIC IMPULSE, VEHICLE INERT WEIGHT DIFFERENTIAL, TOTAL
PROPELLANT, LOX AND CH₄ CONSUMPTION DIFFERENTIALS VS. ENGINE OPERATING
CONDITIONS AND MIXTURE RATIO CONTROLS. THE CONTROL OPTION II SELECTED
PREVIOUSLY IS USED FOR THROTTLING; I.E., NOMINAL OPERATING CONDITION.
CONTROL OPTION II
AT NOMINAL/OFF-NOMINAL CONDITIONS
EFFECT OF T/C AND ENGINE MR CONTROL ON ENGINE
RESULTS/CONCLUSIONS

THESE ARE THE RESULTS AND CONCLUSIONS FROM THIS PRELIMINARY STEADY-STATE OFF-DESIGN STUDY CONDUCTED FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH₄ ENGINES.
RESULTS/CONCLUSIONS

- RECOMMEND 6G MIXTURE RATIO CONTROL
- RECOMMEND COOLANT FLOW SPLIT CONTROL
- NEED T/C OR ENGINE MIXTURE RATIO CONTROL
- NEED ENGINE THRUST CONTROL

THE RATIO CONTROL
- THAT IS SLIGHTLY BETTER THAN THAT WITH ENGINE MIX-
- ENGINE PERFORMANCE WITH T/C MIXTURE RATIO CON-

- BENEFIT ON ENGINE PERFORMANCE
- GG MIXTURE RATIO CONTROL RESULTS IN SIGNIFICANT

- CANDIDATES
- THROTTLING REQUIREMENTS ARE MET BY BOTH ENGINE
RESULTS/CONCLUSIONS
(CONTINUED AND CONCLUDED)

THESE ARE THE THROTTLING VALVES RECOMMENDED FOR THE FUEL-COOL ED LOX/RP-1
(ENGINE 1), LOX/C_3H_8 (ENGINE 2) AND LOX/CH_4 (ENGINE 3) ENGINES.
LOX/CH₄ ENGINE

SELECT CONTROL OPTION II FOR LOX/CH₄ ENGINES 2 AND

SELECT CONTROL OPTION I FOR LOX/RP-1 ENGINE 1

(CONTINUED)

RESULTS/CONCLUSIONS
AGENDA

SECOND QUARTERLY REVIEW

STBE CONFIGURATION STUDY
FINAL SELECTION APPROACH

COMPONENT CANDIDATES

GROUND RULES

REQUIREMENTS

OBJECTIVE/APPROACH

MAINTENANCE SYSTEM AGENDA

CONTROL AND CONDITION
STBE CONTROL AND CONDITION MAINTENANCE
SYSTEM STUDIES

THIS CHART SUMMARIZES THE OBJECTIVE AND APPROACH TO CONDUCTING THE CONTROL AND CONDITION MAINTENANCE SYSTEM TRADE STUDIES. THE CONTROL SYSTEM ARCHITECTURE WILL BE COMMON TO ALL THE CONFIGURATIONS WHILE CERTAIN COMPONENT ELEMENTS WILL SERVE AS DISCRIMINATORS IN CHOOSING A OVERALL SYSTEM FOR EACH CONFIGURATION.
OPTIMUM SYSTEM FOR EACH CANDIDATE
PERFORM LIFE CYCLE COST ANALYSIS TO SELECT
COMPONENT SELECTION
GENERIC ARCHITECTURE
IDENTIFY CANDIDATE SYSTEMS
IDENTIFY REQUIREMENTS
APPROACH
FOR EACH CANDIDATE
SELECT OPTIMUM CONTROL SYSTEM CONFIGURATION
OBJECTIVE

SYSTEM STUDIES
STBE CONTROL AND CONDITION MAINTENANCE
CONTROL AND CONDITION MAINTENANCE SYSTEM
PERFORMANCE CONTROL REQUIREMENTS

THE NEEDED CONTROL AND CONDITION MAINTENANCE SYSTEM FUNCTIONS ARE DRAWN FROM
REQUIREMENTS DERIVED FROM ENGINE LEVEL REQUIREMENTS. THIS CHART SHOWS THE
PERFORMANCE CONTROL PARAMETERS.
<table>
<thead>
<tr>
<th>Functions</th>
<th>Requirement</th>
<th>Parameter</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Redundancy Management</td>
<td>FAIL-OP, FAILSAFE</td>
<td>CONTROL SYSTEM</td>
<td>CONTROL SYSTEM</td>
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<tr>
<td>High Order Language</td>
<td>CONTROL RESPONSE, ACCURACY</td>
<td>SHUTDOWN</td>
<td>SHUTDOWN</td>
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<tr>
<td>System Intelligence</td>
<td>CONTROL RESPONSE, ACCURACY</td>
<td>THRUST ILING</td>
<td>THRUST ILING</td>
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<tr>
<td>Feedback Capability</td>
<td>CONTROL RESPONSE, ACCURACY</td>
<td>START</td>
<td>START</td>
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<tr>
<td>Propellant Flow Control</td>
<td>COOLANT CONTROL</td>
<td>COOLANT FLOW</td>
<td>COOLANT FLOW</td>
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<tr>
<td>Closed Loop Control</td>
<td>MR CONTROL, ACCURACY</td>
<td>Mixture Ratio</td>
<td>Mixture Ratio</td>
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<td>THRUST</td>
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<td>THRUST</td>
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</table>

625 KLB or 75 KLB
CONTROL AND CONDITION MAINTENANCE SYSTEM
CONDITION MAINTENANCE REQUIREMENTS

THE CONDITION MAINTENANCE REQUIREMENTS LEAD TO FUNCTIONS WHICH WILL DETERMINE
HARDWARE HEALTH AND MAINTENANCE REQUIREMENTS RATHER THAN RELYING ON HARDWARE
INSPECTION.
<table>
<thead>
<tr>
<th>Function</th>
<th>Requirement</th>
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<td>Engine</td>
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<td>Prognostics</td>
<td>Monitoring Hardware Condition</td>
<td>Reliability</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Redline Monitoring, Self Test</td>
<td>Life</td>
</tr>
<tr>
<td>Expert System</td>
<td>Expendable Igniters, Engine Ready Signal</td>
<td>Self Diagnostic</td>
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<tr>
<td>Direct</td>
<td>Self Monitoring, Servicing</td>
<td>One Start Without Reserve</td>
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<tr>
<td>Performance</td>
<td>Minimize Pre-Launch</td>
<td>No Externai Redlines</td>
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<tr>
<td>Instrumentation</td>
<td>Servicing</td>
<td>Pre Start Conditioning</td>
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<td>Ground Servicing</td>
<td>24 Hours Of Loading</td>
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<td>No Servicing Within</td>
</tr>
</tbody>
</table>

CONDITION MAINTENANCE REQUIREMENTS

CONTROL AND CONDITION MAINTENANCE SYSTEM

OVERHAUL 25 MISSIONS TO 100 MISSIONS

START

PARAMETER
CONTROL AND CONDITION
MAINTENANCE SYSTEM PHILOSOPHY

THE OVERALL SYSTEM DESIGN PHILOSOPHY WILL BE A CLOSED LOOP SYSTEM WITH
PERFORMANCE CONTROL AND CONDITION MAINTENANCE ASPECTS.
MANAGEMENT SYSTEM PHIL "O S AY

CONTROL AND CONDITION
CONTROL AND CONDITION MAINTENANCE SYSTEM
GROUNDRULES

THIS CHART REFLECTS THE TECHNOLOGY LEVELS FOR THE 1985 AND 2000 ENGINES. THE
ADVANTAGES OF THESE TECHNOLOGIES ARE SHOWN FOR EACH OF THE MAJOR SYSTEM
FEATURES.
<table>
<thead>
<tr>
<th>Advantage</th>
<th>Fiber Optic</th>
<th>Copper</th>
<th>Interconnects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased Weight</td>
<td></td>
<td></td>
<td>Technology</td>
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<tr>
<td>Improved Signal Capabilities</td>
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<td></td>
<td>Microprocessor</td>
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<tr>
<td>Increased Throughput</td>
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<td></td>
<td>Performance</td>
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<tr>
<td>Increased Parallel Parameter</td>
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<td></td>
<td>Instrumentation</td>
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<tr>
<td>Improved Detection</td>
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<td>Control</td>
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<td>Enhanced Failure</td>
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<td>Propellant Flow</td>
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<td>Improved Maintenance</td>
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<td>Reduced System</td>
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<td>Electric</td>
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<td>Electric/Hydraulic</td>
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<thead>
<tr>
<th>Advantage</th>
<th>2000</th>
<th>1995</th>
<th>Features</th>
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<tbody>
<tr>
<td>Decreased Weight</td>
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<td>Improved Signal Capabilities</td>
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<tr>
<td>Electric/Hydraulic</td>
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</table>

**Groundrules**

**Control and Condition Maintenance System**
ADVANCED CONTROL EXTENDS LIFE AND IMPROVES PERFORMANCE

THIS CHART SHOWS HOW ADVANCED CONTROL TECHNIQUES CAN MORE CLOSELY CONTROL TO A GIVEN REQUIREMENT WHICH IMPROVES SYSTEM PERFORMANCE AND CAN INCREASE LIFE.
IMPROVES PERFORMANCE
ADVANCED CONTROLS EXTENDS LIFE AND
CONTROL SYSTEM FUNCTIONAL CAPABILITY vs COST

THE CAPABILITY REQUIRED OF AN ANALOG CONTROL SYSTEM MAKES IT COST PROHIBITIVE AS SHOWN BY THE EXPERIENCE CURVE. A DIGITAL SYSTEM HAS MORE FLEXIBILITY TO MEET MORE REQUIREMENTS FOR THE SAME COST.
CONTROL SYSTEM FUNCTIONAL CAPABILITY vs. COST
CONTROL METHODOLOGY/IMPLEMENTATION
COMPARISON

THE POSSIBLE CONTROL METHODOLOGIES FOR USE ON THE STBE ARE SHOWN ON THIS
CHART. A DIGITAL SYSTEM WILL BE REQUIRED TO TAKE ADVANTAGE OF THE ADVANCED
OPTIMAL AND ADAPTIVE TECHNIQUES.
SOFTWARE DEVELOPMENT vs MAINTENANCE COSTS

THE CHART SHOWS WHY A HIGHER ORDER SOFTWARE LANGUAGE IS NECESSARY. SINCE MAINTENANCE IS 70% OF THE LIFE CYCLE COST OF SOFTWARE, SUCH A LANGUAGE REDUCES THE EFFORT REQUIRED TO CHANGE OR CORRECT THE LOGIC.
HYDRAULIC - ELECTRIC ACTUATOR OPERATING REGIMES

Response Time (Milliseconds)

Operating Power Requirements

Hydraulic-Electric Actuator Operating Regimes

Total Envelope Nominal Power Supply Over
Hydraulic Actuators Have

(LB/SEC)

Flow Rate

Mass

(LB/SEC)

Nominal Size Power Supply
Electric Actuators

Nominal Size Power Supply
Electric Actuators

(Large Size Power Supply)
CONDITION MONITOR PARAMETER SUMMARY

CONDITION MAINTENANCE REQUIRES DIRECT MEASUREMENT OF KEY HARDWARE PARAMETERS. THIS CHART SHOWS EIGHT SUCH DIRECT MEASUREMENT TECHNOLOGIES UNDER DEVELOPMENT AT ROCKETDYNE. FOR EXAMPLE, THESE MEASUREMENTS WOULD ALLOW DELETION OF CERTAIN HARDWARE INSPECTIONS ON THE SSME.
<table>
<thead>
<tr>
<th>CONDITION MONITOR PARAMETER SUMMARY</th>
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<tbody>
<tr>
<td><strong>COMPARABLE</strong></td>
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<tr>
<td>SSME INSPECTIONS</td>
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<tr>
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<tr>
<td>SHAFT TRAVEL</td>
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<tr>
<td>BORE SCOPE</td>
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<td>TURBINE BLADES</td>
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<td>DISK, IMPPELLERS</td>
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<tr>
<td>LEAKAGE</td>
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<td>JOINTS, WELDS</td>
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<td>FATIGUE</td>
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<td>INJECTORS, NOZZLES</td>
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<td>TURBINE BLADES</td>
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</table>
Computing power (speed) of micro-processors has increased rapidly as engines become more complex the need for faster control systems to control and provide condition maintenance functions during normal and abnormal operational conditions has also increased.

In the early 1970's the initial micro-processors were 8 bit machines. With the advent of 16 bit machines in the late 1970's computing power increased 3 to 10 times. With the introduction of 32 bit micro-processors in 1984, such as the M68020 and the 80386-20 MHz, computing power has increased another 3 to 5 times over the 16 bit M68000-12 MHz and 80286-8MHz micro-processors. This increased computing power allows modern control and condition maintenance systems to be implemented in an effective and efficient manner for increased engine system effectiveness.
HAS INCREASED RAPIDLY
COMPUTING POWER (SPEED) OF MICRO-PROCESSORS
CONTROL AND CONDITION MAINTENANCE SYSTEM
1995 vs 2000 CONFIGURATION

THE CONTROL AND CONDITION MAINTENANCE SYSTEM TOP LEVEL SCHEMATIC IS SHOWN ON
THIS CHART. THE BASIC CLOSED LOOP CONTROL PORTION IS SHOWN INSIDE THE BLACK
BORDER. THE CONDITION MAINTENANCE PORTION FOR BOTH THE 1995 AND 2000 ENGINES
IS ALSO SHOWN. THIS BASELINE SYSTEM WILL BE COMMON TO ALL THE STBE CANDIDATE
CONFIGURATIONS.
CONTROL SYSTEM SENSITIVITY RESULTS

THESE ARE THE RESULTS OF THE CONTROL SENSITIVITY STUDY. THEY DEFINE REQUIREMENTS FOR WHICH CONTROL LOOPS ARE NEEDED AND WHICH VALVES HAVE TO BE CONTROLLED.
CONTROL SYSTEM SENSITIVITY RESULTS

LOX/CH4 ENGINE 3
SELECT CONTROL OPTION II FOR LOX/C3H8 ENGINE 2 AND

LOX/CH4 ENGINE 3
SELECT CONTROL OPTION I FOR LOX/RP-1 ENGINE 1

USE MFY-2 FOR COOLANT FLOW SPLIT CONTROL
USE GGY FOR GG MIXTURE RATIO CONTROL
USE MOV FOR T/C OR ENGINE MIXTURE RATIO CONTROL
USE GGV FOR THRUST CONTROL

USE MFY-1 FOR COOLANT FLOW SPLIT CONTROL
USE GGY FOR GG MIXTURE RATIO CONTROL
USE MFY-2 FOR T/C OR ENGINE MIXTURE RATIO CONTROL
USE GGV FOR THRUST CONTROL

USE MFY-1 FOR COOLANT FLOW SPLIT CONTROL
USE GGY FOR GG MIXTURE RATIO CONTROL
USE MOV FOR T/C OR ENGINE MIXTURE RATIO CONTROL
USE GGV FOR THRUST CONTROL
1995 CONTROL AND CONDITION MAINTENANCE DISCRIMINATORS

THE CONTROL AND CONDITION MAINTENANCE (CCM) COMPONENTS HAVE BEEN EVALUATED TO ESTABLISH HOW THEIR CHARACTERISTICS RELATE TO THE 1995 ENGINE CANDIDATES. AS A RESULT OF THIS EVALUATION, THE PRIMARY CCM COMPONENTS THAT WERE FOUND TO BE AFFECTED (DISCRIMINATED) BY THE CANDIDATE ENGINES ARE THE CCM CONTROL LOOPS, INSTRUMENTATION, VALVES AND ACTUATORS. THE EFFECT OF EACH OF THE ENGINE CANDIDATES ON EACH OF THESE CCM DISCRIMINATORS WILL BE DETERMINED TO DEFINE THE CCM SYSTEMS AFFECTS ON THE SELECTION OF THE 1995 ENGINE SYSTEM.
<table>
<thead>
<tr>
<th>Element</th>
<th>CONTROL LOOPS - QUANTITY</th>
<th>INSTRUMENTATION - QUANTITY</th>
<th>CONDITION MONITOR</th>
<th>PERFORMANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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**MANTENANCE DISCRIMINATORS**

1995 CONTROL AND CONDITION
1995 STBE CLOSED LOOP CONTROL DIAGRAM

ENGINE 1 FLOW SCHEMATIC
LOX/RP-1, RP-1 COOLED

THIS SCHEMATIC OF THE LOX/RP-1, RP-1 COOLED ENGINE SHOWS THE LOCATION OF THE PROPELLANT VALVES. THE SCHEMATIC ALSO AIDS IN DETERMINING WHAT PARAMETERS MAY HAVE TO BE MEASURED TO OPERATE EACH OF THE CONTROL LOOPS.
ENGINE 1 FLOW SCHEMATIC
LOX/RP-1, RP-1 COOLED
ENGINE 3 FLOW SCHEMATIC
LOX/CH₄, CH₄ COOLED

THIS IS THE SCHEMATIC OF THE LOX/METHANE, METHANE COOLED ENGINE. THE LOX/CH₃H₈ COOLED ENGINE ALSO HAS THE SAME SCHEMATIC.
LH$_2$ COOLED ENGINE FLOW SCHEMATIC
ENGINES 4, 5, AND 6

THIS SCHEMATIC COVERS THE THREE ENGINES WHICH ARE HYDROGEN COOLED.
LH2-COOLLED ENGINE FLOW SCHEMATIC

ENGINES 4, 5, AND 6

Rockwell International

PB-41
VALVE CANDIDATES

SIX DIFFERENT VALVE DESIGNS WERE EVALUATED FOR USE ON THE STBE. THE FIGURE SHOWS THE MAIN DESIGNS USED IN PAST AND CURRENT ROCKET ENGINES. FOUR OF THE SIX DESIGNS HAVE BEEN REJECTED FOR THE STBE FOR THE REASONS LISTED BELOW. THE NEEDLE VALVE WAS REJECTED BECAUSE IT IS APPLICABLE ONLY FOR EXTREMELY LOW FLOWRATES. THE VENTURI VALVE WAS REJECTED BECAUSE VENTURI VALVES OCCUPY A RELATIVELY LONG SPACE AND ARE MAINLY USED FOR FLOW LIMITATION. THE POPPET VALVE WAS REJECTED BECAUSE OF THE HIGH PRESSURE DROP ASSOCIATED WITH TURNING THE FLOW 90°. THE GATE VALVE WAS REJECTED BECAUSE ITS BULKY NATURE LIMITS IT TO LOW PROPELLANT FLOW APPLICATIONS AND IT IS DIFFICULT TO MEET NORMAL WEIGHT REQUIREMENTS.

THE BALL VALVE WAS CHOSEN AS A DESIGN CANDIDATE BECAUSE IT PERMITS IN LINE UNRESTRICTED FLOW. BALL VALVES ALSO ENHANCE STRUCTURAL SOUNDNESS FOR HIGH PRESSURE SERVICE AND CAN ALSO BE USED EFFECTIVELY FOR DEEP THROTTLING APPLICATIONS. FOR LARGE LINE DIAMETERS BALL VALVES BECOMES VERY BULKY AND HEAVY. CONSEQUENTLY THE BUTTERFLY VALVE WAS CHOSEN AS A POSSIBLE DESIGN FOR THE MAIN LOX VALVE. BESIDES HAVING A LOW PRESSURE DROP AND GOOD THROTTLING CHARACTERISTICS (SIMILAR TO A BALL VALVE), LARGE BUTTERFLY VALVES ARE EXTREMELY LIGHT WEIGHT AND COMPACT. SEALING PROBLEMS LIMIT THE USE OF BUTTERFLY VALVES FOR HIGH PRESSURE APPLICATION.
VALVE CANDIDATES
SUMMARY OF ACTUATOR CHARACTERISTICS

THE ADVANTAGES AND DISADVANTAGES OF PNEUMATIC, HYDRAULIC AND ELECTRIC ACTUATORS ARE SHOWN. IN GENERAL PNEUMATIC SYSTEM HAVE TOO GREAT A RESPONSE TIME FOR STBE CONTROL BUT MAY BE USEFUL AS EMERGENCY SHUTDOWN BACKUP. HYDRAULIC ACTUATORS HAVE FAST RESPONSE TIMES AND REASONABLE POWER SUPPLY REQUIREMENTS. THE ELECTRIC ACTUATION SYSTEM IS MOST ADVANTAGEOUS BUT REQUIRES A LARGE POWER SOURCE FOR HIGH MASS FLOW RATES.
### Summary of Actuator Characteristics

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Advantage</th>
<th>Disadvantage</th>
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#### Actuator Characteristics

1. Need working fluid
2. Need plumbing
3. Need thermal protection
4. Need seals
5. Need control components
6. Ease of modularizing
7. Fire hazard control
8. Compatiblity
9. Ramp rate control
10. slew rate capability
11. Magnitude of electrical supply
12. Size factor
ADVANCED ELECTRIC ACTUATED VALVE

THIS FIGURE SHOWS THE CONFIGURATION AND CHARACTERISTIC VALUES FOR A ROCKEDYNE ELECTRICALLY ACTUATED VALVE. THE ELECTRIC ACTUATOR IS MADE PRACTICAL BY REDUCED TORQUE DUE TO THE VALVE HEAD DESIGN AND A MORE POWERFUL ELECTRIC MOTOR USING RARE EARTH MATERIALS. CURRENT ESTIMATES SHOW THAT THIS TYPE OF VALVE/ACTUATOR CAN BE USED FOR ALL VALVES ON THE CANDIDATE ENGINE SYSTEMS WITH THE POSSIBLE EXCEPTION OF THE MAIN OXIDIZER VALVE. FURTHER STUDY IS NEEDED TO RESOLVE THIS QUESTION.
ADVANCED ELECTRIC ACTUATED VALVE

WEIGHT - 6.0 POUNDS

PRECISION
100° SEC WITH 0.1 DEGREE

CONTROL - MODULATING AT

SCREW LEVEL LINK

ELECTRIC MOTORS WITH BALL

ACTUATOR - DUAL RARE-EARTH

HE MAX

INTERNAL LEAKAGE - 100 SCFM

PRESSURE DROP - 580 PSI MAX

FLOW - 0.3 TO 28 LB SEC

PRESSURE - 2800 PSIG

FLUID - LIQUID OXYGEN

LINE SIZE - 0.06 INCH ID

REPLACEMENT ELEMENTS

SECTOR BALL VALVE WITH LINE
LIGHTWEIGHT, QUIET FLOW.

TYPE - DEEP THROTTLING.
LOX/CH₄, LOX/RP-1 TRANSIENT MODEL
START CHARACTERISTICS

THIS CHART PRESENTS A START TRANSIENT ANALYSIS PREVIOUSLY DONE FOR A
ROCKETDYNE IR&D PROGRAM. THIS TYPE OF ANALYSIS WILL HELP DISCRIMINATE BETWEEN
THE PROPELLANT COMBINATIONS AND WILL FURTHER DEFINE WHAT CONTROL LOOPS ARE
NECESSARY.
Spin start will shorten the engine start time and improves performance.

Helium spin improves the LOX/CH₄ engine start.

Results:

1) Reduced effort to compare possible booster/engine start sequences.

Task:

The turbine temperature limit

1) Main LOX valve throttling is needed to avoid main chamber combustion above.

2) Low density CH₄ printing presents difficulties in keeping GG mixture ratio below.

The design mixture ratio.

<table>
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<tr>
<th>Control (2, 1)</th>
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<th>LOX/RP-1 Tank Head</th>
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<tr>
<td>T/C MR Control (1)</td>
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<td>1.9</td>
<td>LOX/CH₄ Spin Start</td>
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Remarks:

Consumption LBS

Propellant time to 90% pc's

Case
CONTROL SYSTEM FINAL
CONFIGURATION SELECTION

AFTER THE DISCRIMINATORS HAVE BEEN DEFINED THE CONTROL SYSTEM ELEMENTS WILL BE
EVALUATED THROUGH A LIFE CYCLE COST ANALYSIS. THE OPTIMIZED ELEMENTS WILL BE
COMBINED WITH THE COMMON CONTROL SYSTEM ARCHITECTURE TO PRODUCE THE OPTIONAL
CONTROL SYSTEM FOR EACH CANDIDATE.
Reliability/Maintainability •
Risk •
Cost •
Weight •
Performance •

To Select Optimum System Elements
Utilize Life Cycle Cost Analysis •

Configuration Selection
Control System Final
SUMMARY
A. Weiss

CONTROL SYSTEM AND HEALTH MONITOR STUDIES
R. Brezster

D. Nguyen

THROTTLING ON-DESIGN/OFF-DESIGN STUDY
W. Bissell

COMBUSTION DEVICES STUDIES
P. Mekegan

TURBOMACHINERY STUDIES
A. Eastland

SUBSYSTEM OPTIMIZATION APPROACH
A. Weiss

TASK 2 STATUS REVIEW
A. Weiss

TASK 1 SUMMARY
F. Kirby

AGENDA
SECOND QUARTERLY REVIEW
STBE CONFIGURATION STUDY
• CONTROL SYSTEM STUDIES IN WORK

• INITIAL OFF-DESIGN STUDY EFFORT COMPLETE

• SYSTEM THROTTLING DESIGN POINT TRADEOFF COMPLETE

• PRELIMINARY INJECTOR PATTERNS SELECTED

• TURBOPUMP SCREENING COMPLETE FOR FOUR CONFIGURATIONS

SUMMARY