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TRIPROPELLANT ENGINE STUDY
BIMONTHLY TECHNICAL PROGRESS REPORT
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INTRODUCTION

The advanced vehicle studies that have been conducted for the NASA indicate the advantages of a high-pressure oxygen/hydrocarbon engine. Single-stage-to-orbit vehicle studies also show the potential for engines that operate in dual mode with sequential burn of oxygen/hydrocarbon and oxygen/hydrogen. Feasibility of an engine to operate in dual mode must be determined before committing to a dual-mode vehicle concept.

The Space Shuttle Main Engine (SSME) is a high-pressure oxygen/hydrogen engine that potentially could be modified for a dual-mode operation. Such a modification would minimize development cost of a dual-mode engine by maximizing utilization of existing hardware.

The objectives of this study program are: (1) to investigate the feasibility of a tripropellant engine operating at high chamber pressure; (2) to identify the potential applicability of SSME components in the dual fuel mode engine; (3) to define engine performance and weight of engine concepts for both gas generator and staged combustion power cycles; and (4) to provide plans for experimental demonstration of the performance, cooling, and preburner or gas generator operation.

The study program is for nine months of technical effort followed by a period for a final report (Fig. 1). The study is subdivided into seven tasks including a reporting task.

The approach taken in this study is to investigate various high P_c engine configurations derived from the SSME that will allow sequential burning of LOX/hydrocarbon and LOX/hydrogen. Both staged combustion and gas generator pump power cycles are to be considered. Engine cycle concepts are formulated for LOX/RP-1, LOX/CH_4 and LOX/C_3H_8 propellants. Each system must also be

TRIPROPELLANT ENGINE STUDY SCHEDULE

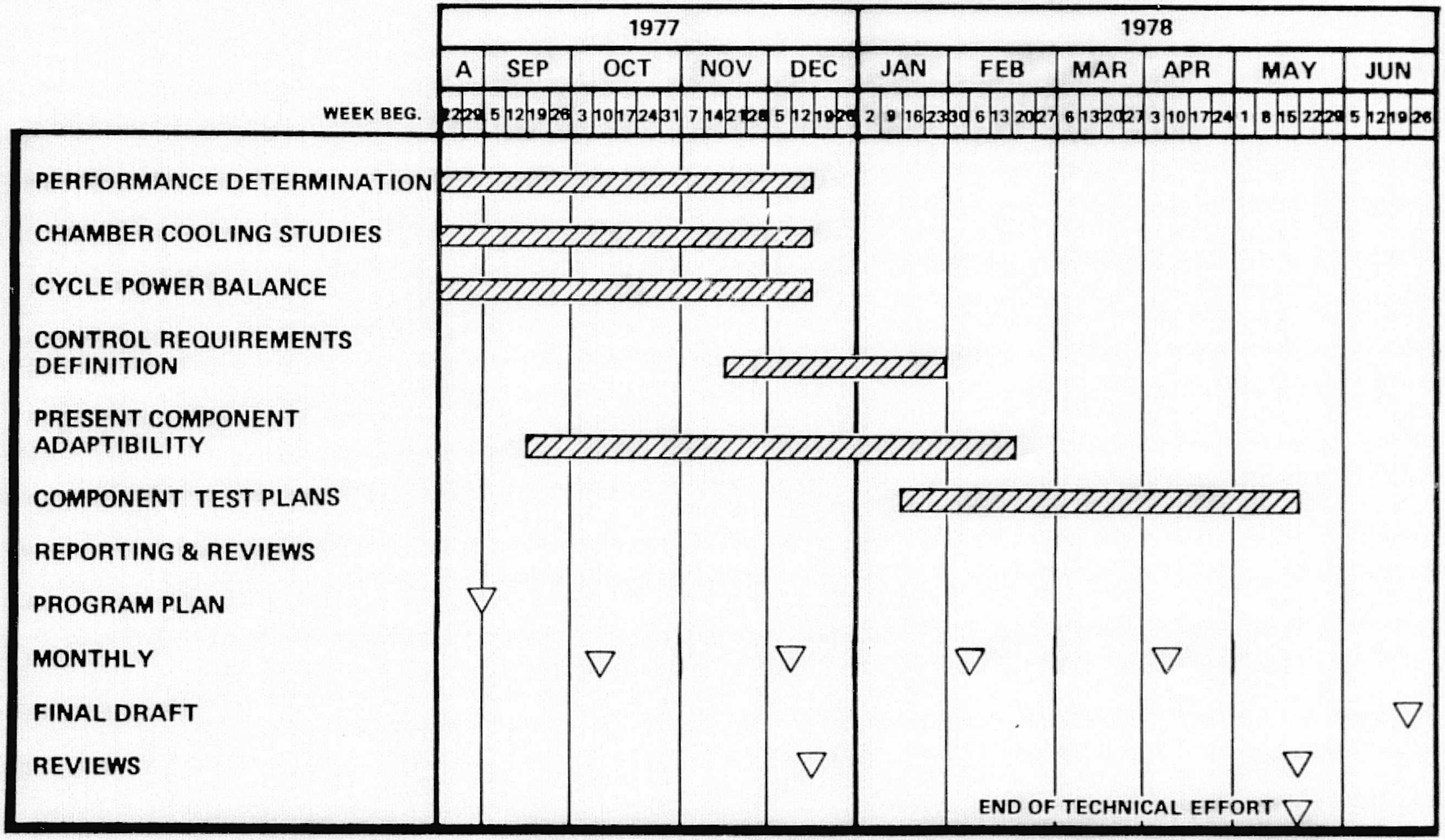

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Figure 1

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capable of operating sequentially with LOX/H_2. Flowrates and operating conditions will be established for this initial set of engine systems and the adaptability of the major components of the SSME will be investigated. The end result will be the identification of high P_c engine system concepts that make maximum use of the SSME hardware and best satisfy the dual mode booster engine system application.

Based on the results of the engine system concept studies, recommendations will be made for additional testing to compliment the already planned experimental program using the existing test facility and 40K test hardware available at MSFC. A test plan will be prepared to establish the objectives of each additional experimental test phase.

SUMMARY

This second bimonthly progress report covers the work conducted from 1 October to 30 November 1977. In Task I additional parametric performance data has been generated for the three candidate mode 1 propellant combinations. A preliminary study was conducted to demonstrate the validity of using a mass averaging method to predict performance where relatively small percentages of H_2 are injected into the chamber along with the LOX/hydrocarbon main propellants. Additional cooling analyses were conducted in Task II for LOX cooling and H_2 cooling at an extendible nozzle. The engine balances for the 15 candidate mode 1 systems were completed with some modifications, and schematics prepared for each type. Engine balances for the LOX/H_2 mode 2 operation are presented. Preliminary results from the SSME component adaptability studies are also presented. It was found that the SSME low pressure and high pressure LOX pumps would satisfy the LOX pumping requirements for the 15 candidate systems. The SSME low pressure oxidizer pump would also satisfy the requirements for the low pressure hydrocarbon fuel pumps. However, it was found that a new main fuel pump would be required in every case. Preliminary results indicate that the SSME main turbines are unsatisfactory for either the higher gas flowrates typical of the LOX/hydrocarbon staged combustion systems or the higher pressure ratio turbine requirements for the gas generator cycle. SSME preburner or main chamber injector applicability to these candidate tripropellant systems has also been investigated and the results show numerous problems making their adaptation not straight forward but not impossible. The best possibility is in the gas generator cycles for the most direct substitution of the SSME injector.

TASK I - PERFORMANCE DETERMINATION

In this task propellant performance data, combustion gas thermodynamic properties and turbine drive gas parameters are generated as required to support the other tasks. Assumed efficiencies used in the engine balance calculations were presented in the previous report along with a table of predicted theoretical performance estimates for the selected operating conditions for each of the propellants. Parametric curves of theoretical sea level and vacuum specific impulse as a function of mixture ratio, chamber pressure and area ratio are shown in Fig. 2 through 7 for the three mode 1 propellant combinations. This data is presented for reference and comparison purposes. During this report period, a preliminary study was conducted to verify the validity of mass averaging the specific impulse when H_2 is injected into the main chamber along with the LOX/hydrocarbon.

Both vacuum and sea-level specific impulse valves were considered. I_s valves computed by mass flow averaging were compared with theoretical (ODE) results for the O_2/RP/H_2 propellant system. Figure 8 presents the results of this comparison.

Sea-level I_s values computed by mass averaging are generally quite close to the theoretical values, usually within 1.5 sec. Vacuum results have a somewhat greater spread.

In general, the mass-averaged I_s values are sufficiently close to the theoretical values to permit their use in system definition studies.

Several mechanisms have been suggested to explain the difference in I_s computed by mass averaging and theoretical values. Mass averaged I_s values are lower than theoretical. This may be due to exothermic reactions which occur in the combustion chamber between propellant components which are not modeled by the assumptions implicit in mass averaging. These reactions arise because the composition of the combined constituents in the chamber is not the same as the mass-averaged composition.

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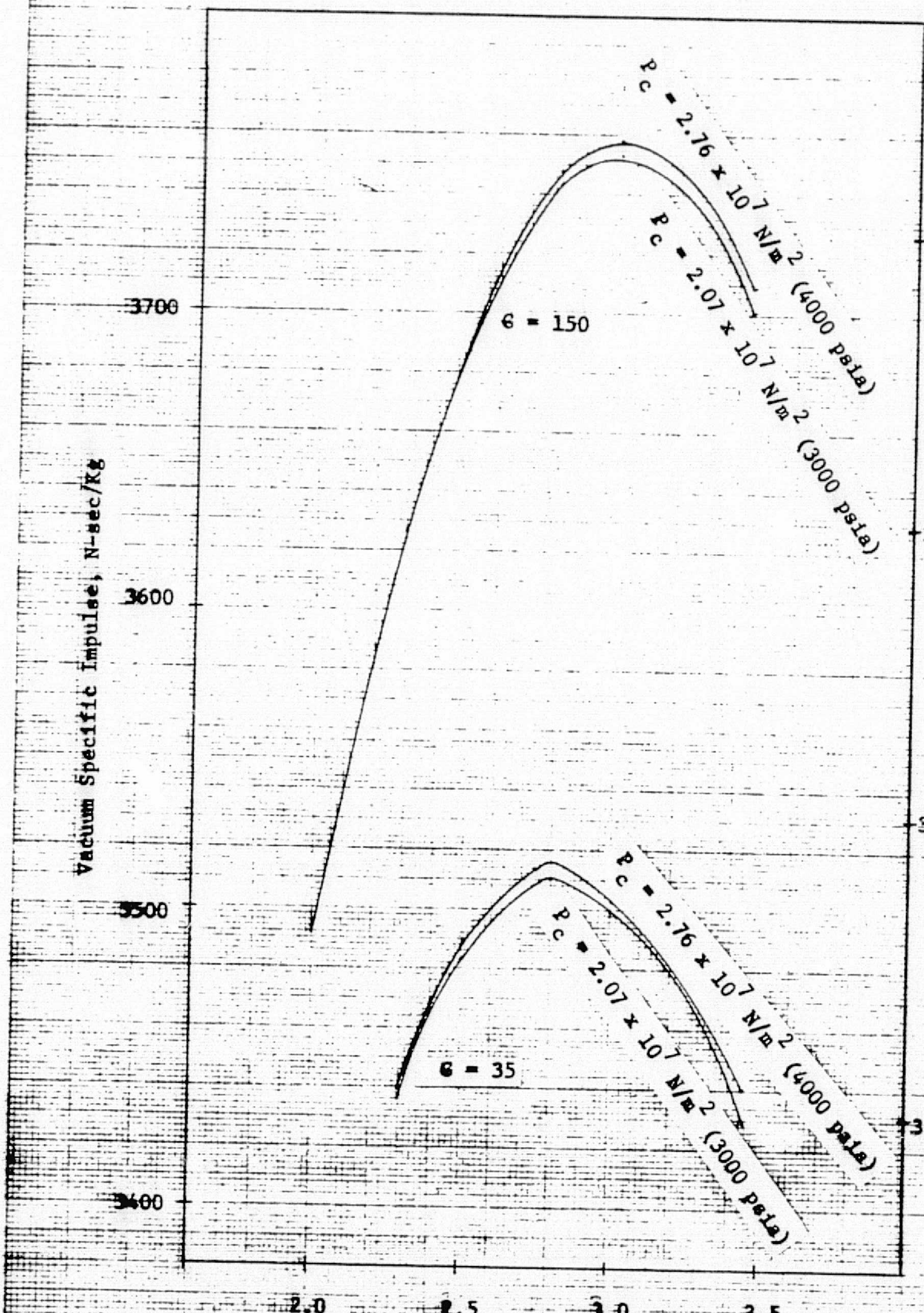

Figure 2 . Theoretical Vacuum Performance for Oxygen/RP-1

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JFG

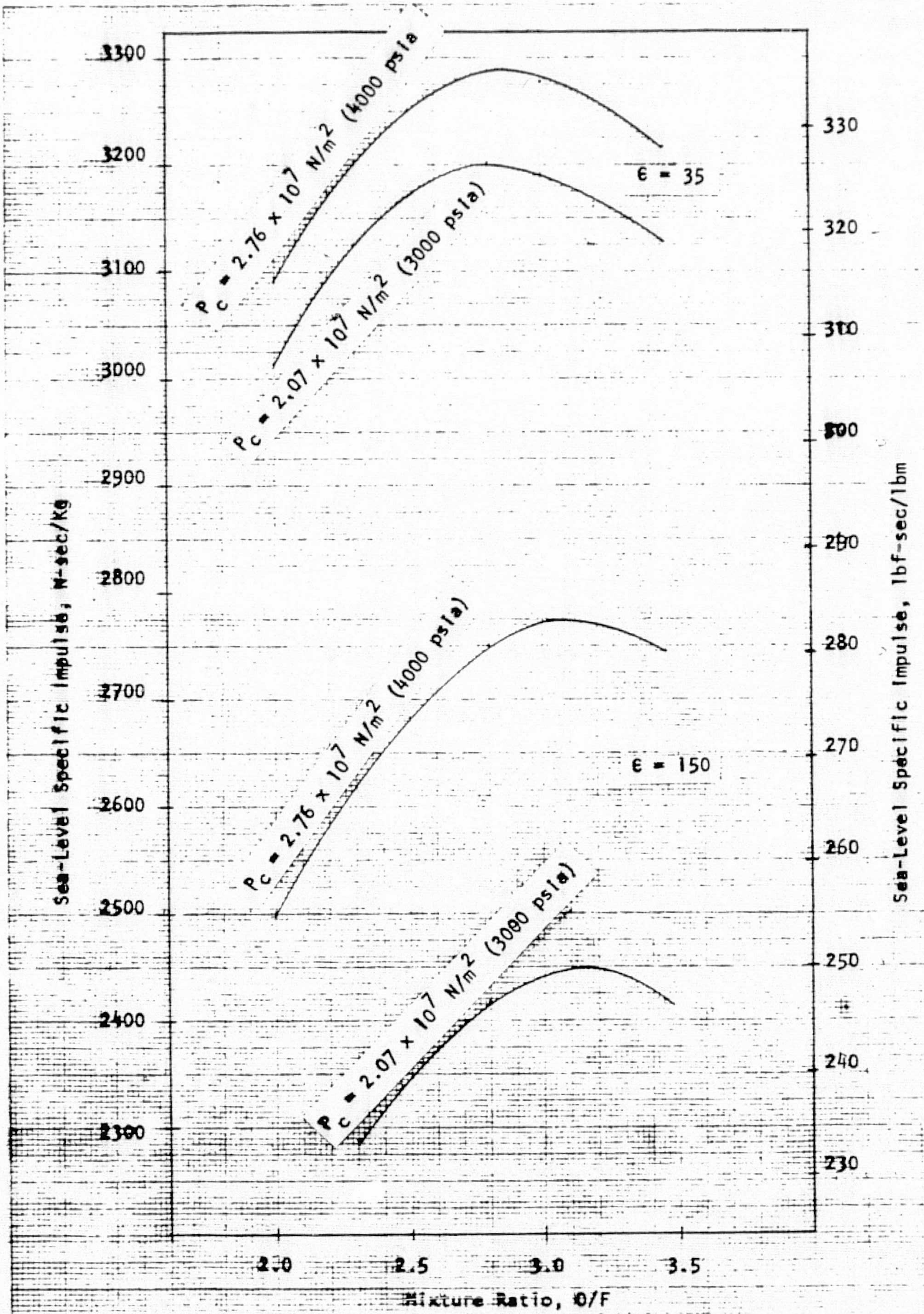

Figure 3. Theoretical Sea-Level Performance for Oxygen/RP-1

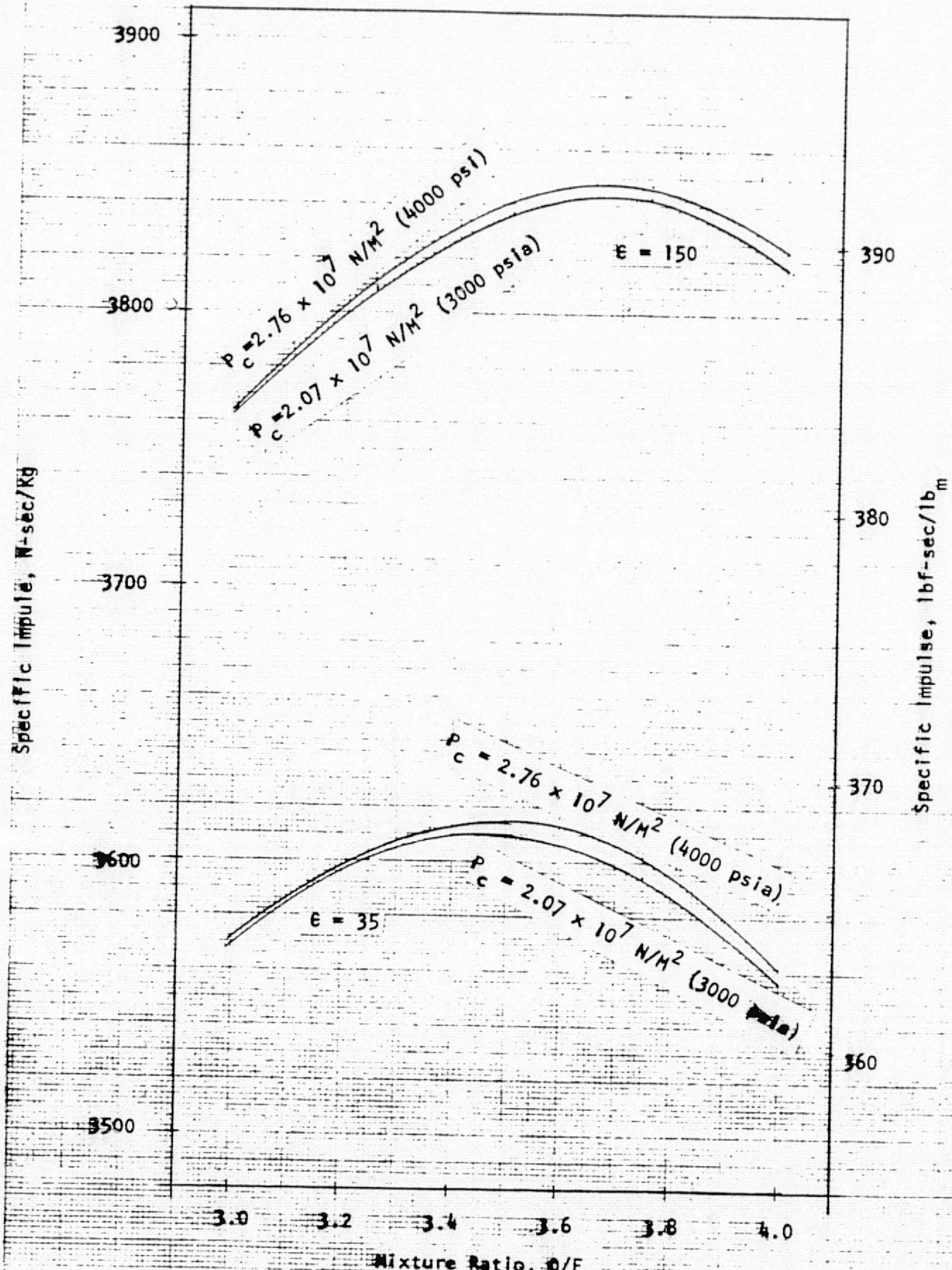

Figure 4. Theoretical Vacuum Performance for O_2/Methane (${O_2}/{CH_4}$)

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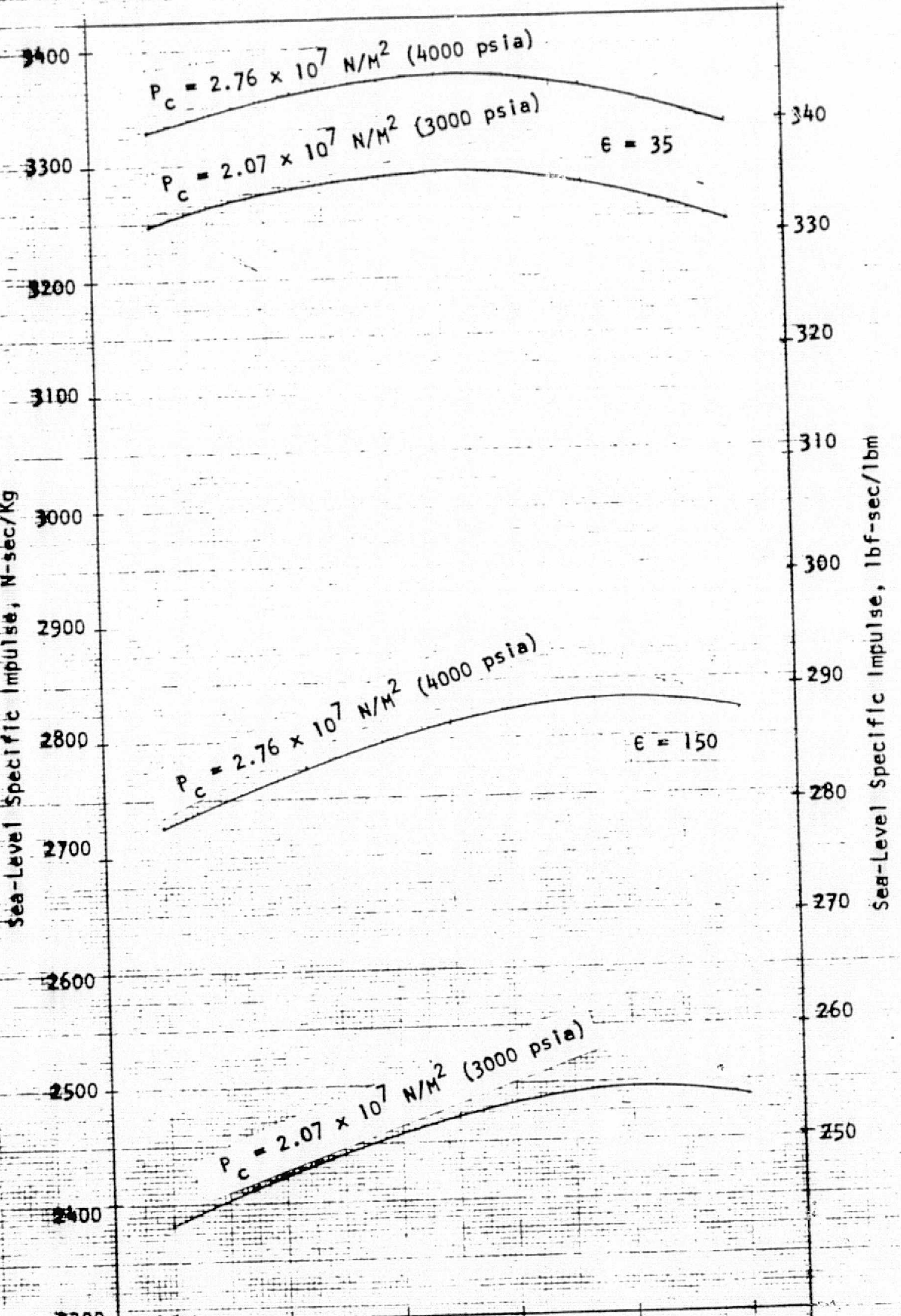

Figure 5. Theoretical Sea-Level Performance for O_2/Methane (O_2/CH_4)

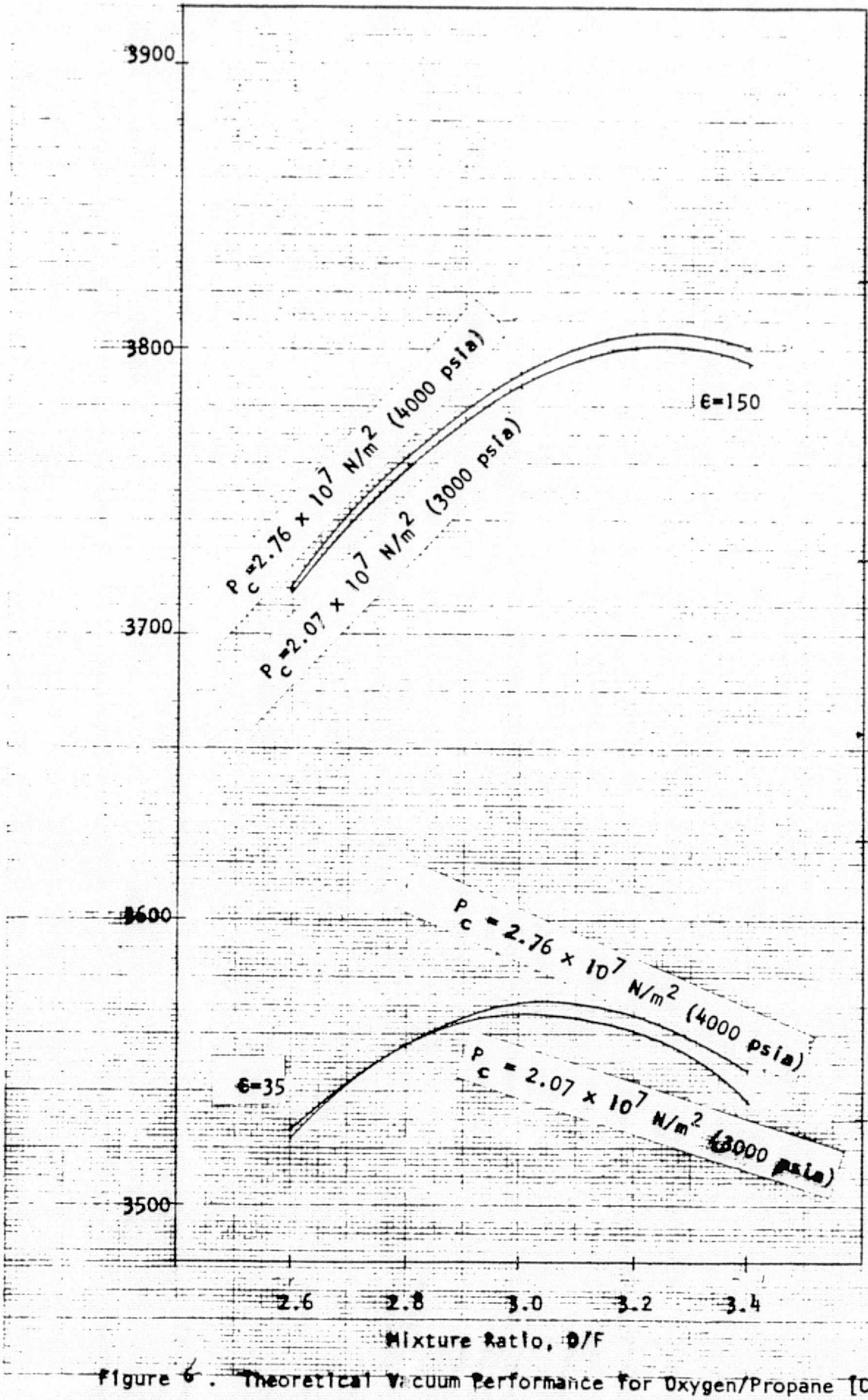

Figure 6 . Theoretical Vacuum Performance for Oxygen/Propane [C_3H_8/O_2]

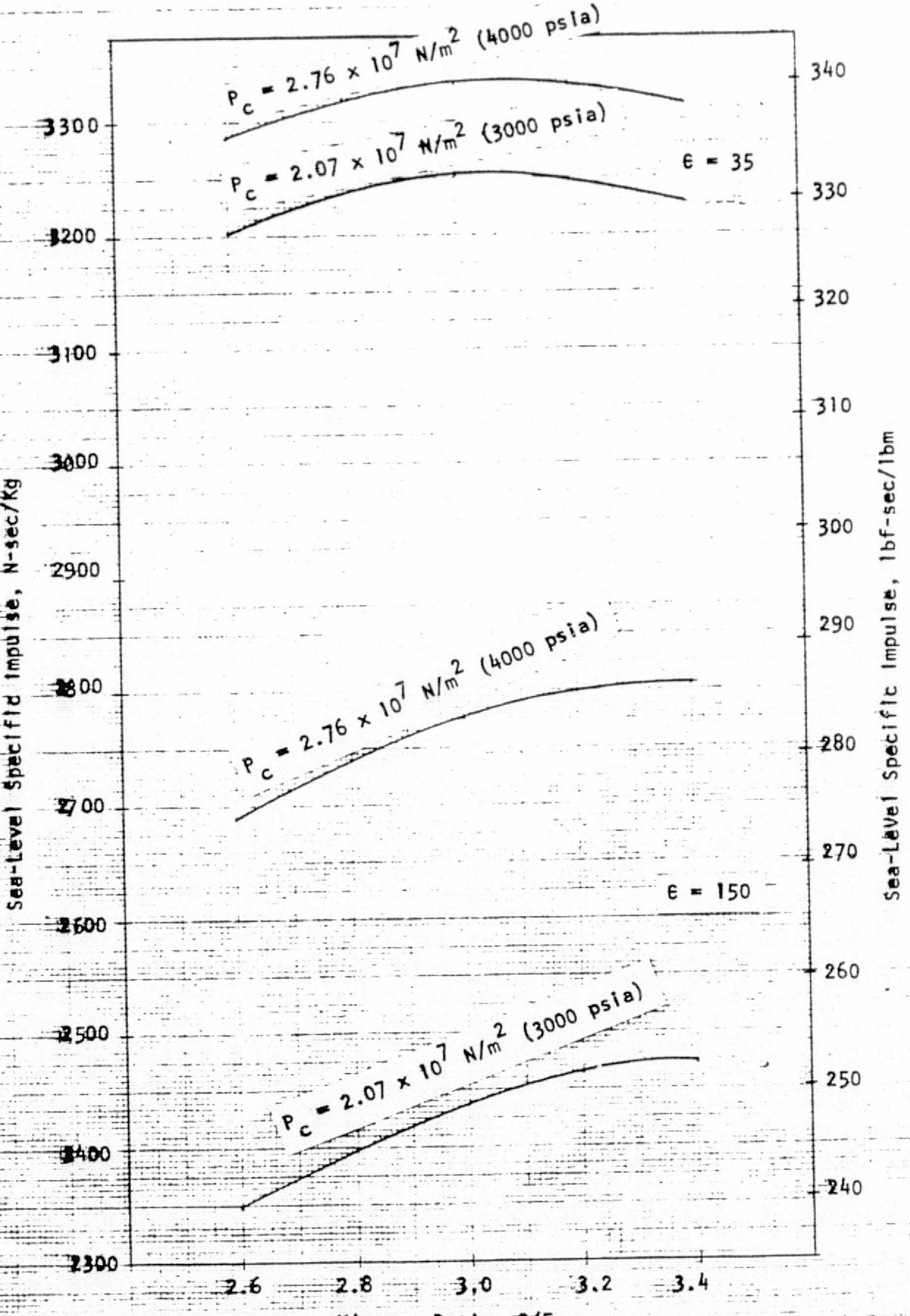

Figure 7. Theoretical Sea-Level Performance for Oxygen/Propane (O_2/C_3H_8)

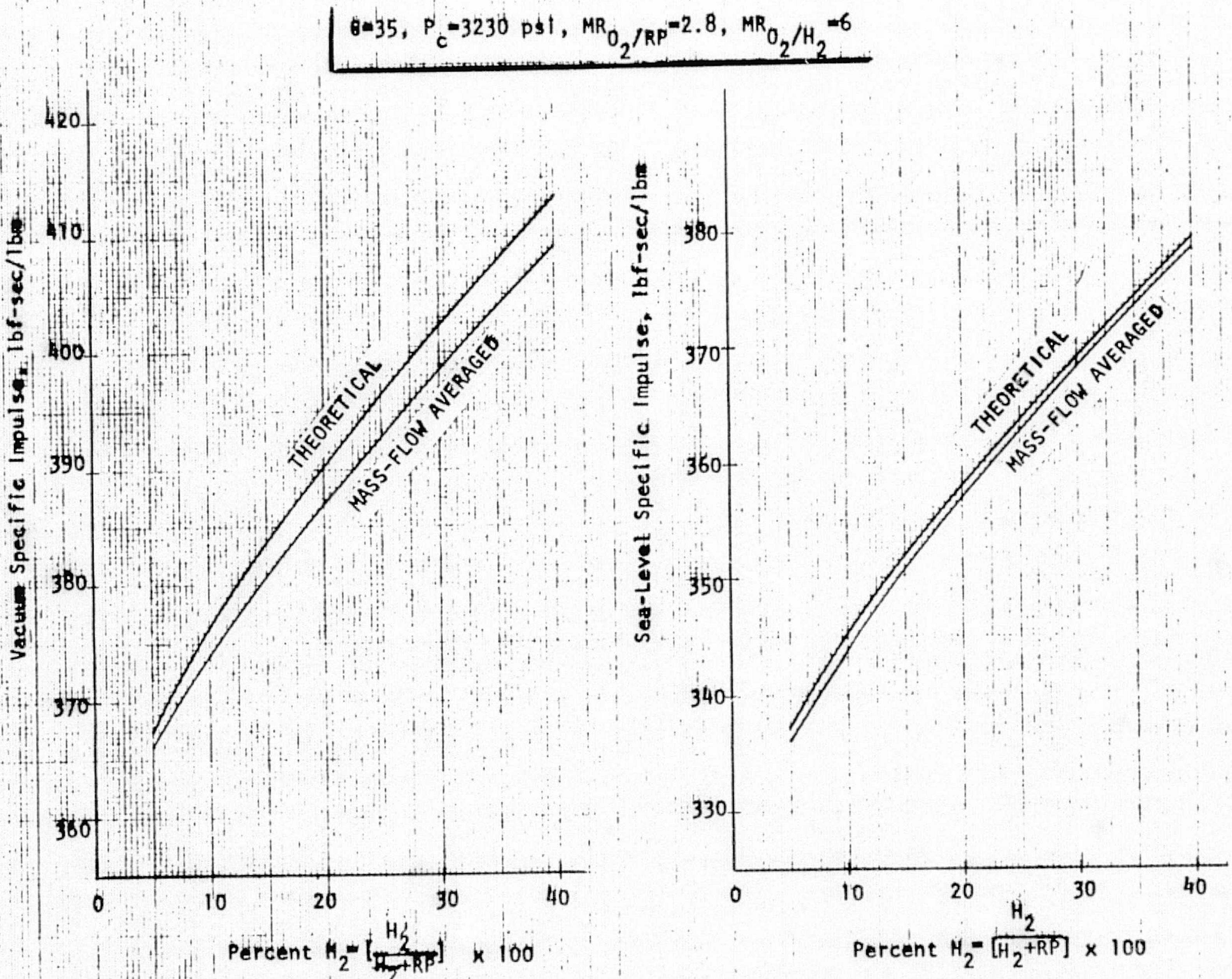

Figure 8. Comparison of Vacuum and Sea-Level Performance for $O_2/RP/H_2$ Calculated by two methods

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In performing the mass-average calculations, specific impulse values are selected for the two bipropellant pairs (O_2/H_2, O_2/RP) at one specific area ratio (ϵ). The values are then used to predict the performance of the combined system. However, each propellant combination results in different gas properties (e.g., γ) which result in different exit pressures at fixed ϵ. This pressure mismatch is ignored in mass-averaging I_s values, and may explain some of the difference between these values and theoretical ones.

Finally, it should be noted that the O_2/H_2 and O_2/RP specific impulse values used to predict O_2/RP/H_2 performance are each based upon a specific mixture ratio (O/F). In theoretical computations of tripropellant performance, the actual proportions of O_2 to H_2 and RP are fixed by the chemistry in the combustion chamber. These proportions may differ from those assumed, resulting in differing performance values computed.

This comparison and the proposed explanations represent only a cursury analysis and a much more thorough investigation would be required in order to reach a more comprehensive conclusion.

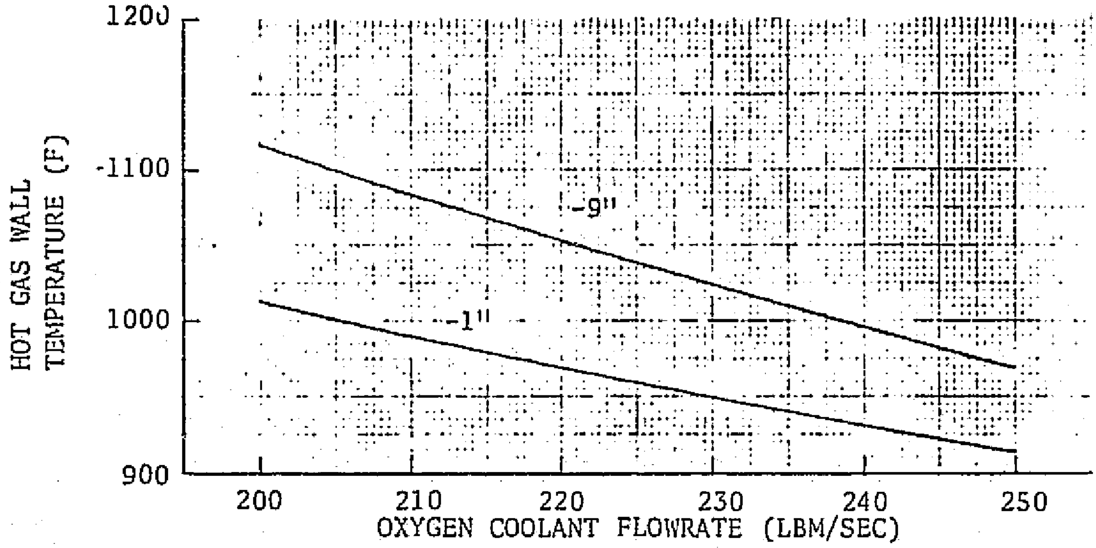
TASK II - CHAMBER COOLING STUDIES

This task effort is concerned with providing the heat transfer and cooling analysis support for the selected engine systems that are being studied. In the previous report, the method of analysis ground rules, and the results of the hydrogen and hydrocarbon cooling systems are presented. During this report period oxygen cooling capabilities and H_2 cooling of an extendible nozzle were investigated.

Oxygen Cooling

The oxygen cooling requirements have been determined for O_2/hydrocarbon combustion in the SSME main chamber and a 35:1 nozzle. A chamber pressure of 3230 psia and the current SSME combustion chamber and coolant channel geometry with a parallel up-pass circuit were assumed. The results of this analysis are presented in Fig. 9 and 10. To maintain a maximum hot gas wall temperature of 1050F (typical of SSME conditions) requires a coolant flowrate of 220 lb/sec and 275 lb/sec in the chamber and nozzle, respectively. At these flowrates a coolant temperature rise and ΔP of 450F and 4000 psi occurs in the chamber and 625F and 500 psia in the nozzle. These values are based on a 9000 psia inlet pressure. Preliminary engine balance results indicate that an inlet pressure of approximately 8600 psia is required to achieve a chamber pressure of 3230 psia (concept No. 10 and 11). If the inlet pressure drops much below that value, there is the danger of the flow choking in the cooling jacket. It was found in the analysis that at 8000 psia inlet pressure, choking would occur at a flowrate of 210 lb/sec or greater. Because of the very high inlet pressure and pressure drop requirements which result for the chamber due to the SSME channel geometry constraint it was decided to conduct an additional analysis to determine how much the inlet pressure and ΔP requirement could be reduced by adopting a more nearly optimum channel configuration for the combustion chamber. A chamber was configured using a narrower channel and thinner hot gas wall and the cooling analysis was repeated. The results, presented in Fig. 11 for an inlet pressure of 7000 psia, show that the combustion chamber coolant flowrate can be reduced to 150 lb/sec with a resulting pressure drop of 2100 psia. The pressure drop could be reduced further by increasing the channel height in order to increase the coolant flowrate for a given mass velocity. This will reduce the coolant temperature rise and the resultant pressure drop. Since the chamber coolant inlet pressure and pressure drop drive the pump discharge pressure requirement, there is no incentive to redesign the nozzle channel geometry.

Further studies are in progress to investigate LOX cooling with LOX/H_2 combustion to be sure this cooling method is applicable for mode 2 operation. The main incentive for LOX cooling is the capability of maintaining the same coolant for mode 1 and 2.



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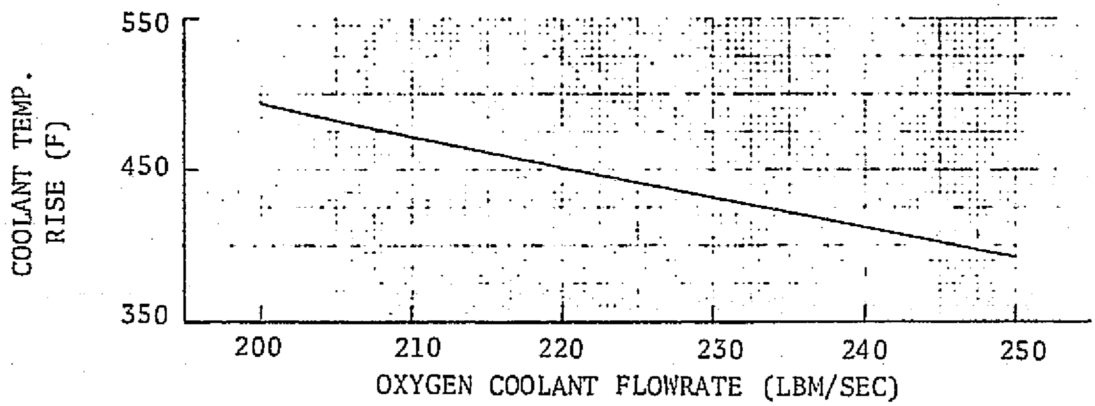

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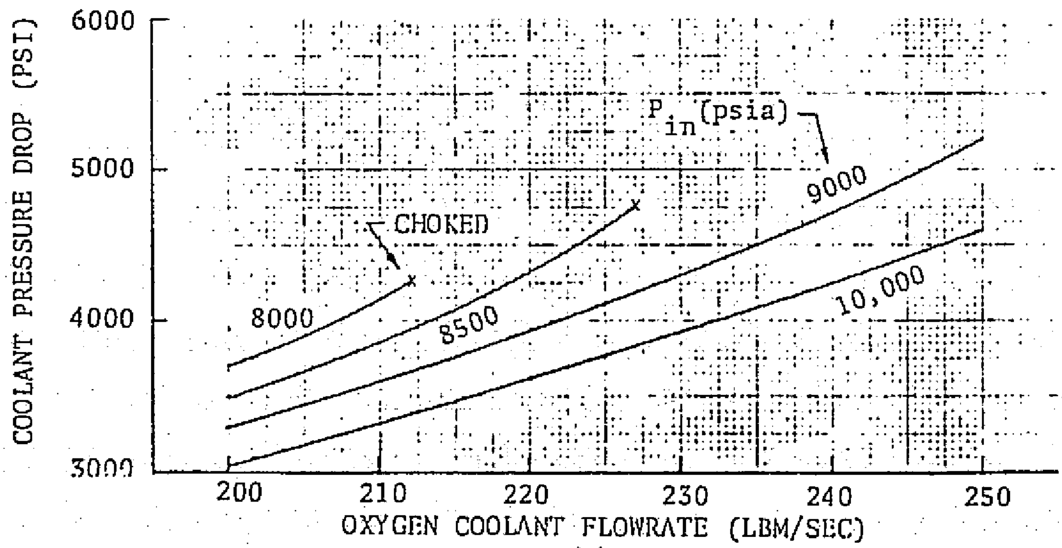

(C)

Figure 9. Wall Temperature, Coolant Temperature Rise, and Coolant Pressure Drop for a P_c=3230 psia O_2/Hydrocarbon O_2 Cooled Up-pass Chamber (Present SSME Channel Design)

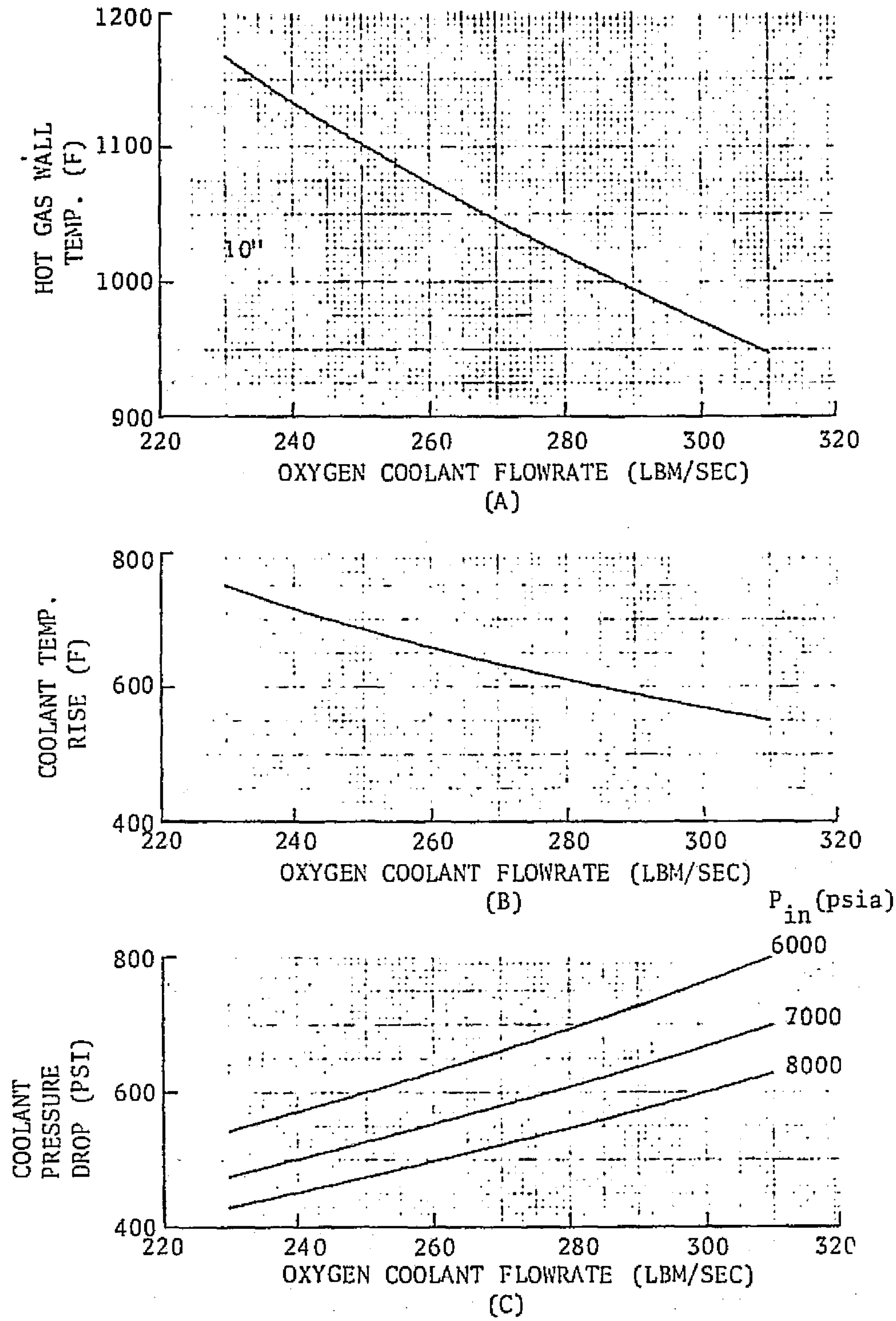

Figure 10. Wall Temperature, Coolant Temperature Rise, and Coolant Pressure Drop for a P_c = 3230 psia O_2/Hydrocarbon O_2 Cooled Up-Pass 35:1 Nozzle

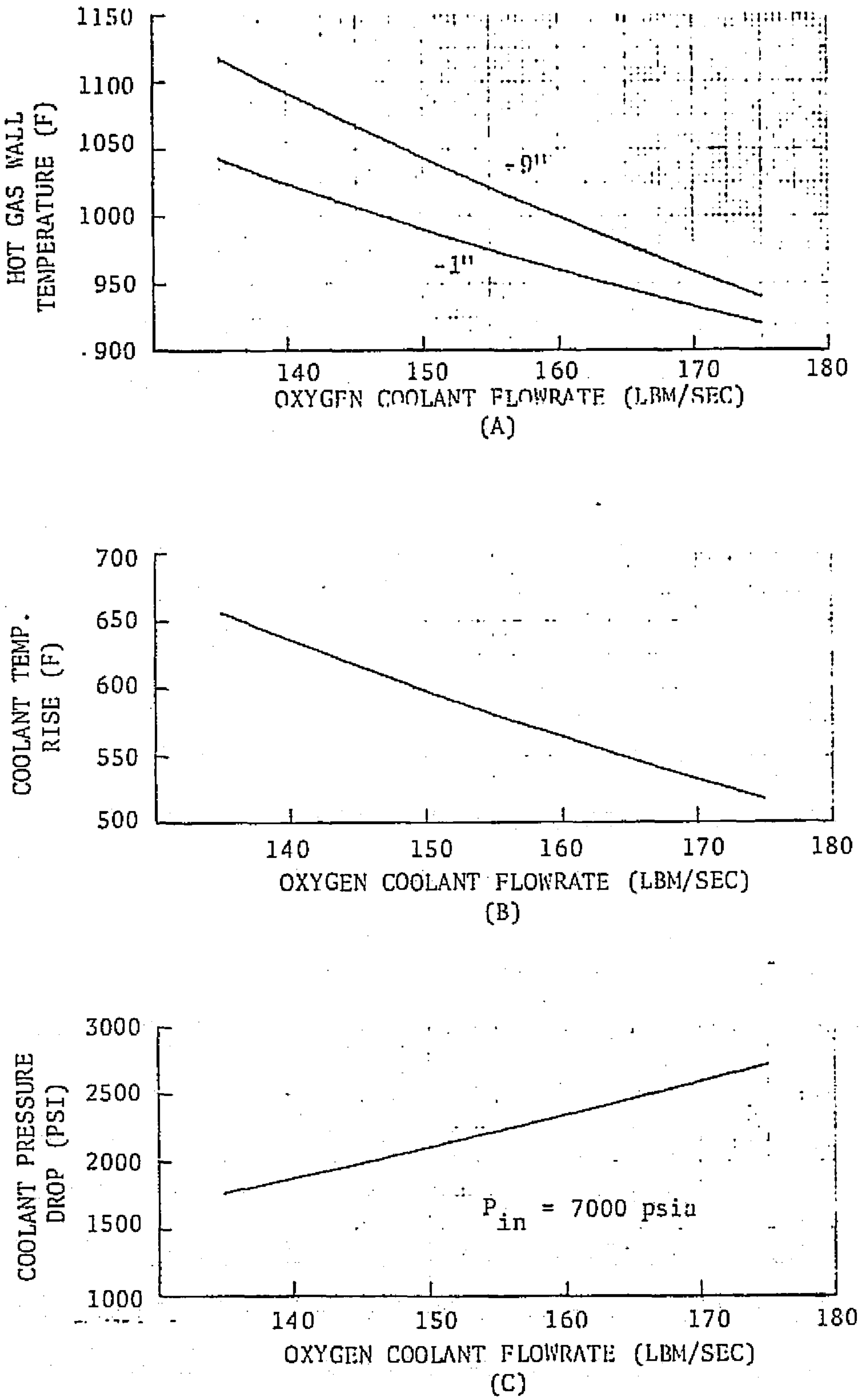

Figure 11. Wall Temperature, Coolant Temperature Rise, and Coolant Pressure Drop for a P_c = 3230 psia O_2/Hydrocarbon O_2 Cooled Up-Pass Chamber (Channel Redesign)

H_2 Cooling of an Extendible Nozzle

The extendible nozzle contour used in this analysis along with the SSME development nozzle contour is shown in Fig. 12. For this analysis no effort was made to optimize the extendible nozzle contour. The chamber throat radius is 5.15 inches (SSME main chamber).

The hot gas heat transfer coefficient as a function of the nozzle expansion ratio is shown in Fig. 13. From ϵ = 5:1 to ϵ - 35:1 the heat transfer coefficient is for the SSME development nozzle at RPL (P_c = 3237 psia). From ϵ = 35:1 to ϵ = 150:1 the heat transfer coefficient is obtained by extrapolation of the curve from ϵ = 5:1 to ϵ = 35:1.

For this analysis a constant diameter tube is assumed. The number of tubes was varied to minimize the coolant flowrate while maintaining a reasonable size tube. The geometry selected consists of 2520 (7x360) tubes with an unformed diameter of 0.16 inch. A tube wall thickness of 0.009 inch was assumed. The tube material is A-286 (same as the SSME nozzles).

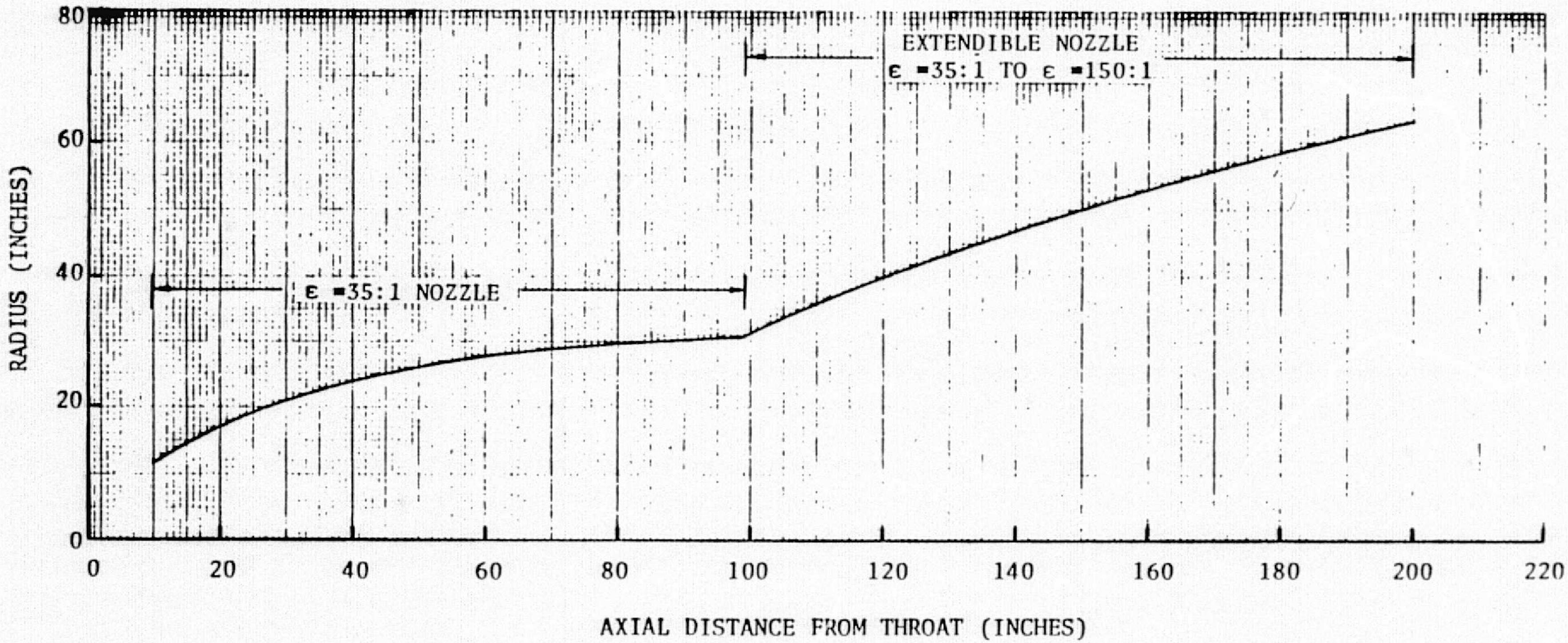

Figure 12. Extendible Nozzle Contour

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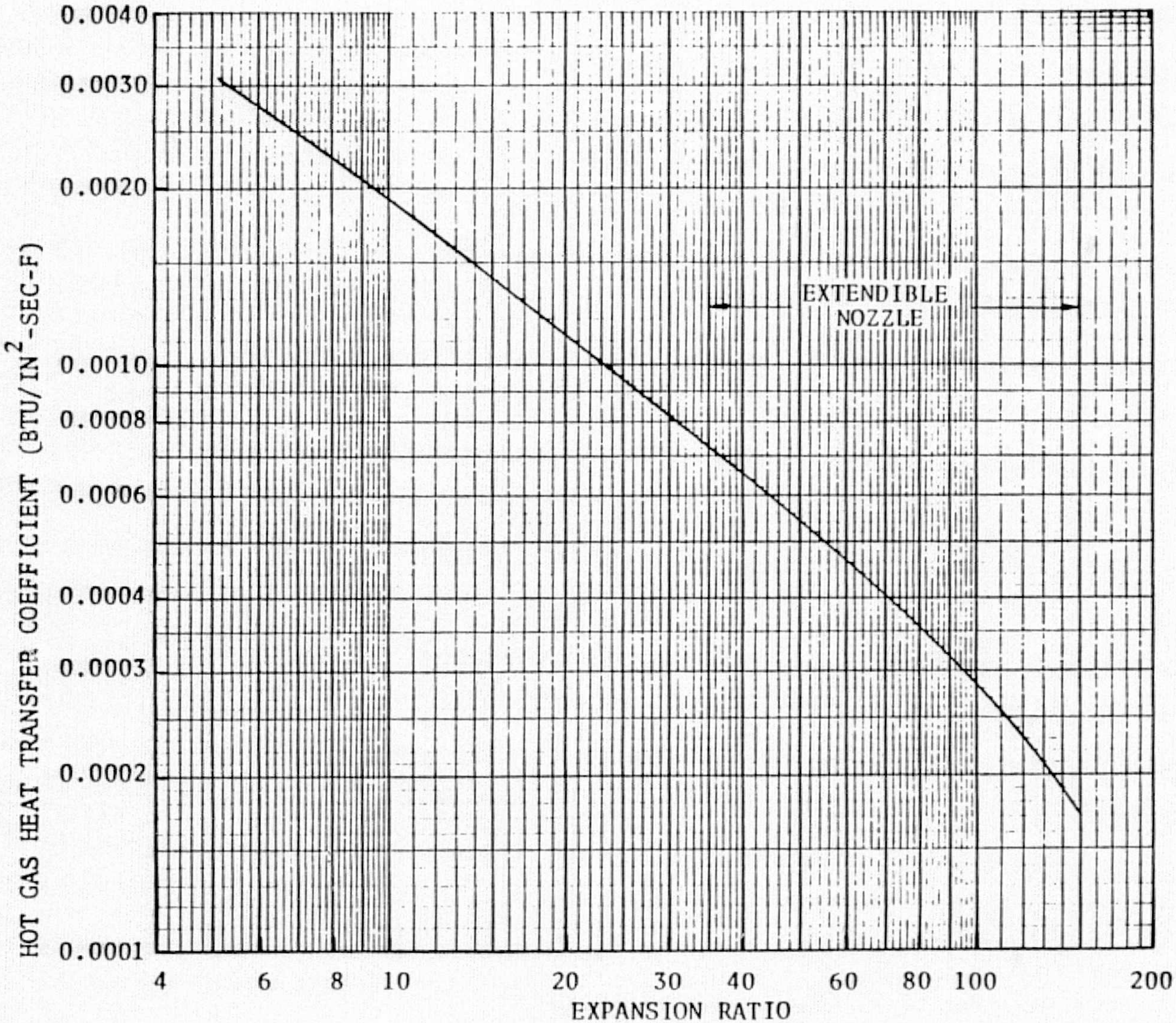


Figure 13. Hot Gas Heat Transfer Coefficient Profile (P_c = 3237 psia)

A downpass coolant circuit has been selected for this design. This provides the low temperature coolant in the maximum heat flux region (minimum expansion ratio). A coolant inlet pressure of 7000 psia and an inlet temperature of -360F are assumed.

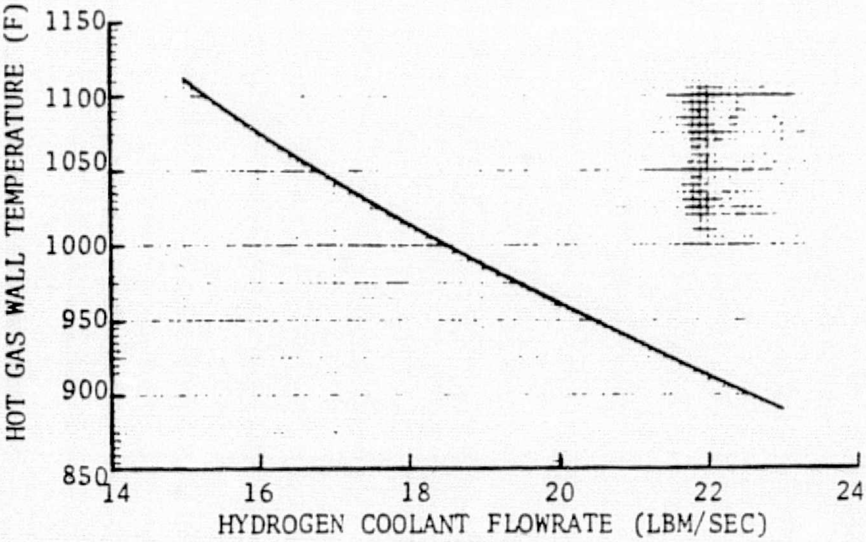
The maximum hot gas wall temperature as a function of the coolant flowrate is shown in Fig. 14 . To keep the maximum wall temperature at 1000F would require a coolant flowrate of 18.5 lbm/sec. The maximum coolant mass velocity is 0.7 lbm/in^2-sec. The maximum heat flux is 3.2 Btu/in^2-sec and the nozzle heat load is 58,500 Btu/sec. For a coolant flowrate of 18.5 lbm/sec the coolant temperature rise is 840F and the pressure drop is only 7 psi. This analysis is definitely preliminary and is only intended to show the feasibility of H_2 cooling of an extendible nozzle and the impact on the system. Considerable further analysis is required before a recommended design could be established.

TASK III - CYCLE AND POWER BALANCE

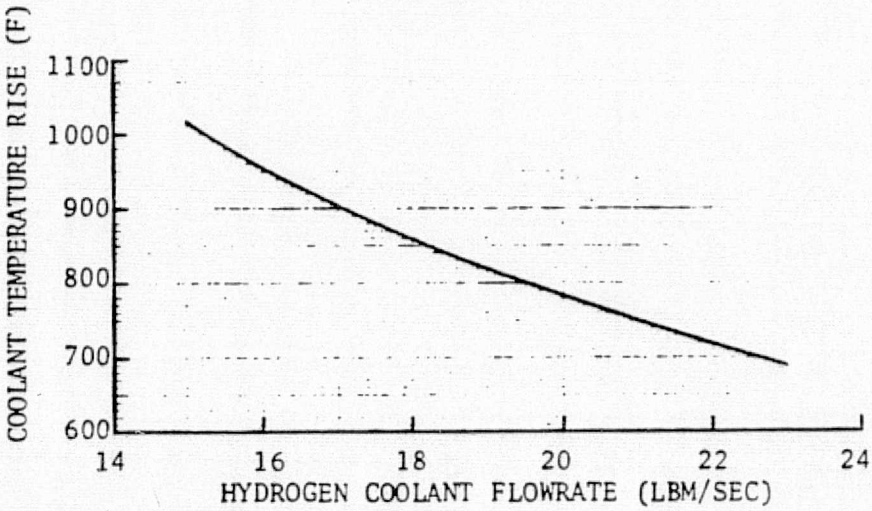
The objectives of this task are to define the cycles and perform cycle power balances to determine the required component flow rates, turbine inlet temperatures and pump discharge pressures based on the pressure losses of the various components. Both staged combustion and gas generator power cycles are being considered along with a variety of cooling schems for these tripropellant engine systems capable of both mode 1 and mode 2 operation in series.

Engine Balances

During this report period the engine balances for the 15 candidate systems were completed and updated. The major component flowrates, turbine inlet temperature and pump discharge pressure requirements are presented in Table 1



(a)



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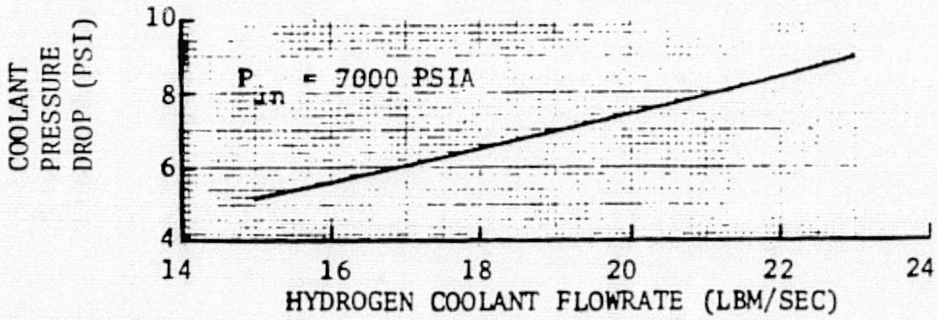

(c)

Figure 14. Wall Temperature, Coolant Temperature Rise and Coolant Pressure Drop for a P_c = 3237 psia O_2/H_2 Hydrogen Cooled Downpass Extendible Nozzle (ε =35:1 to ε =150:1)

Table 1. Candidate Engine Concepts

CONCEPT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CYCLE TYPE	S.C. ①	S.C. ②	S.C. ①	S.C. ②	S.C. ①	S.C. ②	G.G.	G.G.	G.G.	S.C. ①	S.C. ②	S.C. ②	S.C. ②	G.G.	G.G.
P_C	3230	3230	3230	3230	3230	3230	4000	4000	4000	3230	3230	3230	3230	4000	4000
S.L. THRUST	460K	460K	465K	465K	464.6K	464.4K	470K	470K	470K	470K	470K	470K	470K	470K	470K
VAC THRUST	500K	500K	508.6K	508.6K	507.6K	507.6K	502K	504K	503.5K	511.7K	511.7K	516.2K	515K	505K	504K
PROPELLANTS	O_2/RP-1	O_2/RP-1	O_2/CH_4	O_2/CH_4	O_2/C_3H_8	O_2/C_3H_8	O_2/RP-1	O_2/CH_4	O_2/C_3H_8	O_2/RP-1	O_2/RP-1	O_2/CH_4	O_2/C_3H_8	O_2/CH_4	O_2/C_3H_8
COOLANT	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	O_2	O_2	CH_4	C_3H_8	CH_4	C_3H_8
TURBINE DRIVE FLUID	O_2/RP-1	O_2PR-1	O_2CH_4	O_2/CH_4	O_2/C_3H_8	O_2/C_3H_8	O_2/H_2	O_2/H_2	O_2/H_2	O_2/RP-1	O_2/RP-1	O_2/CH_4	O_2/C_3H_8	O_2/CH_4	O_2/C_3H_8
M.R.	2.8	2.8	3.5	3.5	3.0	3.0	2.8	3.5	3.0	2.8	2.8	3.5	3.0	3.5	3.0
I_S S.L., SEC	333.8	333.8	339.2	339.2	335.7	335.7	329.7	336.9	334	317.6	317.6	324	320	332	313.8
I_S VAC, SEC	362.5	362.5	371	371	366.7	366.7	352.3	361.3	358	345.8	345.8	356	351	356	336.6
$T_{TURBINE}$, R	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
PREBURNERS/GG, LB/SEC															
O_2	478.8	733.2	533.8	945.9	549.5	887.8	13.9	15.8	14.7	655.7	765.5	659.2	776	28.6	33.6
FUEL	240.3	22.2	207.1	25.2	247.6	26.1	-	-	-	144.5	23.2	17.6	22.8	66.5	76.4
H_2	-	-	-	-	-	-	17.4	19.7	18.3	-	-	-	-	-	-
$\dot{\omega}_{TURBINE}$, LB/SEC															
O_2	396.8	396.8	459.9	459.9	459.4	459.4	18.5	18.9	18.5	622.4	622.4	378.6	337.6	47.8	62.2
FUEL	174.7	187.3	184.3	324.8	206.7	267.2	5.4	8.5	6.9	177.9	166.2	299	461.2	47.2	47.9
H_2	147.6	171.3	96.1	186.3	131.0	187.2	7.5	7.5	7.5	-	-	-	-	-	-
$\dot{\omega}$ COOLANT, LB/SEC	34	34	34	34	34	34	34	34	34	225COMB 275NOZ	225COMB 275NOZ	97.5 120	140COMB 140NOZ	125COMB 150NOZ	140COMB 140NOZ
$\dot{\omega}_{O_2}$ (TOTAL), LB/SEC	1045	1045	1085	1085	1063.5	1063.5	1056	1084	1058	1090.4	1090.4	1128	1101	1102	1074.5
$\dot{\omega}_{FUEL}$ (TOTAL), LB/SEC	300.3	300.3	252	252	286.5	286.5	335.7	277	314	389.4	389.4	322	367	373	423.3
$\dot{\omega}_{H_2}$ (TOTAL), LB/SEC	34	34	34	34	34	34	34	34	34	-	-				
$\dot{\omega}_{TOTAL}$, LB/SEC	1379	1379	1371	1371	1384	1384	1425	1395	1407	1479.8	1479.8	1450	1468	1476	1497
$\dot{\omega}_{H_2}$ T.C., LB/SEC	34	34	34	34	34	34	17	14.3	15.7	-					-
PUMP DISCHARGE PRESSURE															
LOX P.B. CHAMBER	7331 4123	7331 4123	7331 4123	7331 4123	7331 4123	7331 4123	5106	5106	5106	7331 8600	7331 8600	7331 4123	7331 4123	5106 5106	5106
FUEL P.B. CHAMBER	7331 4123	7331 4123	7331 4123	7331 4123	7331 4123	7331 4123	5106	5106	5106	7331 4123	7331 4123	7331 6064	7331 6064	5466 8606	5107 7712
H_2	4000	4000	4000	4000	4000	4000	6084	6084	6084	-	-	-	-	-	-

① LOX TURBINE LOX RICH
FUEL AND H_2 TURBINE FUEL RICH

② ALL PREBURNERS LOX RICH

for each of the systems. It was shown in the previous report that those cases with fuel rich preburners could not achieve a power balance unless the turbine inlet temperature exceeded 2200R. Those system candidates were changed to incorporate an oxidizer-rich LOX turbine and the fuel-rich fuel and H_2 turbine. In this way sufficient turbine drive gas flow is available with sufficient energy to limit the turbine inlet temperature to 2000R.

System Schematics

Preliminary engine flow schematics have been generated for each of the engine system concept types. These schematics show the flow paths required for both mode 1 and mode 2 operation but all control components (valves, check valves, etc.) are not shown. A separate study conducted within Task IV will develop control requirements and necessary components. It was found that in some cases it was necessary to indicate isolation valves for the purpose of clarity. Boost pump drive methods were maintained as in the SSME where possible. In those cases where additional pumps are required or concepts don't permit the same boost pump drive technique, a logical alternative is selected but is not necessarily the only method that might be considered.

A schematic representative of systems 1 through 6 is shown in Fig. 15. All three turbopumps must operate during mode 1 as the combustion chamber and nozzle are H_2 cooled in both mode 1 and mode 2. The H_2 bypass from the pump to the main chamber and the H_2 flow to the preburners is only required during mode 2 operation. Pump studies are showing that it is questionable whether one pump (SSME main H_2 pump) can satisfy both mode 1 and mode 2 H_2 head and flow requirements. The hydrocarbon (H.C.) pump only operates during mode 1. The LOX high pressure or kick pump stage is required to feed the preburners in both mode 1 and mode 2 operation. The H.C. boost pump is assumed to be driven in parallel with the H.C. main pump by preburner gases. The LOX and

DUAL MODE, HYDROGEN COOLED, STAGED COMBUSTION FLOW SCHEMATIC FOR CONCEPTS #1 THRU #6

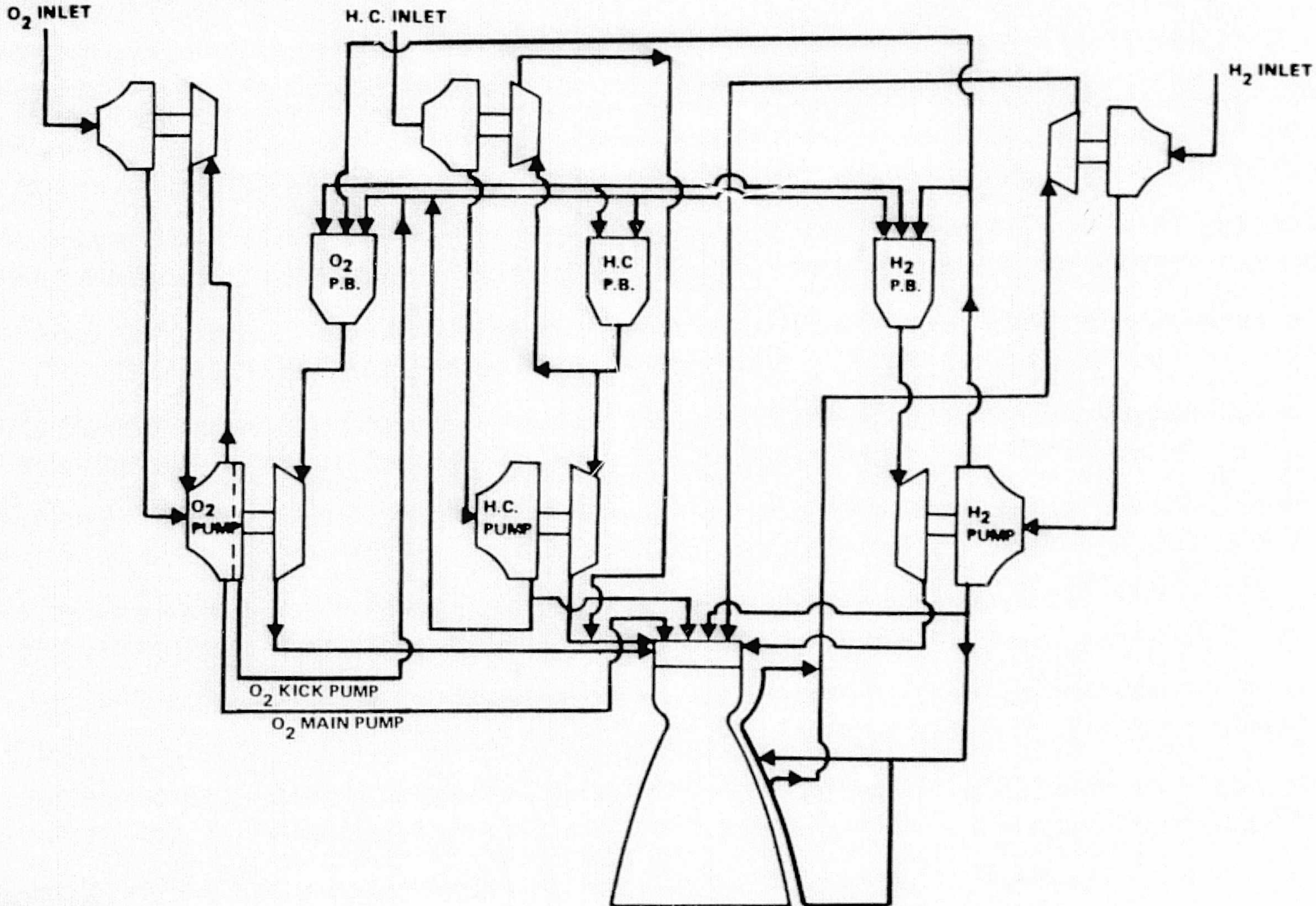

Figure 15

H_2 preburners must operate on either LOX/H.C. or LOX/H_2 as does the main chamber.

The schematic for system concepts 7, 8 and 9 is shown in Fig. 16 and is typical of a low pump discharge pressure gas generator cycle. The chamber and nozzle are H_2 cooled in both mode 1 and mode 2 and the chamber coolant flowrate is adequate to satisfy the gas generator requirements. Again in this case the H_2 flowrates are greatly different between mode 1 and 2 and the H_2 bypass from the pump to the chamber is only needed during mode 2. It is questionable whether the SSME H_2 main pump can satisfy this requirement. All of the turbines are driven in parallel with a single gas generator and the turbine exhaust pressures are collected and ducted into the main nozzle where the expansion pressure matches the turbine exhaust pressure (approximately 200 psia). In this case the H.C. boost pump is driven by the H.C. main pump through a hydraulic turbine as is the case for the SSME LOX boost pump. The H_2 coolant flow through the nozzle supplies the hot gas flow to drive the H_2 boost pump.

System concepts No. 10 and 11, as shown in Fig. 17, are quite similar to No. 1 and 2 except that they are LOX cooled instead of H_2 cooled. The lack of H_2 being injected into the main chamber explains the difference in performance. The LOX coolant requirements for the chamber and nozzle are lower than that required for the preburners and the remainder of the LOX flow is not sufficient for the preburner. Therefore, some of the nozzle coolant flow (GOX) is mixed with the LOX being fed to the preburners. This has the added advantage of heating up the LOX before it is injected into the chamber with the hydrocarbon and reducing the possibility of an explosive gel forming.

The schematic for systems 12 and 13 is shown in Fig. 18. These systems are similar to 1 through 6 except that No. 12 and 13 are hydrocarbon cooled during mode 1 and H_2 cooled during mode 2 while No. 1 through 6 are H_2 cooled

DUAL MODE HYDROGEN COOLED, GAS GENERATOR FLOW SCHEMATIC FOR CONCEPTS #7, 8 & 9

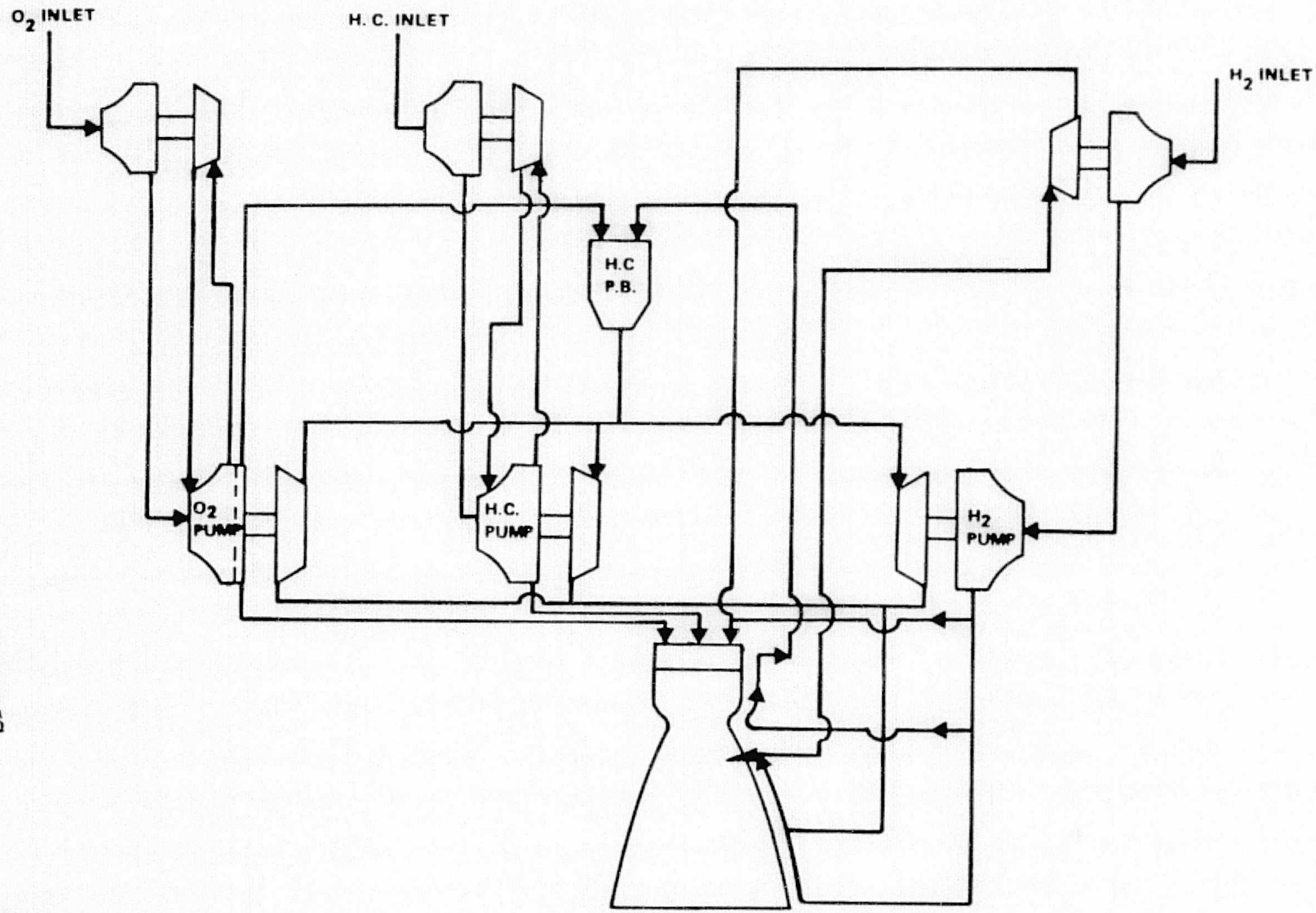

Figure 16

234-582

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DUAL MODE, OXYGEN COOLED, STAGED COMBUSTION FLOW SCHEMATIC FOR CONCEPTS #10 &11

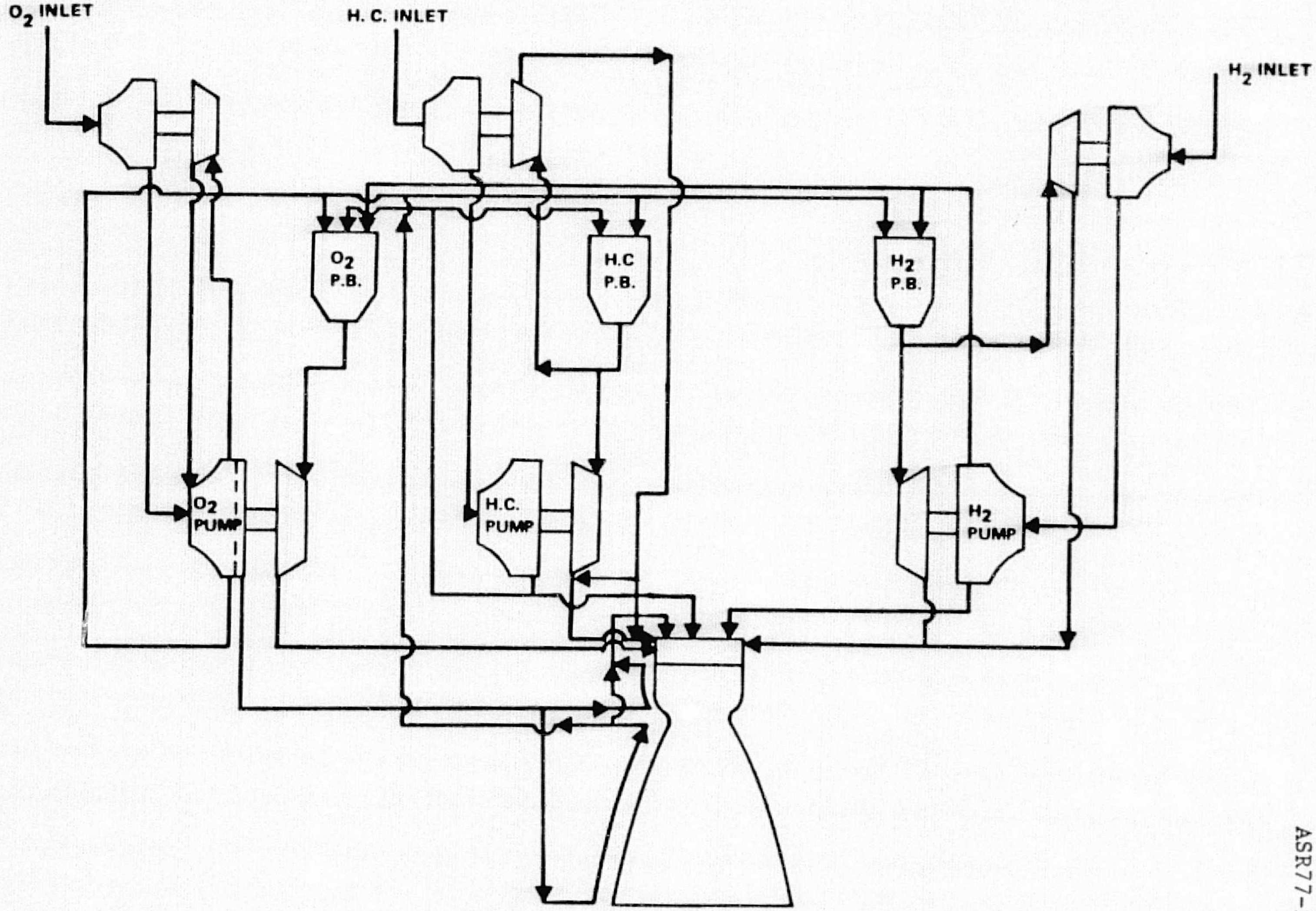

Figure 17

234-583

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DUAL MODE, H.C. H_2 COOLED, STAGED COMBUSTION FLOW SCHEMATIC FOR CONCEPTS #12 & #13

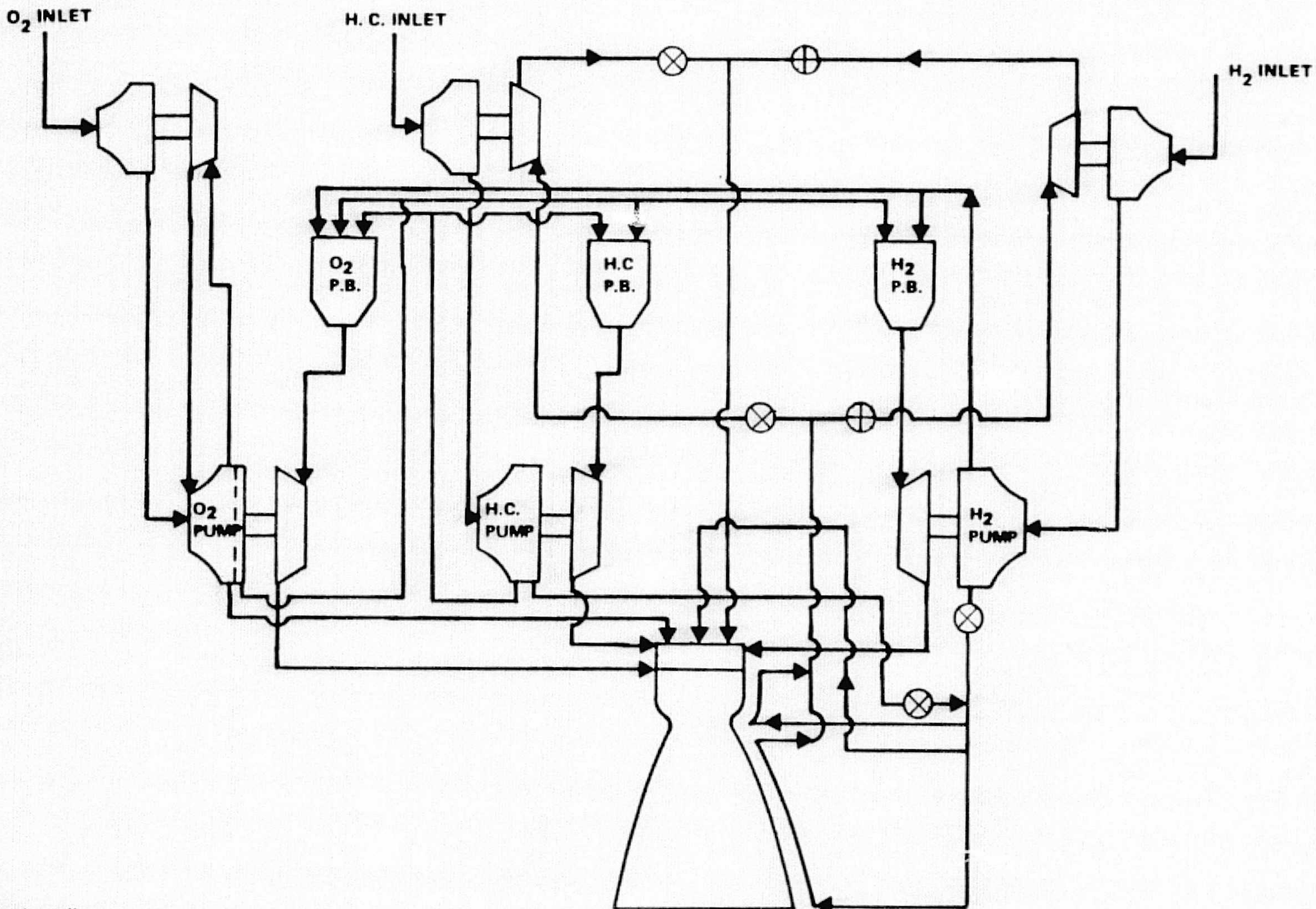

Figure 18

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in both modes. The fuel and the H_2 boost pumps are driven by the nozzle coolant discharge flow. Isolation valves are shown in the boost pump drive gas delivery lines since only the H.C. pump operates during mode 1 (with gaseous H.C. turbine drive gas) and only the H_2 pump operates during mode 2 (GH_2 turbine drive gases). This technique of driving the fuel and H_2 boost pump is only one of several possible; hydraulic turbines or driving them in parallel with the main pumps with the preburner flow could also be considered. The switch of chamber and nozzle cooling from a hydrocarbon in mode 1 to H_2 in mode 2 results in significant system and operational complexities which will be investigated in Task IV.

System concepts 14 and 15 shown schematically in Fig. 19 are again gas generator cycles but differ from No. 7, 8 and 9 in that the chamber and nozzle are hydrocarbon cooled during mode 1 and H_2 cooled during mode 2. The gas generator fuel is supplied by the combustion chamber coolant flow, therefore, the G.G. fuel as well as the main chamber fuel changes between mode 1 and 2. The low pressure booster pumps are driven by the respective nozzle coolants during mode 1 and mode 2.

System Improvements

Mass flow balances shown in Table 1 for system concepts No. 1, 3, 4, 5 and 6 result in a large percentage of either the oxidizer or fuel being combusted in the preburner and the remaining smaller percentage being by-passed directly to the main combustor. This occurs as a result of fixing the turbine pressure ratio, turbine inlet gas temperature and chamber pressure (pump discharge pressure). This results in additional main chamber injector complexity since a third fluid must then be injected into the chamber and where this third flow is relatively small, it would simplify the system if the preburner flows could be increased so that either all of the available oxidizer or fuel could be fed through the preburner.

DUAL MODE H.C. H_2 COOLED, GAS GENERATOR SCHEMATIC FOR CONCEPTS #14 & #15

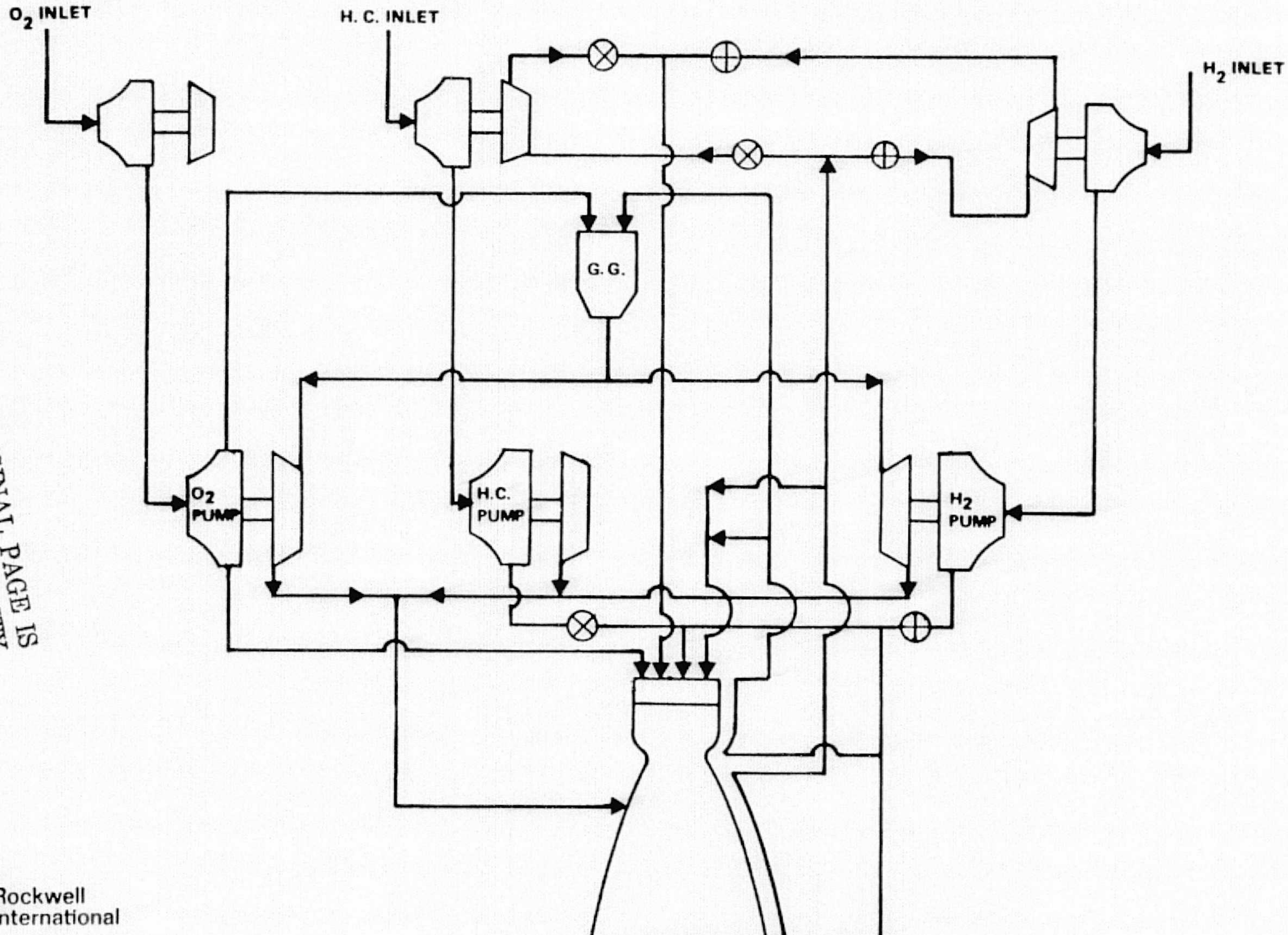

Figure 19

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In system concepts No. 1, 3 and 5, a LOX rich oxygen turbopump and fuel rich fuel and H_2 turbopump were selected since sufficient fuel was not available to run all turbines fuel rich at 2000R inlet temperature. The resulting engine cycle balances use anywhere from 82 to 94 percent of the available hydrocarbon fuel in the preburners. A significant system simplification could be achieved if all of the available fuel were directed through the preburners. A system balance could be achieved with the total hydrocarbon fuel flow to the preburners if one or more of the following alternatives were employed.

1. Increase the chamber pressure by increasing both the oxidizer and fuel flow to the preburners thus providing higher turbine horsepower to accommodate the higher pump discharge pressure requirement.

2. Reduce the turbine pressure ratio thus producing the same horsepower with an increased turbine flow.

3. Reduce the fuel and H_2 turbine inlet temperatures by increasing the fuel flow (reduced mixture ratio) to the respective preburners. The oxidizer turbine inlet temperature could also be reduced by increasing the oxidizer flow to that preburner if desired.

In system concepts 4 and 6 all preburners are operated oxidizer rich with a 2000R turbine inlet temperature and a turbine pressure ratio of 1.6:1. The resulting engine cycle balances require approximately 87 percent of the available O_2 flow to the preburners. Again, the main chamber injector adaptation would be easier if all of the oxidizer were routed through the preburner thus eliminating the need for the liquid oxygen delivery to the main chamber. Again, several alternatives exist as to the possible utilization of this excess oxygen flow to the preburners.

1. The excess oxygen flow could be distributed to the three preburners thus reducing turbine inlet temperature. An iterative flow balance would be required to determine how much this temperature could be reduced since pumping requirements are changing along with turbine drive gas properties.

2. The turbine flows could be increased at the same mixture ratio and temperature thus producing more horsepower and permitting a higher chamber pressure.

3. The turbine flows could be increased, with the same mixture ratio and temperature, with a reduced turbine pressure ratio thus producing the same horsepower at the higher flow.

LOX/H_2 Engine Balances

For the tripropellant engine study it has been assumed that the mode 2 engine operating conditions were well defined since the engine would operate at essentially SSME full power level conditions. This would at least be true for system concepts No. 1 through 6, 12 and 13. For systems 7, 8, 9, 14 and 15 the engine would be required to operate on a gas generator cycle for both mode 1 and 2. Chamber cooling studies with LOX have shown that chamber pressure may be limited with LOX/H_2 combustion due to the poorer cooling capabilities of LOX. Cooling studies are in progress to investigate this and a LOX/H_2 engine balance has not been conducted for the mode 2 operation of system concepts No. 10 and 11.

Engine system mass/pressure balances were established for the LOX/H_2 mode 2 operation to aid in the control system studies being conducted in Task IV. The results are shown in Table 2. The staged combustion system conditions were taken directly from current SSME FPL performance predictions. Balances are shown for both 3230 and 4000 psia chamber pressure for the gas generator cycle.

Table 2. LOX/H_2 ENGINE BALANCE

	STAGED COMBUSTION	GAS GENERATOR	GAS GENERATOR
P_c	3230	4000	3230
S.L. Thrust	379.5K	373.8K	343.4K
Vac. Thrust	525.5K	513.8K	517.5K
Propellants	O_2/H_2	O_2/H_2	O_2H_2
Turbine Drive	O_2/H_2	O_2/H_2	O_2H_2
M.R. (T.C.)	6:1	6:1	6:1
I_s S.L.	337	331.9	304.9
I_s Vac.	466.7	456.3	459.5
$T_{Turbine}$, R			
H.P. Ox	1860	2000	2000
H.P. Fuel	1932	2000	2000
Preburner, R Gas Generator Flowrates, lb/sec			
Oxid			
O_2	32.3	4.88	3.94
H_2	36.1	6.1	4.93
Fuel			
O_2	85.8	23.4	19.0
H_2	87.2	29.3	15.2
$\dot{W}_{Turbine}$			
H.P. Ox.	68.4	10.98	8.87
H.P. Fuel	173.0	52.7	34.2
$\dot{W}_{Coolant}$			
Nozzle	54.5		54.5
Combustor	32.0		32.0
$\dot{W}_{O2}$, Lb/Sec	965	965	965
$\dot{W}_{H2}$, Lb/Sec	161	161	161
$\dot{W}_{Total}$, Lb/Sec	1126	1126	1126
Pump Discharge			
H.P. Lox	4972	5106	4124
Lox Kick	8050		
H.P. H_2	6939	9032	5854

An additional mode 2 staged combustion LOX/H_2 system was investigated which would incorporate LOX rich preburners. This mode 2 system would offer a significant advantage for those mode 1 systems that operate with LOX rich preburners. This would eliminate the main chamber injector difficulties that occur when switching operation from mode 1 to mode 2. This problem is discussed in Task V. It was found that to operate the preburners LOX rich at 2000R temperature, a mixture ratio of 86:1 is required and there is insufficient LOX flow in the system to achieve a power balance. Approximately 1840 lb/sec of LOX are required in the preburner with only 965 lb/sec available. It was therefore concluded that a LOX/H_2 staged combustion engine system at SSME conditions was not feasible with LOX rich preburners.

TASK IV CONTROL REQUIREMENTS DEFINITION

During this task, control methods, their requirements, and the location of control valves in the flow schematic will be investigated. This effort has recently been started and results will be presented in the next report.

TASK V SSME COMPONENT ADAPTABILITY

This task is organized to interact with the efforts of Task I through IV to evaluate the possibility of adapting the already designed and proven SSME components to the candidate systems. Three areas have been addressed during this report period. A study has been conducted to evaluate the adaptability of existing oxidizer and fuel low pressure and high pressure pumps. A separate study is in progress to determine if the existing SSME turbines can satisfy the horsepower and hot gas flow requirements established in the engine balance analysis. A third study is being conducted to investigate the possibility of using the SSME preburners and main injectors in the tri-propellant systems being studies. These studies are not complete but the preliminary results are presented in the following sections.

SSME PUMP APPLICABILITY

The flow and head requirements for each of the candidate systems are presented in Table 3. The part flow pumps supply the fluid flow to the preburners. Pump applicability was determined by plotting the design point head and flow requirements on the SSME pump performance maps (Figs. 20 through 23) that are based on a combination of analytical predictions and experimental test data. The data points that fell within the pump operating limits (defined in Table 4) were then denoted as being acceptable for that application. Due to the very low density of liquid hydrogen relative to the other propellants in Table 3, hydrogen pumps were not applicable to the other propellants. Therefore, hydrogen pumps were considered only for hydrogen and liquid oxygen pumps were used for all other propellants (LOX, RP-1, CH_4, and C_3H_8). For certain very low fuel flowrate cases (Cases 2, 6, 11, 12, and 13), the oxidizer pump for the ASE engine (the MARK 38 oxidizer pump) was found to be very applicable, as shown in Fig. 24. Therefore, that pump was included in the study.

The applicability of the SSME turbines is being evaluated in a separate study; only the pumps are being considered in this discussion. However, the established pump horsepower requirements are being used in the evaluation of the turbines. In some cases if it is found that the turbine is unsatisfactory for a particular application, this will also disqualify the pump for a direct substitution as the SSME turbopumps are an integral unit and it is considered a major modification to separate the two and mate them to a new pump or turbine. The results are summarized in Table 5. As shown, a new pump was indicated if no applicable unit could be found.

As shown in Table 5, the SSME low and high pressure oxidizer turbopumps (LPOTP and HPOTP) were found to be satisfactory for all full flow LOX pumping applications and the HPOTP was found to be satisfactory for all part flow LOX pumping applications. All of the oxidizer part flows (preburner flow) are higher flowrates than the SSME preburner oxidizer turbopump (PBOTB) can handle,

TABLE 3. ENGINE REQUIREMENTS

Case	Propellant	Pump	Weight Flowrate, $\dot{\omega}$, lb/sec	Pressure Rise, ΔP, psi	Propellant Density, ρ, lb/ft^3	Volume Flowrates, Q, gpm	Head Rise, ΔH, ft
1	LOX	Full Flow	1045	4108	71.1	6600	8,320
	LOX	Part Flow	478.8	3208	71.1	3020	6,500
	RP-1	Full Flow	300.3	4108	50.5	2670	11,710
	RP-1	Part Flow	240.3	3208	50.5	2520	9,150
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
2	LOX	Full Flow	1045	4108	71.1	6600	8,320
	LOX	Part Flow	733.2	3208	71.1	4630	6,500
	RP-1	Full Flow	300.3	4108	50.5	2670	11,710
	RP-1	Part Flow	22.2	3208	50.5	197	9,150
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
3	LOX	Full Flow	1085	4108	71.1	6850	8,320
	LOX	Part Flow	533.8	3208	71.1	3370	6,500
	CH_4	Full Flow	252	4108	27.5	4110	21,500
	CH_4	Part Flow	207.1	3208	27.5	3380	16,800
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
4	LOX	Full Flow	1085	4108	71.1	6850	8,320
	LOX	Part Flow	945.9	3208	71.1	5970	6,500
	CH_4	Full Flow	252	4108	27.5	4110	21,500
	CH_4	Part Flow	25.2	3208	27.5	411	16,800
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
5	LOX	Full Flow	1063.5	4108	71.1	6720	8,320
	LOX	Part Flow	549.5	3208	71.1	3470	6,500
	C_3H_8	Full Flow	286.5	4108	36.4	3530	16,250
	C_3H_8	Part Flow	247.6	3208	36.4	3050	12,690
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
6	LOX	Full Flow	1063.5	4108	71.1	6720	8,320
	LOX	Part Flow	887.8	3208	71.1	5610	6,500
	C_3H_8	Full Flow	286.5	4108	36.4	3530	16,250
	C_3H_8	Part Flow	26.1	3208	36.4	322	12,690
	LH_2	TC Coolant	34	3985	4.42	3450	117,500
7	LOX	Full Flow	1056	5091	71.1	6670	10,310
	RP-1	Full Flow	335.7	5091	50.5	2980	14,520
	LH_2	TC Coolant + Turb.	34	6069	4.42	3450	172,700
8	LOX	Full Flow	1084	5091	71.1	6850	10,310
	CH_4	Full Flow	277	5091	27.5	4520	26,700
	LH_2	TC Coolant + Turb.	34	6069	4.42	3450	172,700

TABLE 2. ENGINE REQUIREMENTS (Continued)

Case	Propellant	Pump	Flowrate, $\dot{\omega}$, lb/sec	Pressure Rise, ΔP, psi	Propellant Density, ρ, lb/ft^3	Volume Flowrates, Q, gpm	Head Rise, ΔH, ft
9	LOX	Full Flow	1058	5091	71.1	6680	10,310
	C_3H_8	Full Flow	314	5091	36.4	3870	20,100
	LH_2	TC Coolant + Turb.	34	6069	4.42	3450	172,700
10	LOX	Full Flow	1090.4	7316	71.1	6890	14,820
	LOX	Part Flow	511.9	1269	71.1	3230	2,570
	RP-1	Full Flow	389.4	4108	50.5	3460	11,710
	RP-1	Part Flow	140.1	3208	50.5	1246	9,150
11	LOX	Full Flow	1090.4	7316	71.1	6890	14,820
	LOX	Part Flow	621.5	1269	71.1	3920	2,570
	RP-1	Full Flow	389.4	4108	50.5	3460	11,710
	RP-1	Part Flow	18.8	3208	50.5	167.2	9,150
12	LOX	Full Flow	1128	4108	71.1	7120	8,320
	LOX	Part Flow	659.2	3208	71.1	4160	6,500
	CH_4	Full Flow	322	6049	27.5	5260	31,700
	CH_4	Part Flow	17.6	1267	27.5	287	6,630
13	LOX	Full Flow	1101	4108	71.1	6950	8,320
	LOX	Part Flow	776	3208	71.1	4900	6,500
	C_3H_8	Full Flow	367	6049	36.4	4530	23,900
	C_3H_8	Part Flow	22.8	1267	36.4	281	5,010
14	LOX	Full Flow	1102	5091	71.1	6960	10,310
	CH_4	Full Flow	373	5451	27.5	6090	28,500
	CH_4	Part Flow	66.5	3140	27.5	1086	16,440
15	LOX	Full Flow	1074.5	5091	71.1	6790	10,310
	C_3H_8	Full Flow	423.3	5091	36.4	5220	20,100
	C_3H_8	Part Flow	76.4	2605	36.4	942	10,310

Figure 20. SSME Low-Pressure Oxidizer Pump Performance Map and Limits

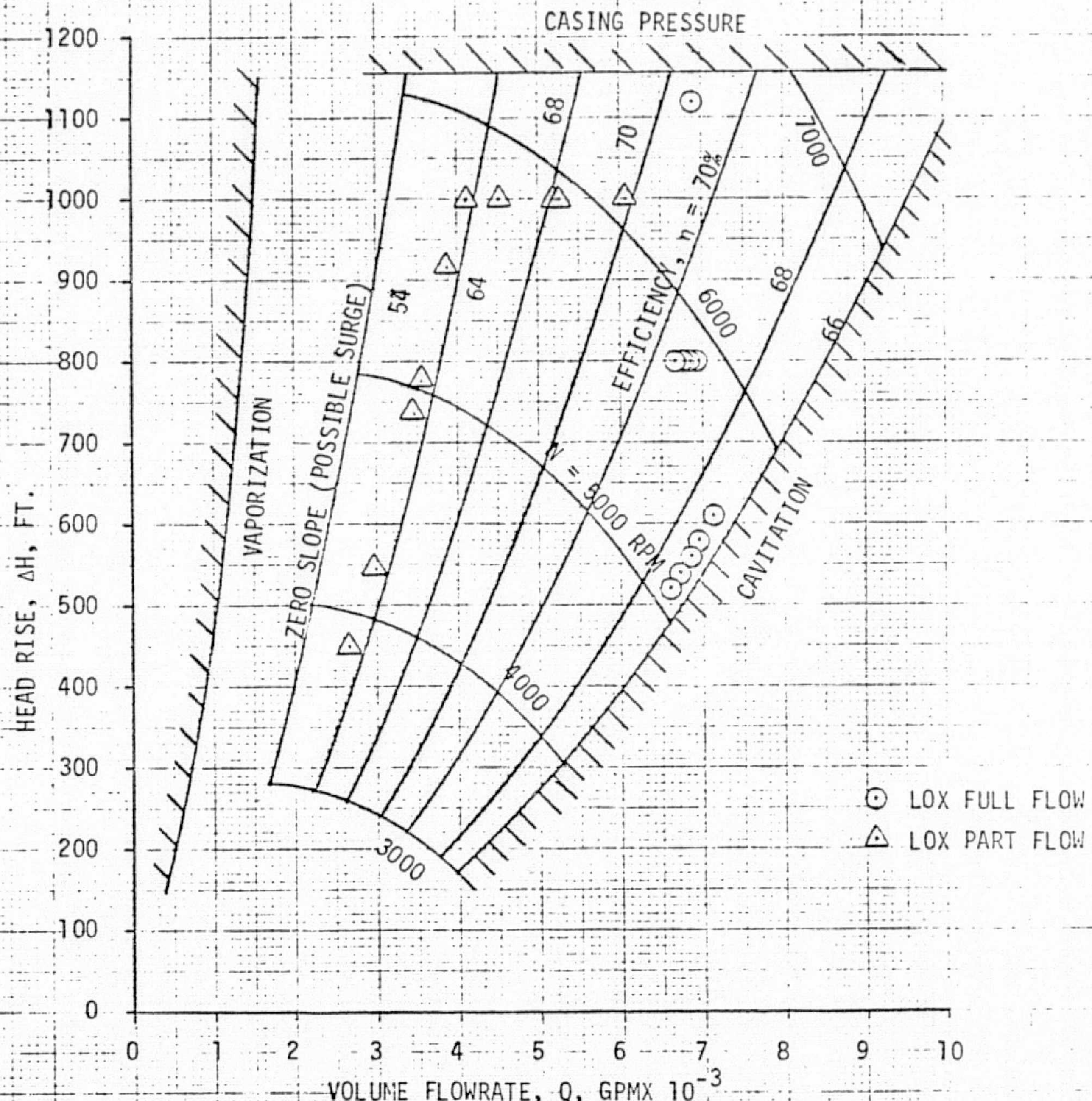

Figure 21. SSME High-Pressure Oxidizer Pump Performance Map and Limits

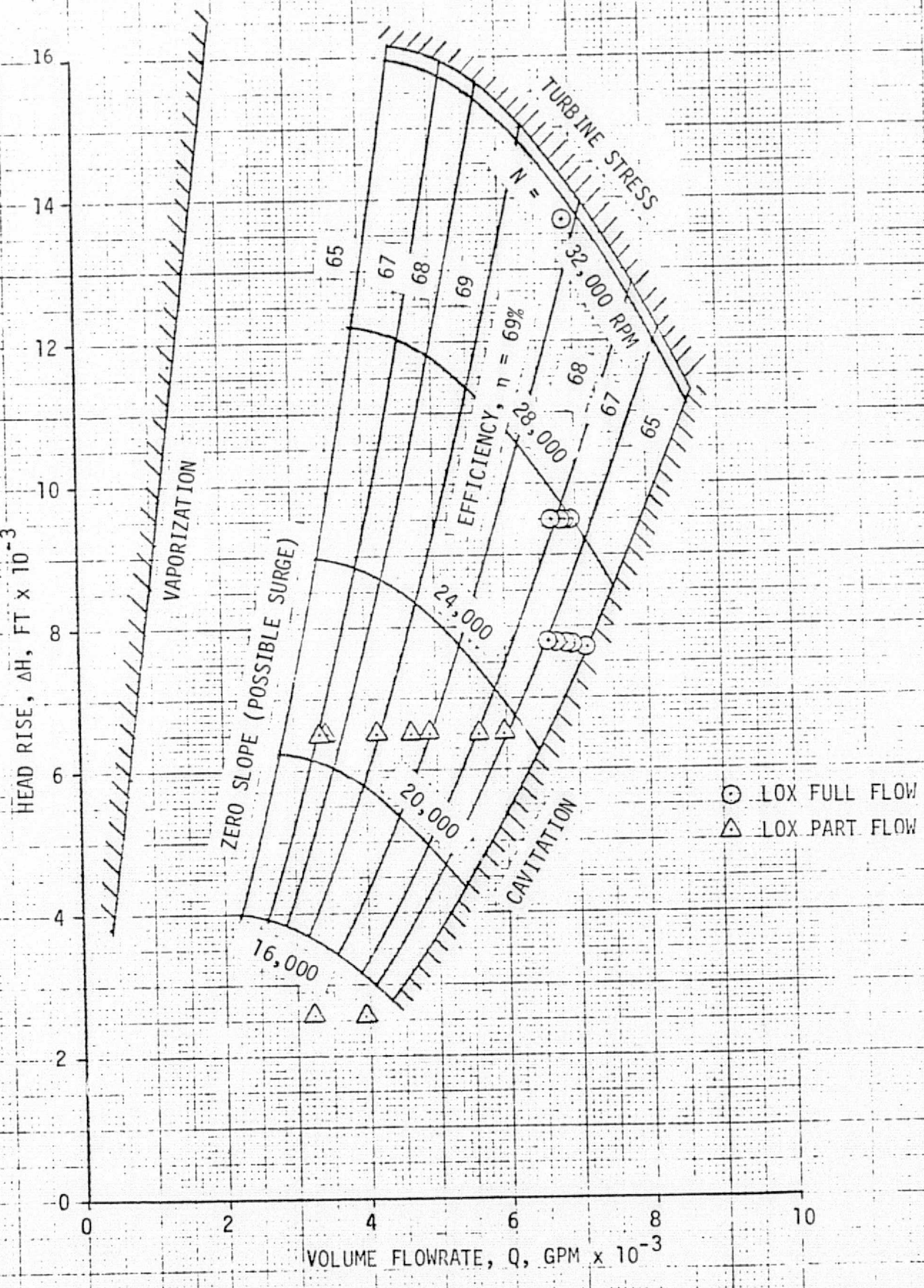

Figure 22. SSME Low-Pressure Fuel Pump Performance Map and Limits

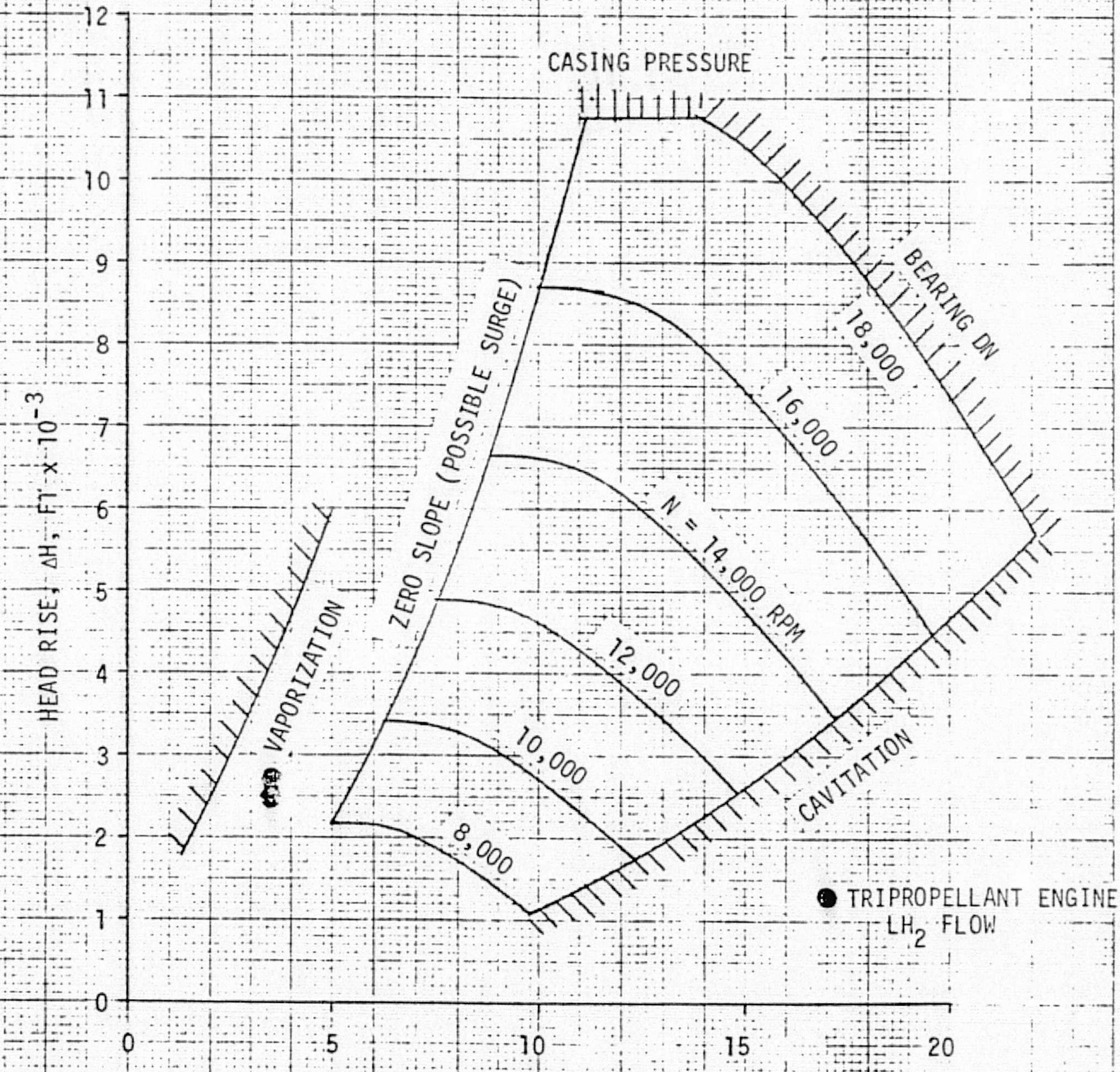

Figure 23. SSME High-Pressure Fuel Pump Performance Map and Limits

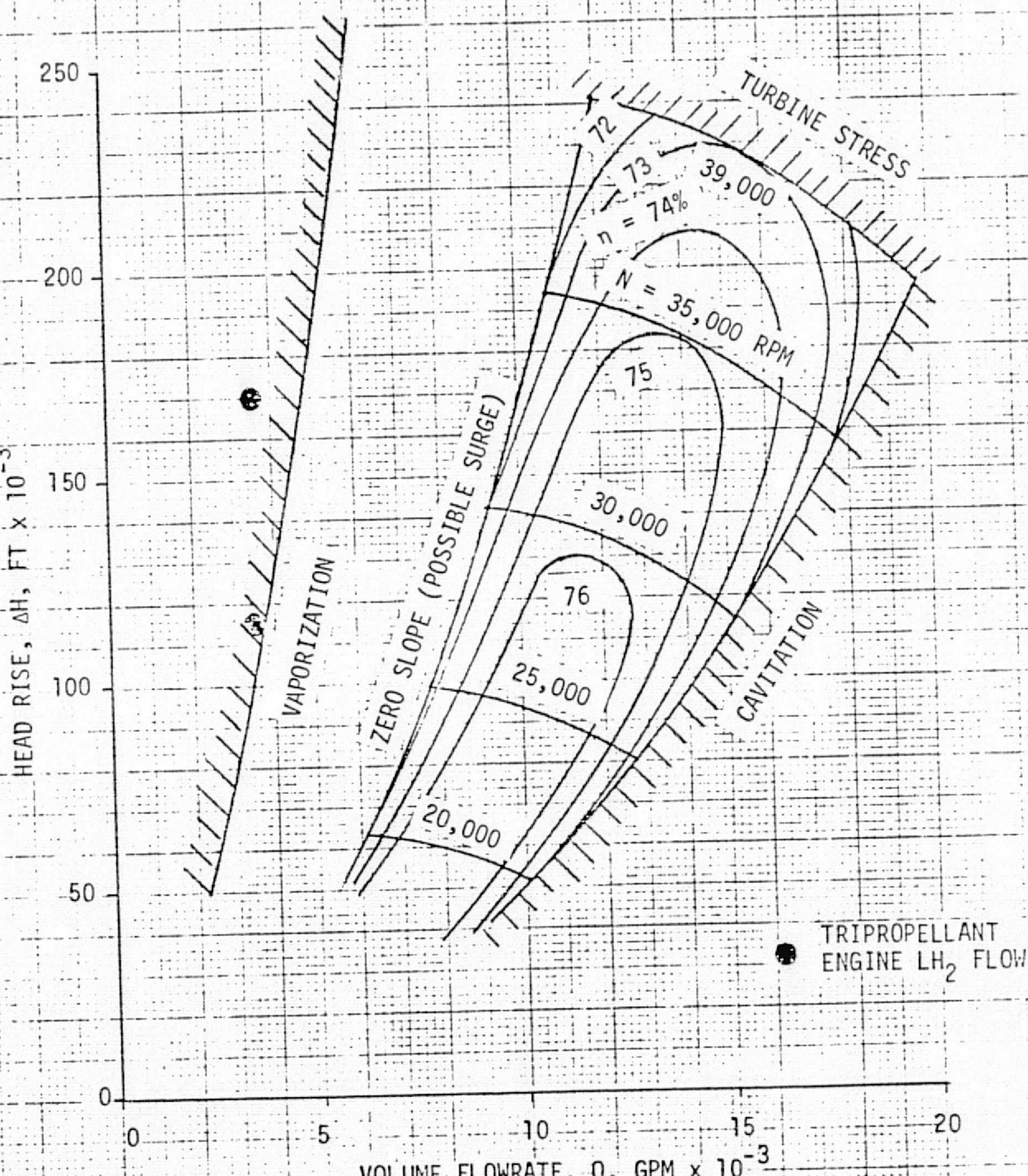

TABLE 4. SSME TURBOPUMP LIMITS

Limit	Description
TURBINE STRESS	TURBINE WHEEL FACTOR OF SAFETY ON ULTIMATE = 1.2 ON ROTATIONAL SPEED (WHEEL BURSTS @ N/N_{DES} = 1.2).
CASING PRESSURE	CASING FACTOR OF SAFETY ON ULTIMATE = 1.5 (CASING BURSTS @ $\Delta P/\Delta P_{DES}$ = 1.5).
VAPORIZATION	HIGH TEMPERATURE RISE AT LOW FLOW CAUSES VAPOR-IZATION AND CONSEQUENT PRESSURE DROP IN PUMP.
CAVITATION	HIGH FLOW COEFFICIENT (Q/N) OPERATION CAUSES DROP IN SUCTION PERFORMANCE CAPABILITY.
BEARING DN	AXIAL THRUST LOADS ARE TOO HIGH FOR THE DN AT WHICH THE BEARING IS OPERATING.
ZERO SLOPE	OPERATION TO THE LEFT OF ZERO SLOPE CAN CAUSE SURGING IN THE PUMP.

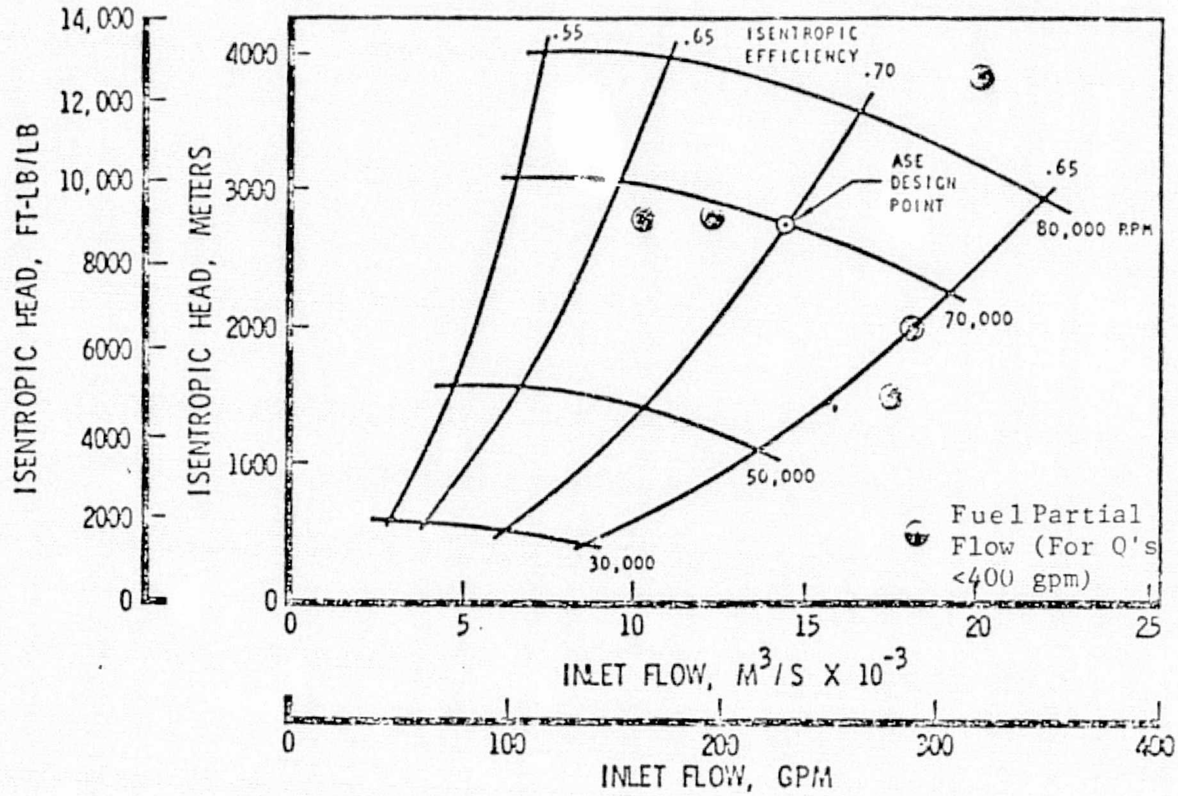

Figure 24. Mark 48 Oxidizer Pump Performance

TABLE 5. PUMP APPLICABILITY

Case	Propellant	Application	Pump Candidates Boost	Pump Candidates Main
1	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	RP-1	Full Flow	LPOTP	New Pump
	RP-1	Part Flow	None	New Pump
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
2	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	RP-1	Full Flow	LPOTP	New Pump
	RP-1	Part Flow	None	ASEOTP
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
3	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	CH_4	Full Flow	LPOTP	New Pump
	CH_4	Part Flow	None	New Pump
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
4	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	CH_4	Full Flow	LPOTP	New Pump
	CH_4	Part Flow	None	New Pump
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
5	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	C_3H_8	Full Flow	LPOTP	New Pump
	C_3H_8	Part Flow	None	New Pump
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
6	LOX	Full Flow	LPOTP	HPTOP
	LOX	Part Flow	None	HPOTP
	C_3H_8	Full Flow	LPOTP	New Pump
	C_3H_8	Part Flow	None	ASEOTP
	LH_2	TC Coolant	LPFTP (Marginal)	New Pump
7	LOX	Full Flow	LPOTP	HPOTP
	RP-1	Full Flow	LPOTP	New Pump
	LH_2	TC Coolant + Turbine	LPFTP (Marginal)	New Pump

TABLE 5. PUMP APPLICABILITY (Continued)

Case	Propellant	Application	Pump Candidates	
			Boost	Main
8	LOX	Full Flow	LPOTP	HPOTP
	CH_4	Full Flow	LPOTP	New Pump
	LH_2	TC Coolant + Turbine	LPFTP (Marginal)	New Pump
9	LOX	Full Flow	LPOTP	HPOTP
	C_3H_8	Full Flow	LPOTP	New Pump
	LH_2	TC Coolant + Turbine	LPFTP (Marginal)	New Pump
10	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	RP-1	Full Flow	LPOTP	New Pump
	RP-1	Part Flow	None	New Pump
11	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	RP-1	Full Flow	LPOTP	New Pump
	RP-1	Part Flow	None	ASEOTP
12	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	CH_4	Full Flow	LPOTP	New Pump
	CH_4	Part Flow	None	ASEOTP
13	LOX	Full Flow	LPOTP	HPOTP
	LOX	Part Flow	None	HPOTP
	C_3H_8	Full Flow	LPOTP	New Pump
	C_3H_8	Part Flow	None	ASEOTP
14	LOX	Full Flow	LPOTP	HPOTP
	CH_4	Full Flow	LPOTP	New Pump
	CH_4	Part Flow	None	New Pump
15	LOX	Full Flow	LPOTP	HPOTP
	C_3H_8	Full Flow	LPOTP	New Pump
	C_3H_8	Part Flow	None	New Pump

therefore, a second HPOTP must be used in series to provide the oxidizer preburner flow. The PBOTB will still be required on the full flow pump for mode 2 operation but the PBOTB could be removed from the second pump in the series arrangement.

As far as the full-flow fuel applications are concerned, the LPOTP is satisfactory as a boost pump and a new pump is required for all main pumps. If the SSME HPOTP is capable of being throttled to the left of the zero slope line on the performance map, the HPOTP may be applicable to the lower pressure, full flow fuel cases (Cases 2, 5, 6, 7, 10 and 11). However, this would be at the expense of pump efficiency. It is also of interest to note that two HPOTP stages (in series) would do the job for all full-flow fuel pumps and most of the part-flow fuel pumps. However, such a design would require a new housing, a new bearing and seal arrangement, a new shaft, and the addition of interstage ducting. It would be considered a new design, and therefore such a candidate was not considered practical.

The ASE oxidizer pump (ASEOTP) was found to be applicable to the part flow fuel pumping applications for Cases 1, 6, 11, 12, and 13 (again, the turbine was not considered). For all other part-flow fuel cases, a new pump was found to be necessary.

As far as liquid hydrogen is concerned, the flows are low enough to possibly cause surging in the SSME LPFTP (Fig. 22) and both surging and vaporization in the SSME HPFTP (Fig. 23). As a result, the LPFTP was deemed marginal and the HPFTP was deemed unacceptable. If future SSME engine throttling studies and modifications are successful in throttling this pump down to these flows, the applicability should be reassessed due to the dual mode engine simplification that could be obtained (for Cases 1 through 9) if the mode 2 pumps could be used. Another possibility is the use of four ASE liquid hydrogen pumps (ASEFTP). This would probably be too complex. However, a redesign possibility would be an ASEFTP scaled up to twice size (twice the diameter and half the speed) so that it would match with the higher flow.

As far as new pump designs are concerned, only one new design is required for Cases 11, 12, and 13. This is for the high-pressure fuel pumps which require more head than can be delivered by the HPOTP because the possible surge limit is exceeded in all three cases and the turbine stress limit is exceeded in Cases 12 and 13. However, all three cases require the addition of four pumps to the SSME system in order to get the dual mode capability. Cases 14 and 15 require the minimum number of additional pumps, which is three. However, two of them have to be new designs.

SSME TURBINE APPLICABILITY

The turbomachinery study phase of this task of the tripropellant engine investigation, is concerned with the utilization of existing SSME and ASE turbomachinery in the propellant feed systems of the candidate engine concepts. The turbine analyses have initially been concentrating on establishing a relationship between the required operating conditions, for the tripropellant feed systems being evaluated, and the operational capability of the turbines. Those designs which could be adaptable to this application would have to either be used as built, or require redesign of the gas path elements only; this includes the nozzles and rotor blades only. Any additional modifications to the turbine assemblies are not practical because of the complexity of the turbomachines. The development of new designs would be more cost effective on the basis of development time, performance characteristics, and modification cost. The criteria used to evaluate the respective high pressure fuel and oxidizer turbines to the fifteen candidate concepts, tabulated in Table 1 are associated with: (1) the engine cycle; (2) turbine working fluid properties and available energy; (3) operating conditions; and required turbine horsepower; and (4) size of the existing gas paths to handle the required turbine flows.

The high pressure SSME turbopumps are driven by two stage, reaction turbine designs; the respective pitch diameters of the fuel and oxidizer turbines are 10.19 inches, and 10.09 inches. The principal turbine operating parameters are as follows:

TURBINE	HPOT	HPFT
1. Working Fluid	LO_2/LH_2	LO_2/LH_2
2. Speed, N, rpm	31,204	38,000
3. Total Inlet Pressure, P_{t1}, psia	5,848	5,916
4. Turbine Pressure Ratio, PR_t, T-T	1.57	1.58
5. Mass Flowrate, W_t, lb/sec	64.24	162.7
6. Horsepower, HP_t	28,658	76,698
7. Total Inlet Temperature, t_{t1}, R	1,567	1,928

A major consideration is the engine cycle that these low pressure ratio turbines, which were designed for the staged combustion SSME, shall be required to operate in. An initial conclusion of the investigation is the turbines can not be used in the gas generator system concepts which operate with the 20 to 1 turbine pressure ratio. This conclusion is based primarily on a mismatch in turbine gas path pressure ratios, and sizing of nozzles and rotor blades.

The gas turbine analyses utilized the working fluid available energy data, and the operating parameters in Table 1. Turbine velocity ratios (Um/co) were established, and predictions of turbine performance were subsequently calculated. The required turbine mass flow rates, based on oxidizer and fuel propellant pump horsepower(s) and speed(s), were evolved. If the required turbines powers could be developed with the propellant feed system operating conditions, the required turbine gas path flow areas were calculated. This determined whether the existing turbine hardware could be used for the application, or the limiting parameters could be pinpointed and gas path modifications could be considered.

This study is now in progress, and is approximately 70 percent completed. A complete tabulation of all design parameters influencing the turbine designs is being prepared, and the limits and problem areas, where applicable, are being defined.

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Results of studies dealing with staged combustion engine cycles to date indicate the SSME turbine gas path areas are too small for the required tripropellant engine turbine working fluid flows. This is attributed in part to the substitution of working fluid propellant combinations which have less available energy than the LO_2/LH_2 used in the SSME staged combustion cycle, thus requiring considerably higher turbine flow rates.

SSME COMBUSTION COMPONENTS ADAPTABILITY

The purpose of this task is to evaluate the SSME preburner and main combustion chamber injectors to determine if they could be used in any of the 15 candidate tripropellant engine systems. This means that these injectors must provide stable, high performance when operating in any of the 15 mode 1, hydrocarbon fuel configurations and then be able to switch to LOX/H_2 operation in mode 2.

The SSME turbopumps are powered by two preburners providing fuel rich gases. The two preburner flows expand through the turbines and are then combined and ducted to the main injector. Both the preburners and the main chambers employ co-axial type injectors. The preburners have liquid oxygen injected through the center post and gaseous H_2 injected from the annulus. In the main injector, the fuel rich turbine exhaust gases are injected through the annulus and liquid oxygen in the center post. SSME injector flow areas are presented in Table 6 .

The ceaxial injector relies on a large velocity ratio between the two streams to enhance the turbulent mixing. If one fluid is in liquid form, atomization can only be achieved by the shearing force between the two streams. Hence, a large velocity differential is promoted to ensure good atomization and subsequently good vaporization and high performance. To determine whether hydrocarbon fuels can be used in the SSME combustion devices, the injection velocities must be estimated for each case based on the fixed injector element flow areas. The calculated injection velocities for the preburners and main chamber are presented in Table 7, 8 and 9 for the staged combustion

Table 6. Total Flow Area*

	Center (Ft^2)	Annulus (Ft^2)
Fuel Preburner	.0114	.025
Oxidizer Preburner	.00388	.01113
Main Chamber	.1012	.1979

*Excluding baffle elements

Table 7. Fuel Preburner Injection Velocities

Case	Fuel $\dot{W}$ (lb/sec)	Fuel V_{inj} (ft/sec)*	Oxidizer $\dot{W}$ (lb/sec)	Oxidizer V_{inj} (ft/sec)*
1	239.6	192	82.7	104
2	10.5	8	348.1	436
3	195.2	332	85.8	108
4	13.3	23	497.9	624
5	234.5	269	103.2	259
6	13.0	15	441.5	553
10**	126.2	227	51.6	493
11**	4.9	9	161.4	1541
12	7.8	36	290.4	364
13	13.2	21	448.0	561
SSME	87.2	898	85.8	107

* Flow Area = 0.025 ft^2 (F), 0.0114 ft^2 (Ox)

** Flow Area = 0.0111 ft^2 (F), 0.0039 ft^2 (Ox)

Table 8. Oxidizer Preburners Injection Velocities

	Fuel		Oxidizer	
Case	$\dot{W}$ (lb-sec)	V_{inj} (ft/sec)	$\dot{W}$ (lb/sec)	V_{inj} (ft/sec)
1	11.7	21	385.1	1418
2	11.7	21	385.1	1418
3	11.9	45	448	1649
4	11.9	45	448	1649
5	13.1	34	446.3	1643
6	13.1	34	446.3	1643
10	18.3	15	604.1	1963
11	18.3	15	604.1	1963
12	9.8	101	368.8	1358
13	9.6	35	328.0	1207
SSME	36.1	830	32.3	117

Table 9. Main Injector Flow Characteristics

Case	Fuel	$\dot{W}$	V_{inj}	Oxidizer	$\dot{W}$	V_{inj}
1	Fuel Rich* Comb Gas	798.1	560	LOX	577.2	82
2	RP-1	278.1	28	GOX	1067.2	1388
3	Fuel Rich* Comb Gas	785.8	551	LOX	551.2	78
4	CH_4	226.8	54	GOX	1110.2	1443
5	Fuel Rich* Comb Gas	836.0	587	LOX	514	73
6	C_3H_8	260.4	37	GOX	1089.6	1417
10	Fuel Rich* Comb Gas	1045.1	754	GOX	434.7	263
11	RP-1	366.2	37	GOX	1113.6	1448
12	CH_4	304.4	252	GOX	1145.6	740
13	C_3H_8	344.2	124	GOX	1078.2	1045
SSME	H_2	241.4	1506	LOX	846.9	120

* Assumes all the fuel mixes with all the combustion gases at 1600F.

cycle engine systems and Table 10 for the gas generator cycles. The SSME conditions are also shown for reference. A velocity ratio of 10 or higher is desirable.

In cases 1, 3, 5 and 10, the oxidizer preburner operates oxidizer rich and the fuel and H_2 preburners operate fuel rich. These two gas streams would either have to be mixed prior to injection into the main chamber of injected separately. The later would require a completely redesigned injector since three streams must be accommodated. If the oxidizer and fuel rich turbine exhaust streams are mixed prior to injection it would be extremely difficult to maintain the mixture non-reactive and avoid a detonation hazard. If they are allowed to react further in another chamber, the cooling would be a substantial engineering problem. The injection velocities shown for these cases in Table 9, were based on the assumption that the two streams are mixed prior to injection and somehow maintained non-reactive. Based on these factors the main chamber injector cannot be used directly in cases 1, 3, 5 and 10. In the case of the preburners, the injection velocity ratios are quite high for the oxidizer preburner but the injection pressure drop will be very high on the oxidizer side. The orifices at the entrance to the injector posts could be enlarged to reduce this pressure loss but this would adversely affect the mode 2 operation. In some of the cases where the preburner fuel injection velocities are low, the pressure drops are also low and combustion stability could be a problem. For the fuel preburner, injection velocity ratios are low in most cases and those cases where the oxidizer injection velocity is high the pressure loss will also be high. In general, the coaxial injector is not considered a good configuration for liquid-liquid injection which is the condition for these preburners. Based on this rather general analysis, it appears that the preburners cannot be directly substituted into these candidate cases. A more detailed evaluation of each case will be conducted to determine if minor changes in orificing could result in these preburners satisfying both mode 1 and mode 2 operational requirements with reasonable injection velocities and pressure drops.

Table 10. Gas Generator Cycles

Case	Fuel	T_{inj} (R)	P_{inj} (lb/ft^3)	$\dot{W}_{inj}$ (lb/sec)	V_{inj}* (ft/sec)	Oxidizer (1)	W_{inj} (lb/sec)	V_{inj}** (ft/sec)
7	RP-1	540	50	335.7	34	LOX	1042.1	147
8	CH_4	330	22.8	277	61	LOX	1068.2	151
9	C_3H_8	540	34.7	314	46	LOX	1043.3	147
14	CH_4	830	8.5	306.5	182	LOX	1073.4	152
15	C_3H_8	840	24.9	346.9	70	LOX	1040.9	147
O_2/H_2 SSME	H_2	300	2.35	122.3	263	LOX	934.1	132

* $A_{inj} = 0.1979\ ft^2$
** $A_{inj} = 0.1012\ ft^2$
(1) $T_{inj} = 190F$, $P_{inj} = 70\ lb/ft^3$

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In the case of systems No. 2, 4, 6 and 11 through 13, all preburners are oxidizer rich and all of the oxidizer enters the main combustion chamber through this source. There are two alternatives as to how this hot, oxidizer rich flow can be introduced into the main chamber. It could be injected through the hot gas manifold and through the annulus in the injector element. The main problem with this approach is that in mode 2, the flow through this side of the injector would suddenly become fuel rich as this is the normal mode of operation for the SSME. There would also be a switch from fuel to oxidizer on the other side of the injector. This presents a detonation problem that is unacceptable. The other approach is to inject the hot oxidizer rich gases through the oxidizer dome of the SSME. Some means of cooling the dome must be provided. Based on the injector flow areas, injection velocity calculations show large velocity differential between the fuel and oxidizer. The present injector should provide adequate velocity ratio for good atomization and mixing. It should be noted that, in these cases, the main injector has liquid fuel through the annulus and gases through the oxidizer post. Due to the low liquid flow rate and large annular flow area, liquid injection velocities and pressure drops appear to be too low and will be prone to low order feed system coupled instability. To correct the instability problem orifices can be installed in the fuel annulus of the injector element.as in the SSME oxidizer injection elements. However this will create excessive pressure drop in mode 2 as the H_2 is injected as a gas. A solution to this problem would be adjustable orifices for either the annulus or the post. However, this obviously requires considerable development and a new injector.

Cases 10 and 11 are both oxygen cooled. Due to the possible detonation problem with direct contact of cold liquid oxygen and RP-1, warm oxygen obtained by mixing the cooling circuit flow with the remaining liquid oxygen is necessary. Case No. 10, with both oxidizer rich and fuel rich preburners, will have the same problem as that described for case 1, 3 and 5. Case 11 is similar to case 2, 4 and 6 with respect to the preburner and main injector problems. It is also necessary to use the SSME fuel preburner as the oxidizer preburner in these 2 cases since there is a large amount of oxygen to be pumped at the high pressure and a considerably high turbine flow is required. The rearrangement of these components may present some hardware interface and packaging problems.

The main injector fuel and oxidizer velocities are presented in Table 10 for the gas generator cycles defined in cases No. 7, 8, 9, 14 and 15. The SSME main injector cannot provide a large velocity differential because of the low fuel injection temperature and hence, high density. The higher densities of the hydrocarbons further reduce their injection velocities relative to H_2. Even in cases 14 and 15 where the hydrocarbon fuel is heated in the cooling circuit, the injection velocity on the fuel side is too low. The mode 2 O_2/H_2 (gas generator cycle SSME) case shown on Table 10 is for a gas generator cycle and it is shown that the velocity ratio for this case is also low. This suggests the possibility of resizing the elements in the SSME main injector to provide acceptable pressure drops and velocities in both mode 1 and mode 2 operation for case 14 and 15. This consideration will be investigated further. In general, the coaxial injector is not suitable for liquid-liquid injection, therefore, cases 14 and 15 have the greatest potential for adaptation of the resized element SSME injector. The same situation occurs in the use of either of the SSME preburners as a gas generator. In general, they are sized for considerably higher flows and a gaseous H_2 fuel. The possibility of resizing the elements in one of these preburners to adapt it to one of these gas generator cycles will be investigated.

Several other factors should be considered in determining the adapatability of these injectors to the candidate tripropellant engines. Little experience is available in the operation of a LOX rich precombustor. It has been suggested that a flame holder may be required to maintain a lower mixture ratio in the center and then provide rapid mixing of the hot combustion gas and the excess oxygen. This remains to be demonstrated.

In those cases where a turbine drive gas is suddenly switched from oxidizer rich to fuel rich hot gases in transitioning from mode 1 to mode 2, the effect of alternately exposing materials to an oxidizing and reducing environment should be investigated.

Another significant factor in injector designs for liquid oxygen is the potential formation of detonatable gel. The cold liquid oxygen mixes with and solidifies most hydrocarbon fuels if directly mixed. The coaxial injectors should be considered not suitable for LOX-RP-1 unless gaseous oxygen can be assured. Methane and propane have melting points above the LOX injection temperature (190R) as shown in Table 11. It is hopeful that detonatable gel would not occur. However, experiments have to be performed to verify that.

In the SSME, the main injector plate is cooled by hydrogen perspiration through the regimesh faces. More analyses should be performed if either methane or propane are used as the coolant. Oxygen is not recommended nor is RP-1. Hence, cases 10 and 11 will require hydrogen cooling for the main injector.

Table 11

	Normal Boiling Point, R	Normal Melting Point, R
RP-1	882	405
CH_4	416	154
C_3H_8	201	163