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HIGH VARIABLE MIXTURE RATIO* OXYGEN/HYDROGEN ENGINE

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ABSTRACT

The ability of an O_2/H_2 engine to operate over a range of high-propellant mixture ratios previously has been shown to be advantageous in single stage to orbit (SSTO) vehicles. This paper presents the results of the analysis of high-performance engine power cycles operating over propellant mixture ratio ranges of 12 to 6 and 9 to 6. A requirement to throttle to 60% of nominal thrust was superimposed as a typical throttle range to limit vehicle acceleration as propellant is expended. The object of the analysis was to determine areas of concern relative to component and engine operability or potential hazards resulting from the unique operating requirements and ranges of conditions that derive from the overall engine requirements.

The SSTO mission necessitates a high-performance, lightweight engine. Therefore, staged combustion power cycles employing either dual fuel-rich preburners or dual mixed (fuel-rich and oxygen-rich) preburners were examined.

Engine mass flow and power balances were made and major component operating ranges were defined. Component size and arrangement were determined through engine layouts for one of the configurations evaluated. Each component is being examined to determine if there are areas of concern with respect to component efficiency, operability, reliability, or hazard. The effects of reducing the maximum chamber pressure were investigated for one of the cycles.

INTRODUCTION

The approach taken in this effort was to first select two high-performing engine cycles potentially capable of meeting SSTO mission requirements. The configurations selected for analyses were both LOX/LH2 staged combustion cycle engines. A dual fuel-rich preburner engine and a dual mixed (fuel-rich and oxygen-rich) preburner were evaluated.

After selection of the cycles to be analyzed, operating ranges were defined and technology ground rules and limits established. In all cases studied, the on-design vacuum thrust at maximum mixture ratio (MR) was set at 580 Klbf and off-design vacuum thrust at 348 Klbf

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(60% NPL). Dual-bell or two-position extendable nozzles were assumed in all cases in order to provide high-vacuum and sea-level performances. Nozzle expansion ratios for altitude operation were established for each engine by fixing the one-dimensional exit (ODE) pressure at 1.33 psia. This value is equal to the ground rule which was in effect for the Space Transportation Main Engine (STME) at the initiation of this study. Current technology limits were adopted and are summarized in Table 1.

The first step in the analysis of each of the cycles was to generate an on-design engine balance at the high mixture ratio maximum thrust condition. This was done by exercising Rocketdyne's Booster Engine Optimization and Design computer program. Outputs from this code provide a power and mass balance within the allowable ground rules and technology limits for a given engine as described in an input file. In addition to top level data such as performance, envelope, and weight, this code provides a description of the engine in sufficient detail (combustor geometry, turbopump speeds and dimensions, etc.) to allow individual component analyses.

After generating the on-design engine balances for the candidate configurations, operation at the reduced MR and thrust conditions was then determined through the use of Rocketdyne's Booster Engine Off-Design Engine Model. The output from the on-design optimization code is used as an input to the off-design model. The off-design model then calculates the various system resistances for the propellant lines, coolant circuits, etc. and generates performance maps for the pumps and turbines. Then, by varying the engine control valve positions/resistances, the off-design code balances the engine at the requested operating condition, if a balance is achievable. As with the on-design code the off-design model output provides detailed information such as turbopump speeds and efficiencies. In addition, the main combustion chamber (MCC) and preburner injection pressure drops are calculated.

Table 1. Ground Rules and Technology Limits

Turbine Inlet Temperature, R	1600
Bearing DN, MM*RPM	No Limit (Hydrostatic)
Turbine Annulus Area*N**2 [(IN*RPM)**2]	8.0 E10
Turbine Pitch-Line Velocity, ft/sec	1600
Maximum Number of Pump Stages	4
Minimum Injection Pressure Drop, %	10% of Pc (P/B or MCC)

In many instances, an iterative approach was required in that off-design operation predicted injector pressure drops that were too low for combustion stability requirements. In these cases, it was necessary to go back to the on-design model and start over again. By increasing the injection pressure drops at full-thrust/high-mixture ratio operation, sufficient delta p (ΔP) at off-design operation was attained for combustion stability.

DUAL FUEL-RICH PREBURNER CYCLE

The first cycle analyzed was the dual fuel-rich preburner configuration with an on-design vacuum thrust of 580 Klbf and mixture ratio of 12.0. A schematic of this engine is provided in Figure 1. This engine incorporated a LOX boost pump to minimize the LOX main pump size and a LOX kick pump to raise the preburner LOX to the elevated pressures required. The use of the kick pump conserves turbine power requirements by taking advantage of the two pressure levels occurring on the LOX side of the cycle and ultimately increases achievable chamber pressure and performance. A four-stage fuel pump, single-stage LOX pump, and two-stage turbines are used. Six valves are incorporated in this configuration of which four are employed as control elements. Parallel flow hydrogen cooling circuits were used to provide optimum thrust chamber assembly cooling.

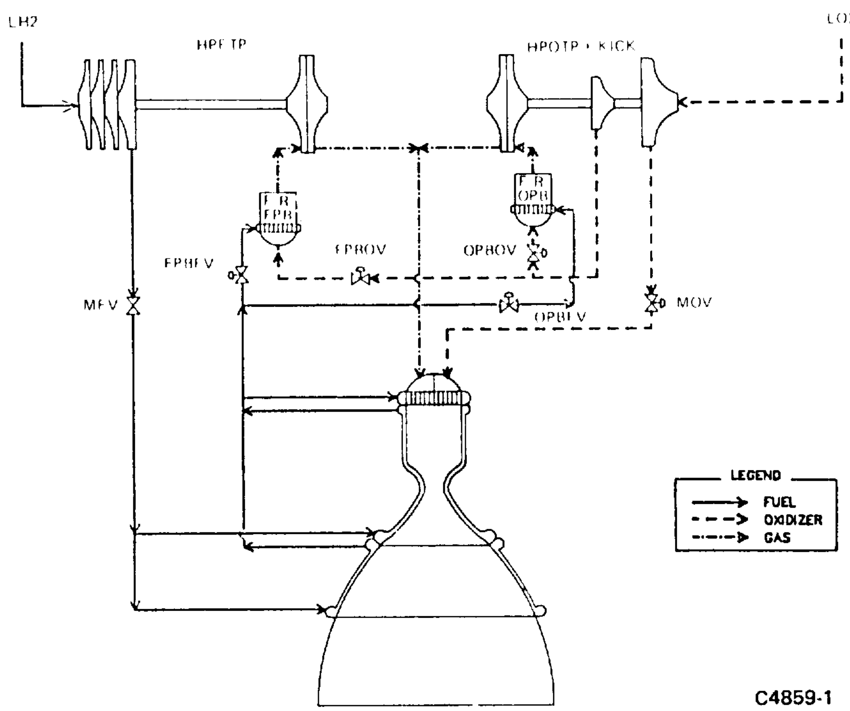

Figure 1. Dual Fuel-Rich Preburner Cycle

Results of the iterative on-design, off-design, on-design procedure described above provide an engine with a chamber pressure of 2590 psia and nozzle expansion ratio of 170, delivering a vacuum specific impulse of 415.1 sec. A regeneratively cooled nozzle configuration to an epsilon of 55 with a dump-cooled extension to 170 and a 300-lb extension mechanism were incorporated. This resulted in an overall engine weight of 7210 lb. The engine length is 254 in. with a nozzle exit diameter of 151 in. A side view and top view of the engine layout for this configuration is provided in Figures 2 and 3, respectively.

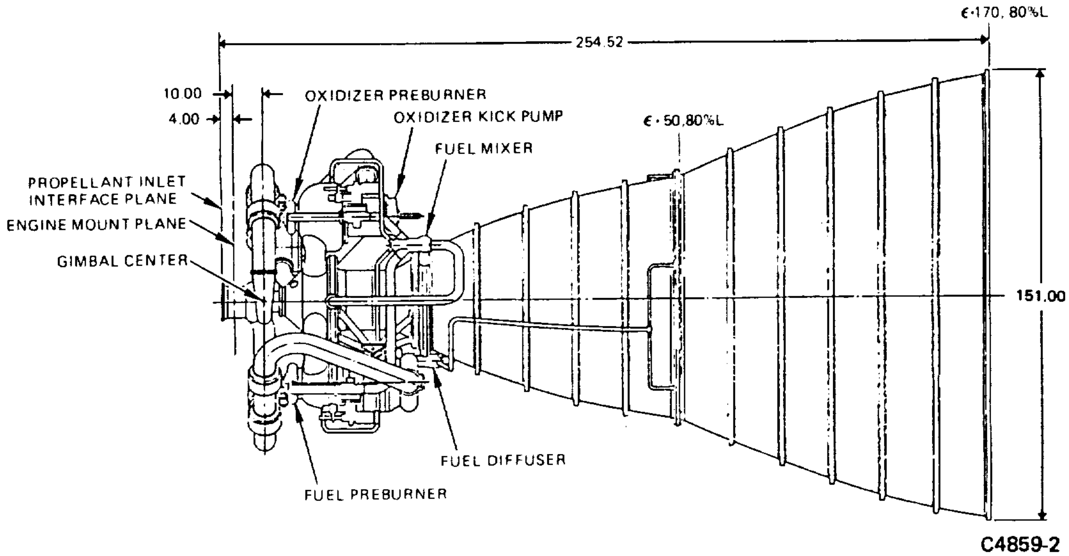

Figure 2. Dual Fuel-Rich Preburner Engine Layout, Side View

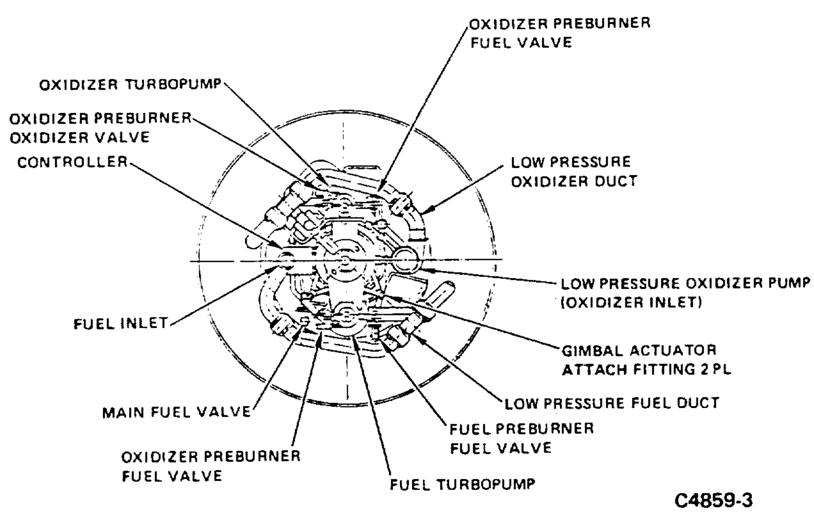

Figure 3. Dual Fuel-Rich Preburner Engine Layout, Top View

Off-design balances were generated for this engine at 348-Klbf (60% nominal) thrust at mixture ratios of 12.0, 10.0, 8.0, and 6.0. Critical parameters for these balances including injection pressure drops are summarized in Table 2. At the end point with MR = 6.0, the chamber pressure is down to 1767 psia, but vacuum Isp up to 462.5 sec due to the more optimal MR.

Table 2. Dual Fuel-Rich Preburner Engine Operating Parameters

F_{vac} = 580 Klbf, Length = 254 in., Diameter = 151 in., Weight = 7210 lb

	F = 580 MR = 12 on Design	F = 348 MR = 12 off Design	F = 348 MR = 10 off Design	F = 348 MR = 8 off Design	F = 348 MR = 6 off Design
Pc, psia	2590	1554	1625	1696	1767
Isp (VAC) ϵ = 170 sec	415.1	410.9	429.9	447.1	462.5
Isp (SL) ϵ = 55 sec	294.8	291.6	309.4	326.5	341.2
P_{NOZ} exit, psia	1.32	0.79	0.72	0.64	0.55
$\dot{M}$ PROP, lb/sec	1397.4	847.0	809.6	778.4	752.4
$\dot{M}$ H_2, lb/sec	1289.9	781.8	736.1	691.9	644.9
$\dot{M}$ O_2, lb/sec	107.5	65.2	73.6	86.5	107.5
$\dot{M}$ COMB COOL, lb/sec	53.7	32.6	36.8	43.2	53.8
P COMB COOL IN, psia	8121	4268	4783	5507	6408
Q COMB, Btu/sec	59317	38767	44394	48034	49687
T COMB OUT, °R	419	403	411	396	403
ΔP COMB, psid	678	391	467	560	670
$\dot{M}_{NOZ}$ COOL, lb/sec	53.7	32.6	36.8	43.2	53.8
P_{NOZ} COOL IN, lb/sec	7511	4298	4810	5522	6409
Q_{NOZ}, Btu/sec	102134	66729	76554	82878	85701
T_{NOZ} OUT, °R	641	632	644	608	628
ΔP_{NOZ}, psid	68	42	49	58	67
MCC H_2 ΔPinj/Pc %	10.0	7.9	8.9	10.2	12.0
MCC HOT GAS ΔPinj/Pc %	10.0	10.0	10.0	10.0	10.0
MCC O_2 ΔPinj/Pc %	34.5	22.0	18.5	15.6	13.1
FPB H_2 ΔPinj/Ppb %	10.0	12.2	12.1	11.4	10.4
FPB O_2 ΔPinj/Ppb %	40.8	12.2	15.1	19.5	24.4
OPB H_2 ΔPinj/Ppb %	10.0	13.5	17.7	23.3	45.3
OPB O_2 ΔPinj/Ppb %	40.8	9.8	5.2	1.5	DNA

Oxygen flow is down to half of on-design while the hydrogen flow is the same due to the competing effects of decreased thrust and decreased MR. Combustor and nozzle heat loads are down considerably due to the lower Pc, while coolant pressure drops are relatively unchanged due to the equal coolant flow rates.

In order to maintain acceptable injection pressure drops (ΔP_{inj} > 10% Pc) at the off-design condition, relatively high oxidizer injection pressure drops were required at on-design operation. These stability-dictated requirements result in high pump exit pressures for a moderate chamber pressure. Without a more complex system such as multiple parallel preburners or variable geometry injection orifices, these pressure drops are a necessity.

As mentioned above, four control valves were required to transition from on-design operation to the MR = 6.0 and low thrust. The main fuel valve (MFV) and fuel preburner fuel valve (FPBFV) are simply on/off valves. At the reduced thrust level and lowest MR of 6.0, the oxidizer flow and pump exit pressure are so drastically reduced, relative to on-design, that the oxidizer turbine power requirement is low enough to run in an expander mode. At this operating condition, the oxidizer preburner valve (OPBOV) is closed completely and the coolant hydrogen heated to 515°R in the coolant circuits powers the oxidizer turbine without supplemental combustion in the preburner.

In addition, to obtain a power balance at MR = 6.0, the fuel preburner oxidizer valve (FPBOV) and oxidizer preburner valve (OPBFV) positions are opened and the main oxidizer valve (MOV) closed down. A summary of the valve pressure drops, resistances, and normalized resistances (relative to on-design) is provided in Table 3.

Table 3. Dual Fuel-Rich Preburner Engine Valve Parameters

	F = 580 K MR = 12 ON-D	F = 348 K MR = 12 OFF-D	F = 348 K MR = 10 OFF-D	F = 348 K MR = 8 OFF-D	F = 348 K MR = 6 OFF-D
MFV ΔP psid	259	100	126	172	238
MFV RES $sec^2/in.^5$	0.2531 E-03	0.2531 E-03	0.2531 E-03	0.2531 E-03	0.2531 E-03
MFV R/R_{DES}	1.0	1.0	1.0	1.0	1.0
MOV ΔP psid	259	99	87	76	485
MOV RES $sec^2/in.^5$	0.7112 E-05	0.7112 E-05	0.7112 E-05	0.7112 E-05	5.250 E-05
MOV R/R_{DES}	1.0	1.0	1.0	1.0	7.4
FPBFV ΔP psid	599	363	404	442	479
FPBFV RES $sec^2/in.^5$	0.1484 E-03	0.1484 E-03	0.1484 E-03	0.1484 E-03	0.1484 E-03
FPBFV R/R_{DES}	1.0	1.0	1.0	1.0	1.0
FPBOV ΔP psid	1197	1592	1113	326	50
FPBOV RES $sec^2/in.^5$	0.2873 E-01	0.2585	0.1293	0.2520 E-01	6.191 E-04
FPBOV R/R_{DES}	1.0	9.0	4.5	0.88	2.15 E-02
OPBFV ΔP psid	599	391	535	737	277
OPBFV RES $sec^2/in.^5$	0.8178 E-03	0.8178 E-03	0.8178 E-03	0.8178 E-03	1.510 E-04
OPBFV R/R_{DES}	1.0	1.0	1.0	1.0	0.18
OPBOV ΔP psid	1197	1737	1780	1754	DNA
OPBOV RES $sec^2/in.^5$	0.1584	0.1979 E-01	0.3642 E-01	0.1214 E-02	CLOSE
OPBOV R/R_{DES}	1.0	12.5	23.0	76.6	∞

Details of the turbine and pump operations are provided in Table 4. In comparing the two end points, the hydrogen turbomachinery is not extremely far off-design during MR = 6.0 operation, whereas the oxygen turbopumps operate far from on-design. Pump performance maps in the form of head versus flow plots are provided in Figures 4 through 6. Lines of constant pump speeds and efficiencies are cross plotted. The on-design and off-design operating points are plotted on these maps. The fuel main pump does not experience overly demanding off-design operation, particularly if only the end points are considered. Even the oxygen main pump does not pose an excessively demanding operating range in that it is throttling over a reasonable Q/RPM range. However the oxygen kick pump may experience stability problems during off-design operation since it is required to operate in the "positive slope" region of the performance map. A possible solution to this situation is recirculation of a portion of the LOX. In this manner, the operating point is shifted to the right on the map and into the stable negative slope region. The details are being investigated through an in-depth component analysis.

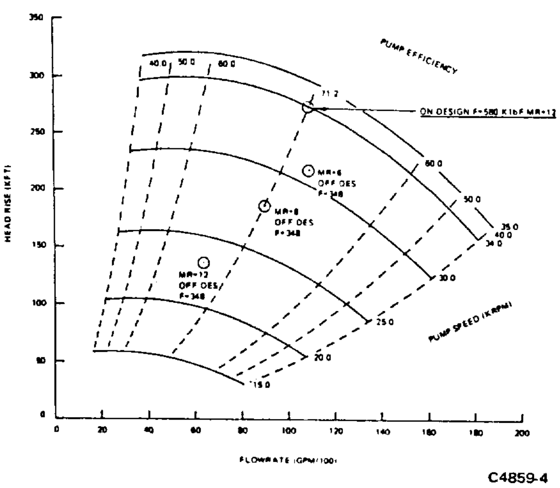

Figure 4. Variable MR Fuel Pump Map

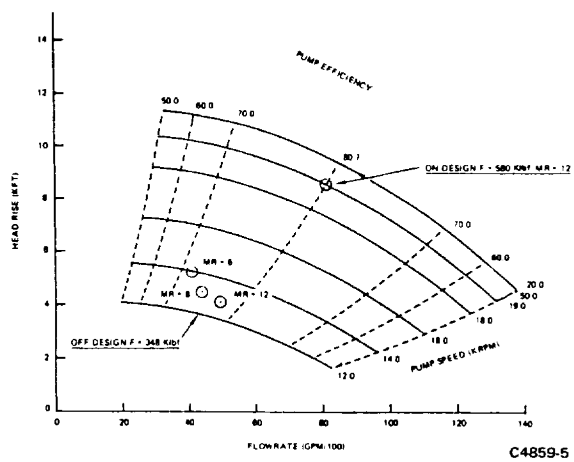

Figure 5. Variable MR Ox. Main Pump Map

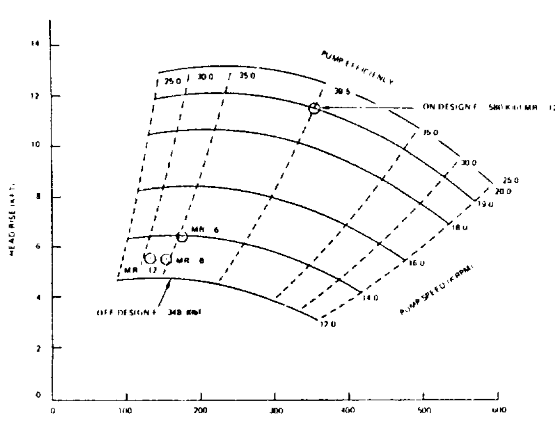

Figure 6. Variable MR Ox. Kick Pump Map

Table 4. Dual Fuel-Rich Preburner Engine Turbomachinery Parameters

	F = 580 MR = 12 ON-D	F = 348 MR = 12 OFF-D	F = 348 MR = 10 OFF-D	F = 348 MR = 8 OFF-D	F = 348 MR = 6 OFF-D
H_2 Turbine					
Power, hp	74976	23493	30189	41440	60208
N, rpm	33780	23575	25411	27866	30850
η	70.2	65.5	65.6	66.2	67.8
$\dot{M}$, lb/sec	107.3	56.7	63.4	73.4	85.5
Cp, Btu/lb	2.386	2.651	2.497	2.475	2.585
T_{in}, °R	1600	1210	1277	1316	1327
γ	1.378	1.374	1.391	1.390	1.390
PR	2.101	1.734	1.868	2.076	2.358
P_{in}, psia	5987	2964	3339	3875	4572
Pout, psia	2849	1710	1788	1866	1944
O_2 Turbine					
Power, hp	27692	8214	8260	8054	9372
N, rpm	19100	13054	13169	13128	14000
η	60.9	58.6	59.9	61.1	62.3
$\dot{M}$, lb/sec	45.7	24.1	26.5	30.4	39.9
Cp, Btu/lb	2.386	2.750	3.001	3.266	3.646
T_{in}, °R	1600	1113	907	685	515
γ	1.378	1.378	1.385	1.390	1.402
PR	2.101	1.695	1.688	1.692	1.705
P_{in}, psia	5987	2897	3018	3157	3314
Pout, psia	2849	1710	1788	1866	1944
H_2 Pump					
Power, hp	74976	23493	30187	41438	60208
η	71.2	70.0	70.6	71.2	71.0
$\dot{M}$, lb/sec	107.5	65.2	73.6	86.5	107.5
Q, gpm	10917	6255	7474	8784	10310
P_{in}, psia	24.5	24.5	24.5	24.5	24.5
Pout, psia	8878	4532	5200	6116	7129
LOX Main Pump					
Power, hp	24749	7536	7541	7316	8455
η	80.7	79.7	78.3	76.8	72.0
$\dot{M}$, lb/sec	1290	782	736	692	645
Q, gpm	8128	4927	4637	4360	4064
P_{in}, psia	47	47	47	47	47
Pout, psia	4261	2136	2230	2257	2615
LOX/Kick Pump					
Power, hp	2943	685	719	743	917
η	39.5	31.7	32.7	34.5	35.5
$\dot{M}$, lb/sec	56.2	21.4	22.7	22.9	27.8
Q, gpm	354	135	143	144	175
P_{in}, psia	4261	2136	2230	2257	2615
Pout, psia	9886	4960	5007	4993	5800

The relatively high pump exit pressures experienced in this engine may adversely affect reliability and life of the turbopumps. Lower chamber pressures can alleviate this potential problem. In order to quantitatively establish the effect of chamber pressure upon pump exit pressures, a parametric scan was generated for on-design Pc's ranging from 2590 down to 1700 psia. Results of this effort are presented in Figures 7 through 10. By decreasing the on-design Pc from 2590 to 2300 psia, the vacuum Isp drops only 3 sec while the LOX kick pump exit pressure drops from 9890 to 6680 psia and the LH2 main pump exit pressure drops from 8900 to only 6250 psia.

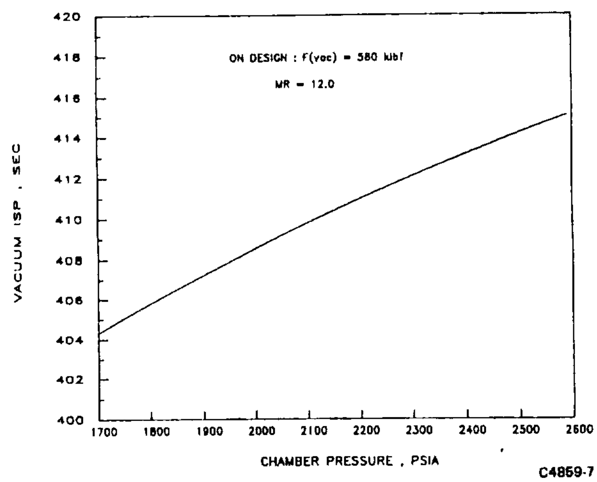

Figure 7. STME Variable MR
Isp vs. Pc

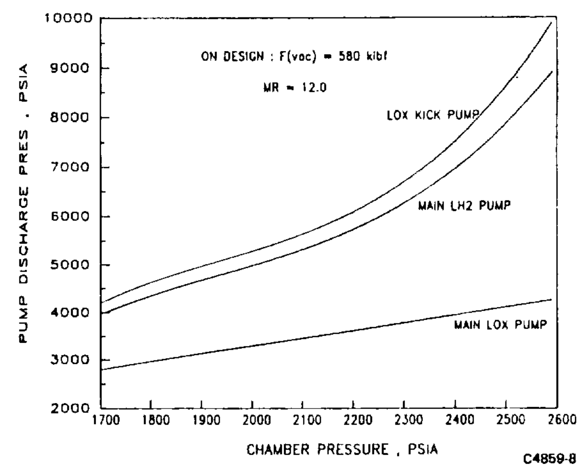

Figure 8. STME Variable MR
Pump Pd vs. Pc

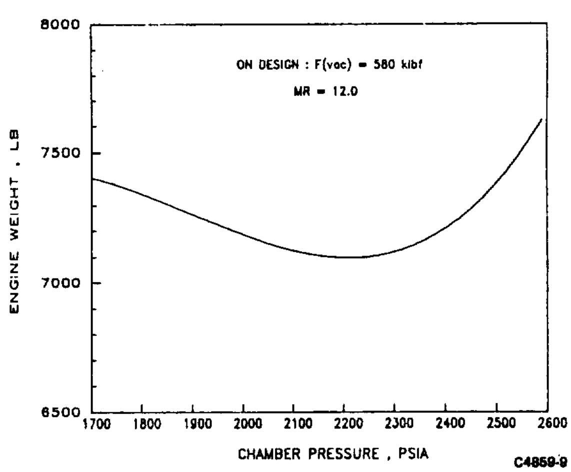

Figure 9. STME Variable MR
Weight vs. Pc

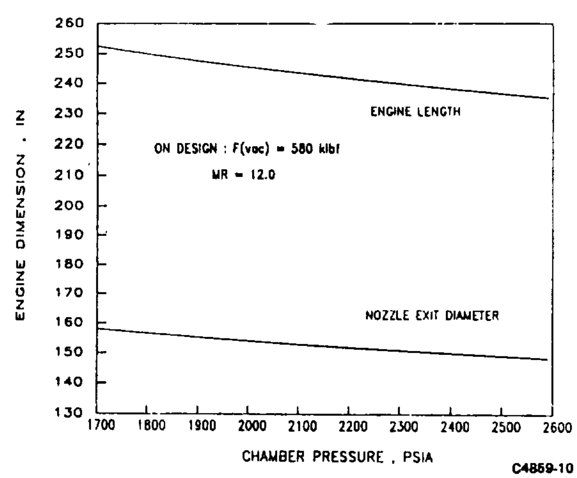

Figure 10. STME Variable MR
Envelope vs. Pc

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The operating parameters of the preburners are summarized in Table 5. Comparing the end points reveals that the fuel preburner does not operate extremely far from on-design. In the oxidizer preburner, however, the oxygen flow is completely shut off at the extreme end point and simply provides a flow path for the heated hydrogen into the oxidizer turbine. As with the turbomachinery, detailed components analyses are being conducted for the combustion devices.

Table 5. Dual Fuel-Rich Preburner Engine Preburner Parameters

	F = 580 MR = 12 ON-D	F = 348 MR = 12 OFF-D	F = 348 MR = 10 OFF-D	F = 348 MR = 8 OFF-D	F = 348 MR = 6 OFF-D
Fuel Preburner					
PRES, psia	5987	2964	3339	3875	4572
$\dot{M}TOT$, lb/sec	107.3	56.7	63.4	73.4	85.5
$\dot{M}O_2$, lb/sec	39.4	15.5	18.3	22.5	27.8
$\dot{M}H_2$, lb/sec	67.9	41.2	45.1	50.9	57.7
MR	0.581	0.376	0.407	0.442	0.481
TEMP, °R	1600	1210	1277	1316	1327
Ox. Preburner					
PRES, psia	5987	2897	3018	3157	3314
$\dot{M}TOT$, lb/sec	45.7	24.1	26.5	30.4	39.9
$\dot{M}O_2$, lb/sec	16.8	5.9	4.4	2.4	0
$\dot{M}H_2$, lb/sec	28.9	18.2	22.1	28.0	39.0
MR	0.581	0.321	0.198	0.080	0
TEMP, °R	1600	1113	907	685	515

MIXED PREBURNER CYCLE

Similar analyses were conducted for the dual mixed preburner cycle. A schematic of this cycle is presented in Figure 11. In this configuration the hydrogen turbine is driven by fuel-rich combustion gas but the oxidizer turbine is powered by oxygen-rich combustion gas from an oxidizer-rich preburner. The advantage of this approach is that more total drive gas is available to the turbines than in the dual fuel-rich preburner cycle. With more mass flow to power the turbines, lower pressure ratios are required enabling higher chamber pressures and performance. In addition, the oxidizer-rich gas obviates the need for an inter-propellant seal on the oxidizer turbopump.

The combustor is cooled with hydrogen as in the dual fuel-rich cycle, but, for this configuration, the nozzle is oxygen cooled. The heating of the oxygen in the nozzle cooling circuit minimizes the hydrogen required in the oxidizer-rich preburner. Due to the low heat capacity of the oxygen, this configuration was unable to operate in an expander mode on the oxidizer side of the cycle at low thrust and mixture ratio. Therefore, combustion in the oxidizer preburner is still required at the off-design end point. Since nearly all the propellants are pumped up to the high pressure required in the preburners, there is no advantage to a kick pump in this cycle.

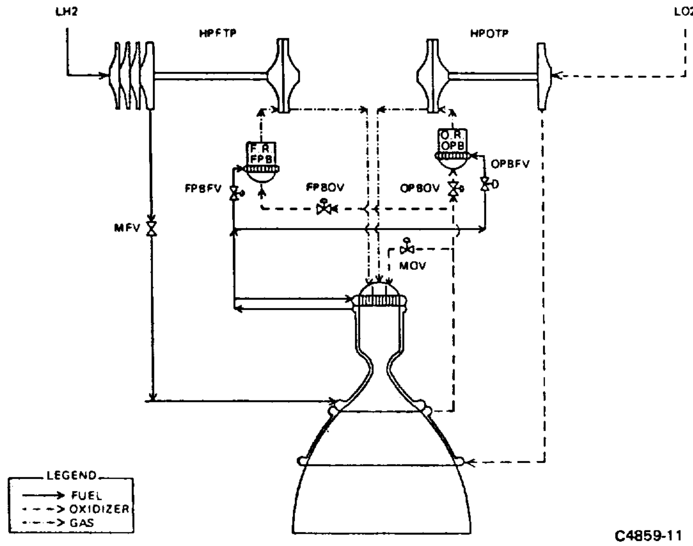

Figure 11. Mixed PBs Staged Combustion Cycle

The on-design engine balance for the mixed preburner cycle achieved a chamber pressure of 2815 psia. The delivered vacuum impulse was 417.1 sec at 580 Klbf thrust and MR of 12 with a nozzle expansion ratio of 180. As explained above, the mixed preburners allowed an increase in Pc (+225 psid) and performance (+2.0 sec) over the dual fuel-rich preburner configuration. The off-design end point at MR = 6 and 348-Klbf thrust also reflects this advantage providing 2.4 sec more vacuum Isp at a Pc 145 psid higher than the dual fuel-rich preburner engine.

Four control valves are required to execute the transition down in thrust and MR. The resistance ranges required of these control elements are all within acceptable ranges.

A summary of all the pertinent engine parameters is provided for both the on-design and end point off-design operating conditions in Table 6. In addition, the pump performance maps for the main pumps are presented in Figures 12 and 13. As with the dual fuel-rich preburner cycle, detailed component analyses are being conducted to verify the feasibility of operating over this range.

The effect of reducing the range over which the MR is required to shift was also investigated for the dual mixed preburner cycle. In this effort, the range was reduced to 9.0 to 6.0. The same thrust reduction as in the previous engines was retained, however. The major impact of this change was an increase in the vacuum Isp at the on-design operation with MR = 9.0. An increase of 25.1 sec relative to the dual fuel-rich preburner case was observed, primarily due to the more advantageous MR. The engine operating parameters are provided in Table 7 and pump performance maps in Figures 14 and 15.

Table 6. LOX/H_2 Mixed PBS SC Engine Parametrics (12.0 > MR > 6.0)

ENGINE PARAMETER DESCRIPTION		ON DESIGN	OFF DESIGN
ENGINE VACUUM THRUST	(KLB)	580.00	348.00
ENGINE SEA LEVEL THRUST	(KLB)	504.76	262.05
ENGINE VACUUM ISP (EPS=181)	(SEC)	417.11	464.89
ENGINE SEA LEVEL ISP (EPS=55)	(SEC)	363.00	350.07
CHAMBER PRESSURE	(PSIA)	2815.16	1911.84
ENGINE MIXTURE RATIO	(O/F)	12.00	6.000
ENGINE FUEL FLOWRATE	(LB/SEC)	106.96	106.94
ENGINE OXIDIZER FLOWRATE	(LB/SEC)	1283.57	641.63
COMBUSTOR COOLANT FLOWRATE	(LB/SEC)	106.96	106.94
COMBUSTOR COOLANT DELTA-P	(PSID)	823.27	771.70
COMBUSTOR HEAT INPUT	(BTU/SEC)	58827.	46904.
COMBUSTOR JACKET OUTLET PRESSURE	(PSIA)	7216.2	6460.6
COMBUSTOR JACKET OUTLET TEMP.	(DEG-R)	284.72	263.01
NOZZLE COOLANT FLOWRATE	(LB/SEC)	1283.57	641.63
NOZZLE COOLANT DELTA-P	(PSID)	387.76	87.800
NOZZLE HEAT INPUT	(BTU/SEC)	103152.	82368.
NOZZLE JACKET OUTLET PRESSURE	(PSIA)	8259.9	12643.3
NOZZLE JACKET OUTLET TEMP.	(DEG-R)	463.80	384.96
MAIN FUEL INJECTOR DELTA-P	(PSID/% Pc)	282/10	291/15.2
MAIN GAS INJECTOR DELTA-P	(PSID/% Pc)	282/10	191/10
MAIN OXIDIZER INJECTOR DELTA-P	(PSID/% Pc)	282/10	155/8.1
FUEL PB FUEL-INJECTOR DELTA-P	(PSID/% PB)	1284/25	1300/30.
FUEL PB OXID-INJECTOR DELTA-P	(PSID/% PB)	2096/41	640/14.7
OXID PB FUEL-INJECTOR DELTA-P	(PSID/% PB)	1284/25	328/6.1
OXID PB OXID-INJECTOR DELTA-P	(PSID/% PB)	2096/41	518/9.6
HIGH PRESSURE FUEL PUMP			
# OF STAGES	(NONE)	4	4
PUMP SPEED	(RPM)	33822.	32513.
PUMP INLET PRESSURE	(PSIA)	24.50	24.50
PUMP DISCHARGE PRESSURE	(PSIA)	8884.	8082.4
PUMP FLOW RATE	(LB/SEC)	106.96	106.94
PUMP EFFICIENCY	(PERCENT)	71.20	71.09
PUMP HORSEPOWER	(HP)	74502.	67858.
HIGH PRESSURE OXID PUMP			
# OF STAGES	(NONE)	2	2
PUMP SPEED	(RPM)	13739.	15398.
PUMP INLET PRESSURE	(PSIA)	47.00	47.00
PUMP DISCHARGE PRESSURE	(PSIA)	8929.	12818.
PUMP FLOW RATE	(LB/SEC)	1283.57	641.63
PUMP EFFICIENCY	(PERCENT)	79.20	54.89
PUMP HORSEPOWER	(HP)	52911.	54866.
HIGH PRESSURE FUEL TURBINE			
TYPE	(NONE)	REACTION	REACTION
# OF STAGES	(NONE)	2	2
HORSEPOWER	(HP)	74502.	67858.
SHAFT SPEED	(RPM)	33822.	32513.
EFFICIENCY	(NONE)	76.93	74.59
FLOWRATE	(LB/SEC)	139.20	121.09
PRESSURE RATIO	(NONE)	1.659	2.071
PITCH LINE VELOCITY	(FT/SEC)	1649.7	1585.9
PITCH DIAMETER	(IN)	11.17	11.17
INLET TEMPERATURE	(DEG-R)	1600.00	1070.48
OUTLET TEMPERATURE	(DEG-R)	1441.06	926.02
INLET PRESSURE	(PSIA)	5136.76	4355.61
OUTLET PRESSURE	(PSIA)	3096.68	2103.01
GAS SPECIFIC HEAT	(BTU/LB-R)	2.381	2.743
GAS SPECIFIC HEAT RATIO	(NONE)	1.376	1.376
GAS MOLECULAR WEIGHT	(LB/LB-MOLE)	3.188	2.672
HIGH PRESSURE OXID TURBINE			
TYPE	(NONE)	REACTION	REACTION
# OF STAGES	(NONE)	2	2
HORSEPOWER	(HP)	52911.	54868.

ENGINE PARAMETER DESCRIPTION		ON DESIGN	OFF DESIGN
HIGH PRESSURE OXID TURBINE (CONTINUED)			
SHAFT SPEED	(RPM)	13739.	15398.
EFFICIENCY	(NONE)	79.45	82.61
FLOWRATE	(LB/SEC)	934.74	487.35
PRESSURE RATIO	(NONE)	1.659	2.570
PITCH LINE VELOCITY	(FT/SEC)	1172.6	1314.2
PITCH DIAMETER	(IN)	19.55	19.55
INLET TEMPERATURE	(DEG-R)	1600.00	1598.35
OUTLET TEMPERATURE	(DEG-R)	1456.02	1333.03
INLET PRESSURE	(PSIA)	5136.76	5405.38
OUTLET PRESSURE	(PSIA)	3096.68	2103.01
GAS SPECIFIC HEAT	(BTU/LB-R)	0.278	0.300
GAS SPECIFIC HEAT RATIO	(NONE)	1.312	1.312
GAS MOLECULAR WEIGHT	(LB/LB-MOLE)	30.14	30.141
FUEL PREBURNER			
PRESSURE	(PSIA)	5136.76	4355.61
GAS TEMPERATURE	(DEG-R)	1600.0	1070.48
GAS FLOWRATE	(LB/SEC)	139.20	121.09
FUEL FLOWRATE	(LB/SEC)	87.99	91.372
OXIDIZER FLOWRATE	(LB/SEC)	51.21	29.714
GAS MIXTURE RATIO	(NONE)	0.582	0.325
OXID PREBURNER			
PRESSURE	(PSIA)	5136.76	5405.38
GAS TEMPERATURE	(DEG-R)	1600.0	1598.35
GAS FLOWRATE	(LB/SEC)	934.74	487.354
FUEL FLOWRATE	(LB/SEC)	8.34	4.347
OXIDIZER FLOWRATE	(LB/SEC)	926.40	483.007
GAS MIXTURE RATIO	(NONE)	111.012	111.220
CONTROL VALVE			
MAIN OXIDIZER VALVE			
DELTA-P	(PSID)	4130.5	10522.2
FLOW RESISTANCES	(SEC**2/IN**5)	.117E-2	1.87E-2
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	16.0
EFFECTIVE FLOW AREA	(IN**2)	1.05285	.263212
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	4.00
FUEL PREBURNER OXIDIZER VALVE			
DELTA-P	(PSID)	1027.0	7649.0
FLOW RESISTANCES	(SEC**2/IN**5)	1.05E-2	25.6E-2
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	24.4
EFFECTIVE FLOW AREA	(IN**2)	.35154	.071167
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	4.94
OXIDIZER PREBURNER FUEL VALVE			
DELTA-P	(PSID)	513.7	655.6
FLOW RESISTANCES	(SEC**2/IN**5)	.129E-1	.646E-1
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	5.00
EFFECTIVE FLOW AREA	(IN**2)	.316469	.141529
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	2.24
OXIDIZER PREBURNER OXIDIZER VALVE			
DELTA-P	(PSID)	1027.0	6720.4
FLOW RESISTANCES	(SEC**2/IN**5)	.321E-4	6.50E-4
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	26.5
EFFECTIVE FLOW AREA	(IN**2)	6.3526	1.23408
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	5.15

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Table 7. LOX/H_2 Mixed PBS SC Engine Parametrics (9.0 > MR > 6.0)

ENGINE PARAMETER DESCRIPTION		ON DESIGN	OFF DESIGN
ENGINE VACUUM THRUST	(KLB)	580.00	348.00
ENGINE SEA LEVEL THRUST	(KLB)	500.39	259.35
ENGINE VACUUM ISP (EPS=156)	(SEC)	440.46	462.07
ENGINE SEA LEVEL ISP (EPS=55)	(SEC)	380.00	344.36
CHAMBER PRESSURE	(PSIA)	2856.70	1814.29
ENGINE MIXTURE RATIO	(O/F)	9.000	6.000
ENGINE FUEL FLOWRATE	(LB/SEC)	131.68	107.59
ENGINE OXIDIZER FLOWRATE	(LB/SEC)	1185.12	645.54
COMBUSTOR COOLANT FLOWRATE	(LB/SEC)	131.68	107.59
COMBUSTOR COOLANT DELTA-P	(PSID)	852.52	519.00
COMBUSTOR HEAT INPUT	(BTU/SEC)	58742.	39209.
COMBUSTOR JACKET OUTLET PRESSURE	(PSIA)	7198.9	4576.0
COMBUSTOR JACKET OUTLET TEMP.	(DEG-R)	257.72	229.65
NOZZLE COOLANT FLOWRATE	(LB/SEC)	1185.12	645.54
NOZZLE COOLANT DELTA-P	(PSID)	400.81	99.500
NOZZLE HEAT INPUT	(BTU/SEC)	103334.	68914.
NOZZLE JACKET OUTLET PRESSURE	(PSIA)	8234.42	8843.0
NOZZLE JACKET OUTLET TEMP.	(DEG-R)	482.87	369.36
MAIN FUEL INJECTOR DELTA-P	(PSID/% Pc)	286/10	182/10
MAIN GAS INJECTOR DELTA-P	(PSID/% Pc)	286/10	181/10
MAIN OXIDIZER INJECTOR DELTA-P	(PSID/% Pc)	286/10	281/15.5
FUEL PB FUEL-INJECTOR DELTA-P	(PSID/% PB)	1280/25	814/25.
FUEL PB OXID-INJECTOR DELTA-P	(PSID/% PB)	2089/41	357/11.3
OXID PB FUEL-INJECTOR DELTA-P	(PSID/% PB)	1280/25	341/9.8
OXID PB OXID-INJECTOR DELTA-P	(PSID/% PB)	2089/41	513/14.8
HIGH PRESSURE FUEL PUMP			
# OF STAGES	(NONE)	4	4
PUMP SPEED	(RPM)	30501.	24458.
PUMP INLET PRESSURE	(PSIA)	24.50	24.50
PUMP DISCHARGE PRESSURE	(PSIA)	8908.42	5695.77
PUMP FLOW RATE	(LB/SEC)	131.68	107.59
PUMP EFFICIENCY	(PERCENT)	71.10	71.07
PUMP HORSEPOWER	(HP)	92042.	48025.
HIGH PRESSURE OXID PUMP			
# OF STAGES	(NONE)	2	2
PUMP SPEED	(RPM)	12607.	11983.
PUMP INLET PRESSURE	(PSIA)	47.00	47.00
PUMP DISCHARGE PRESSURE	(PSIA)	8920.90	9029.21
PUMP FLOW RATE	(LB/SEC)	1185.12	645.54
PUMP EFFICIENCY	(PERCENT)	77.70	63.54
PUMP HORSEPOWER	(HP)	49725.	33526.
HIGH PRESSURE FUEL TURBINE			
TYPE	(NONE)	REACTION	REACTION
# OF STAGES	(NONE)	2	2
HORSEPOWER	(HP)	92042.	48024.
SHAFT SPEED	(RPM)	30501.	24458.
EFFICIENCY	(NONE)	77.85	74.95
FLOWRATE	(LB/SEC)	179.67	123.952
PRESSURE RATIO	(NONE)	1.630	1.631
PITCH LINE VELOCITY	(FT/SEC)	1648.76	1322.14
PITCH DIAMETER	(IN)	12.379	12.379
INLET TEMPERATURE	(DEG-R)	1600.00	1077.84
OUTLET TEMPERATURE	(DEG-R)	1444.92	976.68
INLET PRESSURE	(PSIA)	5120.91	3254.80
OUTLET PRESSURE	(PSIA)	3142.37	1995.74
GAS SPECIFIC HEAT	(BTU/LB-R)	2.335	2.708
GAS SPECIFIC HEAT RATIO	(NONE)	1.374	1.376
GAS MOLECULAR WEIGHT	(LB/LB-MOLE)	3.281	2.710
HIGH PRESSURE OXID TURBINE			
TYPE	(NONE)	REACTION	REACTION
# OF STAGES	(NONE)	2	2
HORSEPOWER	(HP)	49725.	33526.
HIGH PRESSURE OXID TURBINE (CONTINUED)			
SHAFT SPEED	(RPM)	12607.	11983.
EFFICIENCY	(NONE)	79.96	82.04
FLOWRATE	(LB/SEC)	902.68	488.215
PRESSURE RATIO	(NONE)	1.630	1.741
PITCH LINE VELOCITY	(FT/SEC)	1128.19	1072.32
PITCH DIAMETER	(IN)	20.493	20.493
INLET TEMPERATURE	(DEG-R)	1600.00	1597.27
OUTLET TEMPERATURE	(DEG-R)	1459.88	1435.43
INLET PRESSURE	(PSIA)	5120.91	3475.40
OUTLET PRESSURE	(PSIA)	3142.37	1995.74
GAS SPECIFIC HEAT	(BTU/LB-R)	0.278	0.300
GAS SPECIFIC HEAT RATIO	(NONE)	1.312	1.312
GAS MOLECULAR WEIGHT	(LB/LB-MOLE)	30.140	30.143
FUEL PREBURNER			
PRESSURE	(PSIA)	5120.91	3254.80
GAS TEMPERATURE	(DEG-R)	1600.0	1077.84
GAS FLOWRATE	(LB/SEC)	179.67	123.952
FUEL FLOWRATE	(LB/SEC)	110.43	92.215
OXIDIZER FLOWRATE	(LB/SEC)	69.24	31.737
GAS MIXTURE RATIO	(NONE)	0.627	0.344
OXID PREBURNER			
PRESSURE	(PSIA)	5120.91	3475.40
GAS TEMPERATURE	(DEG-R)	1600.0	1597.27
GAS FLOWRATE	(LB/SEC)	902.68	488.215
FUEL FLOWRATE	(LB/SEC)	8.059	4.351
OXIDIZER FLOWRATE	(LB/SEC)	894.621	483.863
GAS MIXTURE RATIO	(NONE)	111.012	111.204
CONTROL VALVE			
MAIN OXIDIZER VALVE			
DELTA-P	(PSID)	4107.1	6666.7
FLOW RESISTANCES	(SEC**2/IN**5)	.211E-2	1.20E-2
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	5.70
EFFECTIVE FLOW AREA	(IN**2)	.782818	.327836
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	2.39
FUEL PREBURNER OXIDIZER VALVE			
DELTA-P	(PSID)	1024.0	5220.9
FLOW RESISTANCES	(SEC**2/IN**5)	.545E-2	15.8E-2
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	29.0
EFFECTIVE FLOW AREA	(IN**2)	.487335	.090496
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	5.39
OXIDIZER PREBURNER FUEL VALVE			
DELTA-P	(PSID)	512.1	683.0
FLOW RESISTANCES	(SEC**2/IN**5)	.146E-1	.732E-1
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	5.00
EFFECTIVE FLOW AREA	(IN**2)	.297437	.133018
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	2.24
OXIDIZER PREBURNER OXIDIZER VALVE			
DELTA-P	(PSID)	1024.0	4854.5
FLOW RESISTANCES	(SEC**2/IN**5)	.328E-4	6.33E-4
RESISTANCES RATIO (R/R-ON)	(NONE)	1.0	19.3
EFFECTIVE FLOW AREA	(IN**2)	6.28597	1.43085
EFF. FLOW AREA RATIO (A-ON/A)	(NONE)	1.0	4.39

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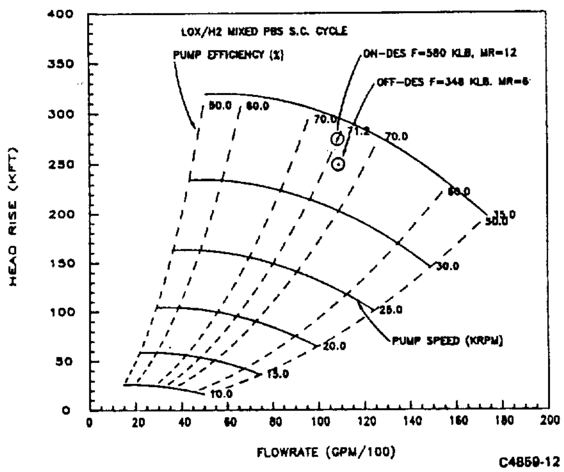

Figure 12. Variable MR Fuel Pump Map

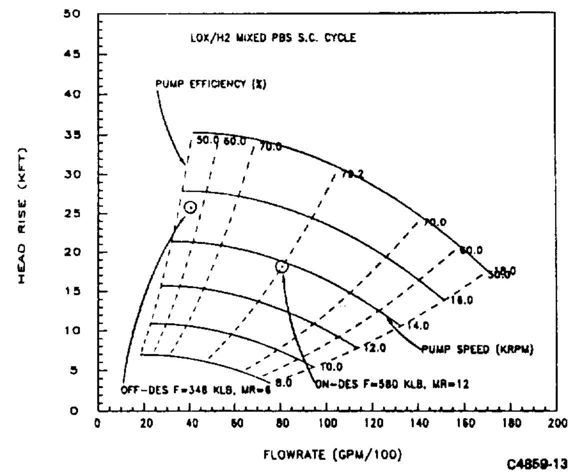

Figure 13. Variable MR Oxid Pump Map

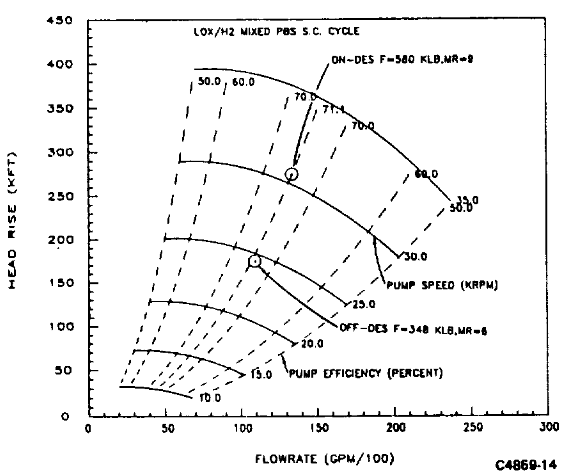

Figure 14. Variable MR Fuel Pump Map

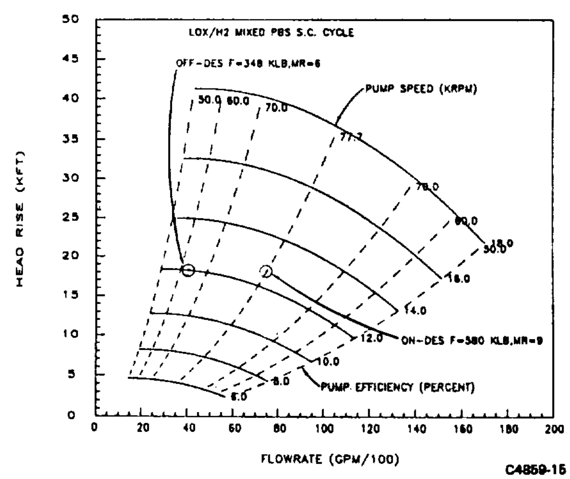

Figure 15. Variable MR Oxid Pump Map

Finally, the effect of reducing the oxidizer rich preburner temperature from 1600 to 1000 R was investigated for the mixed preburner cycle at MR = 9.0. This reduction in operating temperature may alleviate potential materials problems encountered in the oxidizer rich environment. The net effect of the decrease was a reduction in chamber pressure of 262 psia and a loss of 1.8 sec of vacuum Is. A summary of the top-level engine data for the two temperature conditions is provided in Table 8.

Table 8. Effect of Lowered Oxidizer Preburner Temperature in Dual Mixed Preburner Cycle (F_{vac} = 580 Klfb, MR = 9.0)

	OPB Temperature 1600°R	OPB Temperature 1000°R
Is vac, sec	440.5	438.7
Is SL (E = 55), sec	380.0	372.2
Pc, psia	2857	2595
ϵ	156	146
Weight, lb	7637	7707
Length, in.	223	226
Diameter, in.	140	142

CONCLUSIONS

The major conclusions arrived at in this study are:

1. System level analysis indicates the ranges of operation examined are feasible

2. Four control valves are required for both the dual fuel-rich preburner cycle and the mixed preburner cycle

3. All control valve resistance ranges required are reasonable

4. Transition to an expander cycle drive on the LOX side of the cycle at low MR operation in the dual fuel-rich preburner engine is observed

5. Further components analysis is required to verify feasibility.

5319e/slw