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BIMONTHLY TECHNICAL PROGRESS REPORT
NO. 3

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PREPARED BY
D. B. Wheeler
D. B. Wheeler
Project Engineer

APPROVED BY
F. M. Kirby
F. M. Kirby
Program Manager

ROCKETDYNE DIVISION OF ROCKWELL INTERNATIONAL CORPORATION
6633 Canoga Avenue, Canoga Park, CA 91304

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

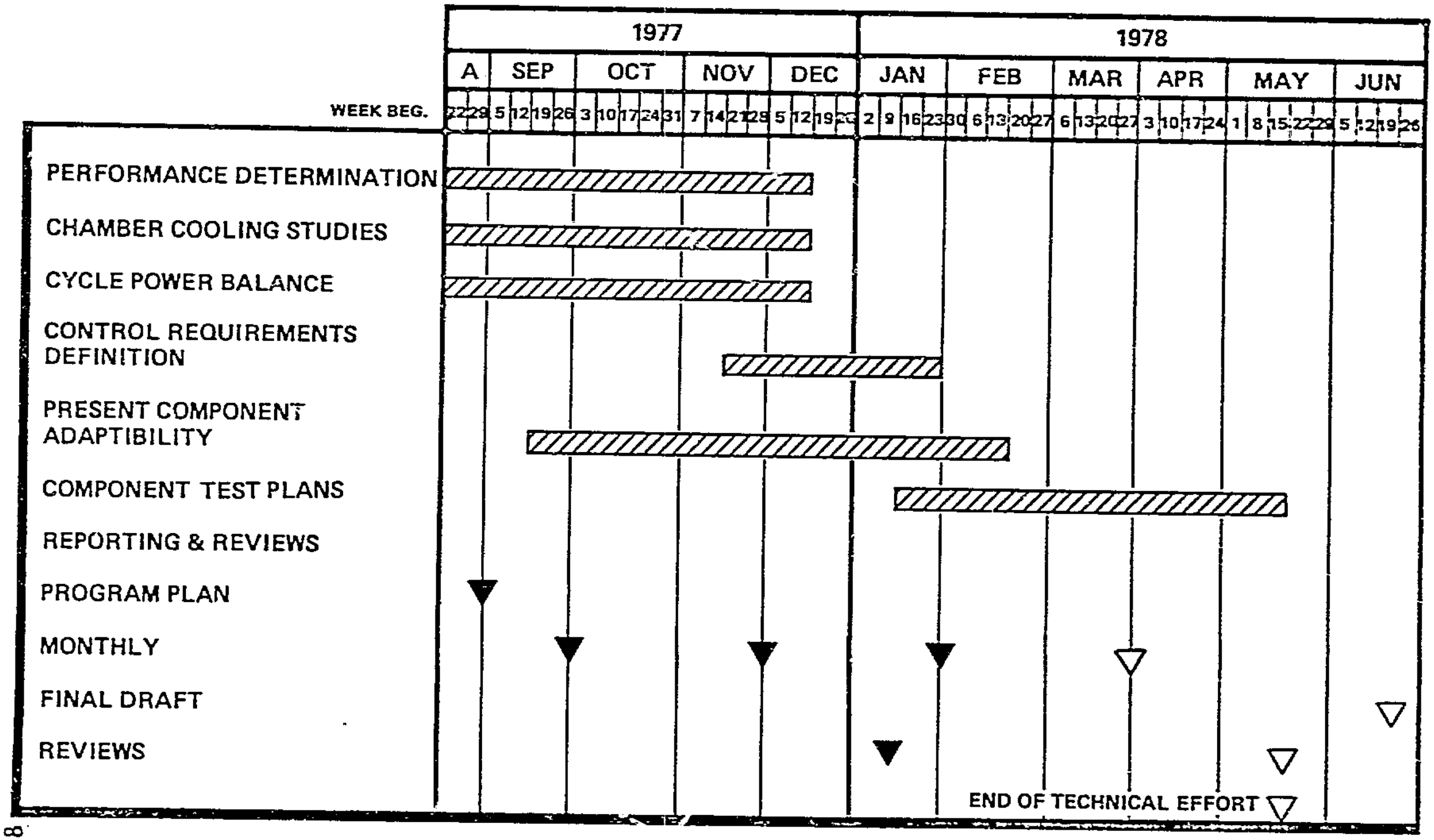

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Figure 1

capable of operating sequentially with LOX/H_2. Flowrates and operating conditions have been established for this initial set of engine systems and the adaptability of the major components of the SSME are being 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 establisy the objectives of each additional experimental test phase.

SUMMARY

This third bimonthly progress report covers the work conducted 1 December to 31 January 1978. A mid-contract review was presented at MSFC on 12 January. A major part of the technical effort had been completed at this time and the preliminary conclusions that were presented, stated that the conversion of an SSME engine to a dual mode, dual fuel engine is not practical without major modifications to the hardware and/or the addition of a significant number of new engine components. However the study results have shown numerous possibilities for the use of SSME hardware in single mode LOX/hydrocarbon engines.

Some additional work has been conducted in the areas of performance, chamber cooling and engine balances to update some of the candidate systems and investigate several system alternatives that were recognized as possible means of achieving the dual mode, dual fuel operational objective. The major part of the effort was devoted to the completion of the SSME component adaptability studies and the control requirements definition study. The Task VI effort was initiated to develop component test plans that could be conducted with the 40K SSME subscale hardware to demonstrate some of the critical areas uncovered in this study.

TASK I - PERFORMANCE DETERMINATION

This task was to produce the necessary engine performance data, combustion gas thermodynamic properties and turbine drive gas parameters to support the other tasks within the study. This effort has been essentially completed.

TASK II -

This task is concerned with providing the heat transfer and cooling analysis support for the selected engine systems that are being studied. Results were presented in the previous reports describing the hot gas wall temperatures, coolant bulk temperature and coolant pressure drop as a function of coolant flow rate for the various cooling techniques and fluids to be considered in this study. A summary of the mode 1 regenerative cooling system design points is shown in Table 1. The heat transfer/cooling analysis was conducted assuming the current SSME chamber and cooling channel geometry except in the one LOX cooled case where the channel dimensions were increased to reduce the ΔP. These design points were used in the mode 1 engine system mass/pressure balances.

The main incentive in considering a LOX cooled chamber is that it would not be necessary to switch coolants between mode 1 and mode 2 operation. Results were presented in the previous report showing that LOX could be employed as a coolant in the SSME combustion chamber with LOX/hydrocarbon combustion, but no consideration was given to LOX cooling capabilities with LOX/H_2 combustion in mode 2. During this report period a brief study was conducted to determine if LOX cooling would be applicable for the SSME operation in mode 2 (O_2/H_2 combustion). It was found that with the current coolant channel geometry, the maximum chamber pressure would be limited to below 2000 psia. If the channel height were doubled in the chamber to permit an increase in coolant flowrate, the maximum chamber pressure would be 2500 psia with a flowrate of 700 lb/sec and a ΔP of 5400 psi. A chamber pressure of 3230 psia could only be achieved with a complete redesign of the chamber cooling geometry and would still require an excessively high cooling ΔP. With these results it seems apparent that LOX cooling is not a feasible candidate for a dual fuel engine using LOX/hydrocarbon in mode 1 and LOX/H_2 in mode 2 since the mode 2 operation is greatly limited.

TASK III - CYCLE AND POWER BALANCE

The objectives of this task were 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

Table 1

Mode 1 COMBUSTION CHAMBER AND NOZZLE COOLING DESIGN POINTS

$T_{WALL\ MAX} \approx 1050^0F$

COOLANT	CHAMBER			NOZZLE		
	$\dot{\omega}$, lb/sec	ΔT, ^0F	ΔP, psi	$\dot{\omega}$, lb/sec	ΔT, ^0F	ΔP, psi
LH_2 (P_c=3230)	15.5	600	500	18.5	750	75
(P_c=4000)	16.5	575	600	19.5	700	90
LO_2 (P_c=3230)	225	450	4500	275	625	450
(P_c=3230)*	150	600	2100			
CH_4 (P_c=3230)	85	550	1600	107	690	200
(P_c=4000)	125	460	3500	150	620	340
C_3H_8** (P_c=3230)	160	320	2600	150	500	175
(P_c=4000)	200	270	5600	175	400	400

* Redesign of SSME coolant channels

** May have coolant side wall coking problem and a variety of cooling schemes are included in these tripropellant engine systems capable of both mode 1 and 2 operation in series.

The major component flowrates, turbine inlet temperatures, and pump discharge pressure requirements are presented in Table 2 for each of the candidate systems. Some corrections have been made to the numbers presented previously and some variations of a couple of the cases have been added. A correction to the coolant flowrate was incorporated into the balance for concept 15 and concept 15A was added to illustrate how the pump discharge pressure could be reduced to a reasonable value by reducing the chamber pressure to 3230 psia. The relatively high coolant ΔP's associated with the C_3H_8 coolant result in the excessive pump discharge pressure on the fuel side in concept 15.

Two variations on concept 12 were added to the list of candidate systems, not because of advantages with respect to adaptation of SSME hardware, but because they are important systems to be considered in any future studies concerning dual fuel engines. Concept 12 is a staged combustion cycle using LOX/CH_4 propellants and CH_4 cooling and utilizes oxidizer rich preburners since if both preburners are fuel rich it would be necessary to increase the turbine inlet temperature above 2000R or reduce the chamber pressure below 3230 psia to achieve a cycle power balance. However, it was decided to add concept 12A and 12B and a cycle balance was conducted to establish operating conditions. The results are presented in Table 2.

A brief analysis was also conducted to establish an engine balance for mode 2, LOX/H_2 SSME with LOX cooling. However, with the cooling ΔP established in the cooling analysis, the required LOX pump discharge pressure is excessively high and it was decided that running the SSME with LOX cooling is not a practical alternative. This in essence eliminates LOX cooling for the dual mode applications.

Table 2

O_2/RP-1/H_2 STAGED COMBUSTION

	Hydrogen-Cooled			Oxygen-Cooled		
	All PB's Fuel-Rich	Fuel & H_2 PB Fuel-Rich & O_2 PB O_2-Rich	All PB Ox-Rich	All PB's Fuel-Rich	Fuel PB Fuel-Rich & O_2 PB O_2-Rich	All PB Ox-Rich
CONCEPT NO.		1	2		10	11
Cycle Type	S.C.	S.C.	S.C.	S.C.	S.C.	S.C.
P_c	3230	3230	3230	3230	3230	3230
S.L. Thrust		460K	460K		470K	470K
Vac. Thrust		500K	500K		511.7K	511.7K
Propellants		O_2/RP-1	O_2/RP-1		O_2/RP-1	O_2/RP-1
Coolant		H_2	H_2		O_2	O_2
Turbine Drive Fluid		O_2/RP-1	O_2/RP-1		O_2/RP-1	O_2/RP-1
M.R.		2.8	2.8		2.8	2.8
I_S S.L., Sec		333.8	333.8		317.6	317.6
I_S Vac, sec		362.5	362.5		345.8	345.8
$T_{Turbine}$, R	2250	2000	2000	2100	2000	2000
Preburner/GG, lb/sec						
O_2		478.8	733.2		655.7	765.5
Fuel		240.3	22.2		144.5	23.2
H_2		-	-		-	-
$\dot{\omega}_{Turbine}$, lb/sec						
O_2		395.8	396.8		622.4	622.4
Fuel		174.7	187.3		177.9	166.2
H_2		147.6	171.3		-	-
$\dot{\omega}_{Coolant}$, lb/sec		34	34		225COMB 275NOZ	225COMB 275NOZ
$\dot{\omega}_{O_2}$ (Total), lb/sec		1045	1045		1090.4	1090.4
$\dot{\omega}_{Fuel}$ (Total), lb/sec		300.3	300.3		389.4	389.4
$\dot{\omega}_{H_2}$ (Total), lb/sec		34	34		-	-
$\dot{\omega}_{Total}$, lb/sec		1379	1379		1479.8	1479.8
$\dot{\omega}_{H_2}$ T.C., lb/sec		34	34		-	-
Pump Discharge Pressure						
LOX PB		7331	7331		7331	7331
Chamber		4123	4123		8600	8600
Fuel PB		7331	7331		7331	7331
Chamber		4123	4123		4123	4123
H_2		4000	4000		--	--

Table 2. (Continued)

$O_2/CH_4/H_2$ STAGED COMBUSTION

	Hydrogen-Cooled			CH_4-Cooled	CH_4-Cooled	CH_4 Cooled
	Fuel-Rich	Fuel PB Fuel-Rich & O_2 PB O_2-Rich	All PB's O_2-Rich	All PB's O_2-Rich	All PB's Fuel-Rich	All PB's Fuel-Rich
CONCEPT NO.		3	4	12	12A	12B
Cycle Type	S.C.	S.C.	S.C.	S.C.	S.C.	S.C.
P_c	3230	3230	3230	3230	3230	2950
S.L. Thrust		465K	465K	470K	470K	429.3
Vac. Thrust		508.6K	508.6K	516.2K	514.9K	473.3
Propellants		O_2/CH_4	O_2/CH_4	O_2/CH_4	O_2/CH_4	O_2/CH_4
Coolant		H_2	H_2	CH_4	CH_4	CH_4
Turbine Drive Fluid		O_2/CH_4	O_2/CH_4	O_2/CH_4	O_2/CH_4	O_2/CH_4
M.R.		3.5	3.5	3.5	3.5	3.5
I_S S.L., Sec		339.2	339.2	324	324	322
I_S Vac, sec		371	371	356	355	355
$T_{Turbine}$, R	2250	2000	2000	2000	2125	2000
Preburner/GG, lb/sec						
O_2		553.8	945.9	659.2	162.2	126.1
Fuel		207.1	25.2	17.6	318.1	293.3
H_2		-	-	-	-	-
$\dot{\omega}_{Turbine}$, lb/sec						
O_2		459.9	459.9	378.6	190.7	165.7
Fuel		184.3	324.8	299	289.6	253.7
H_2		96.1	186.3	-	-	-
$\dot{\omega}_{Coolant}$, lb/sec		34	34	97.5 120	96.9 120.6	96.9 120.6
$\dot{\omega}_{O_2}$ (Total), lb/sec		1085	1085	1128	1127	1036.6
$\dot{\omega}_{Fuel}$ (Total), lb/sec		252	252	322	322	295.9
$\dot{\omega}_{H_2}$ (Total), lb/sec		34	34		-	-
$\dot{\omega}_{Total}$, lb/sec		1371	1371	1450	1449	1332
$\dot{\omega}_{H_2}$ T.C., lb/sec		34	34		-	-
Pump Discharge Pressure						
LOX PB		7331	7331	7331	7077	6470
Chamber		4123	4123	4123	4107	3760
Fuel PB		7331	7331	7331	8540	7757
Chamber		4123	4123	6064	-	-
H_2		4000	4000	--	-	-

Table 2. (Continued)

$O_2/C_3H_8/H_2$ STAGED COMBUSTION

	Hydrogen-Cooled			C_3H_8-Cooled
	Fuel-Rich	Fuel PB Fuel-Rich & O_2 PB O_2-Rich	All PB's O_2-Rich	All PB's O_2-Rich
CONCEPT NO.		5	6	13
Cycle Type	S.C.	S.C.	S.C.	S.C.
P_c	3230	3230	3230	3230
S.L. Thrust		464.6K	464.4K	470K
Vac. Thrust		507.6K	507.6K	515K
Propellants		O_2/C_3H_8	O_2/C_3H_8	O_2/C_3H_8
Coolant		H_2	H_2	C_3H_8
Turbine Drive Fluid		O_2/C_3H_8	O_2/C_3H_8	O_2/C_3H_8
M.R.		3.0	3.0	3.0
I_S S.L., Sec		335.7	335.7	320
I_S Vac, sec		366.7	366.7	351
$T_{Turbine}$, R	2375	2000	2000	2000
Preburner/GG, lb/sec				
O_2		549.5	887.8	776
Fuel		247.6	26.1	22.8
H_2		-	-	-
$\dot{\omega}_{Turbine}$, lb/sec				
O_2		459.4	459.4	337.6
Fuel		206.7	267.2	461.2
H_2		131.0	187.2	-
$\dot{\omega}_{Coolant}$, lb/sec		34	34	140COMB 140NOZ
$\dot{\omega}_{O_2}$ (Total), lb/sec		1063.5	1063.5	1101
$\dot{\omega}_{Fuel}$ (Total), lb/sec		286.5	286.5	367
$\dot{\omega}H_2$ (Total), lb/sec		34	34	
$\dot{\omega}_{Total}$, lb/sec		1384	1384	1468
$\dot{\omega}_{H_2}$ T.C., lb/sec		34	34	
Pump Discharge Pressure				
LOX PB		7331	7331	7331
Chamber		4123	4123	4123
Fuel PB		7331	7331	7331
Chamber		4123	4123	6064
H_2		4000	4000	--

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Table 2. (Concluded)

GAS GENERATOR CYCLES

CONCEPT NO.	7	8	9	14	15	16A
Cycle Type	G.G.	G.G.	G.G.	G.G.	G.G.	G.G.
P_c	4000	4000	4000	4000	4000	3230
S.L. Thrust	470K	470K	470K	470K	470K	470K
Vac. Thrust	502K	504K	503.5K	505K	505.5K	505K
Propellants	O_2/RP-1	O_2/CH_4	O_2/C_3H_8	O_2/CH_4	O_2/C_3H_8	O_2/C_3H_8
Coolant	H_2	H_2	H_2	CH_4	C_3H_8	C_3H_8
Turbine Drive Fluid	O_2/H_2	O_2/H_2	O_2/H_2	O_2/CH_4	O_2/C_3H_8	O_2/C_3H_8
M.R.	2.8	3.5	3.0	3.5	3.0	3.0
I_S S.L., Sec	329.7	336.9	334	318.5	311.3	308.6
I_S Vac, sec	352.3	361.3	358	342.2	334.5	337.1
$T_{Turbine}$, R	2000	2000	2000	2000	2000	2000
Preburner/GG, lb/sec						
O_2	13.9	15.8	14.7	28.6	39.6	32.1
Fuel	-	-	-	66.5	90.1	72.9
H_2	17.4	19.7	18.3	-	-	
$\dot{\omega}_{Turbine}$, lb/sec						
O_2	18.5	18.9	18.5	47.8	61.6	51.1
Fuel	5.4	8.5	6.9	47.2	68.2	53.9
H_2	7.5	7.5	7.5	-	-	
$\dot{\omega}_{Coolant}$, lb/sec	36	36	36	125COMB 150NOZ	200 COMB 175 NOZ	160 COMB 175 NOZ
$\dot{\omega}_{O_2}$ (Total), lb/sec	1056	1084	1058	1102	1072	1094.8
$\dot{\omega}_{Fuel}$ (Total), lb/sec	335.7	277	314	373	434.6	427.2
$\dot{\omega}_{H_2}$ (Total), lb/sec	34	34	34			
$\dot{\omega}_{Total}$, lb/sec	1425	1395	1407	1476	1508	1523.1
$\dot{\omega}_{H_2}$ T.C., lb/sec	17	14.3	15.7		-	
Pump Discharge Pressure						
LOX PB Chamber	5106	5106	5106	5106	5106	4123
Fuel PB Chamber	5106	5106	5106	5466 8606	5107 11300	4123 6723
H_2	6084	6084	6084	-	-	

TASK IV - CONTROL SYSTEM REQUIREMENTS

The start sequence and control system selection for the tripropellant engine are patterned after the Space Shuttle Engine (SSME). During normal power level, it takes the SSME (a closed-loop controlled stage combustion engine) approximately 3.6 seconds to attain 90 percent of rated thrust (Fig. 2). With closed-loop control and proper selection of valve operating sequences, the start and cutoff transients of the tripropellant engine can be made to follow closely those of the SSME (Fig. 2 and 3).

It is intended that the tripropellant engine utilize SSME turbomachinery, therefore, valve opening schedules and utilization of open- and closed-loop control procedures are expected to be similar to those of the SSME. Engine start and shutdown criteria is indicated in Table 3.

Staged Combustion Cycle Concepts

The stage combustion cycle cooling options for the tripropellant engine are: hydrogen-cooled in both modes 1 and 2, hydrocarbon-cooled in mode 1 and hydrogen-cooled in mode 2, and oxygen cooled. There are ten engine concepts (1-6 and 10-13) which fall within these three cooling categories. Schematics for these ten concepts are shown respectively in Figs. 4 through 6. Required control valves are indicated in each schematic. Start and shutdown procedures and transients are similar for all three schematics.

Mode 1 Operation. The start sequence for the tripropellant LOX/Hydrocarbon engine (Concepts 1-6, 10-13) employ the open-loop control mode during early start phases and switches to closed-loop operation for buildup to rated thrust. Initial valve opening and sequencing provides ignition sequencing, engine priming, and initial turbine power buildup. Closed-loop control is then activated to achieve a start to the desired power level without transient overshoots or undershoots.

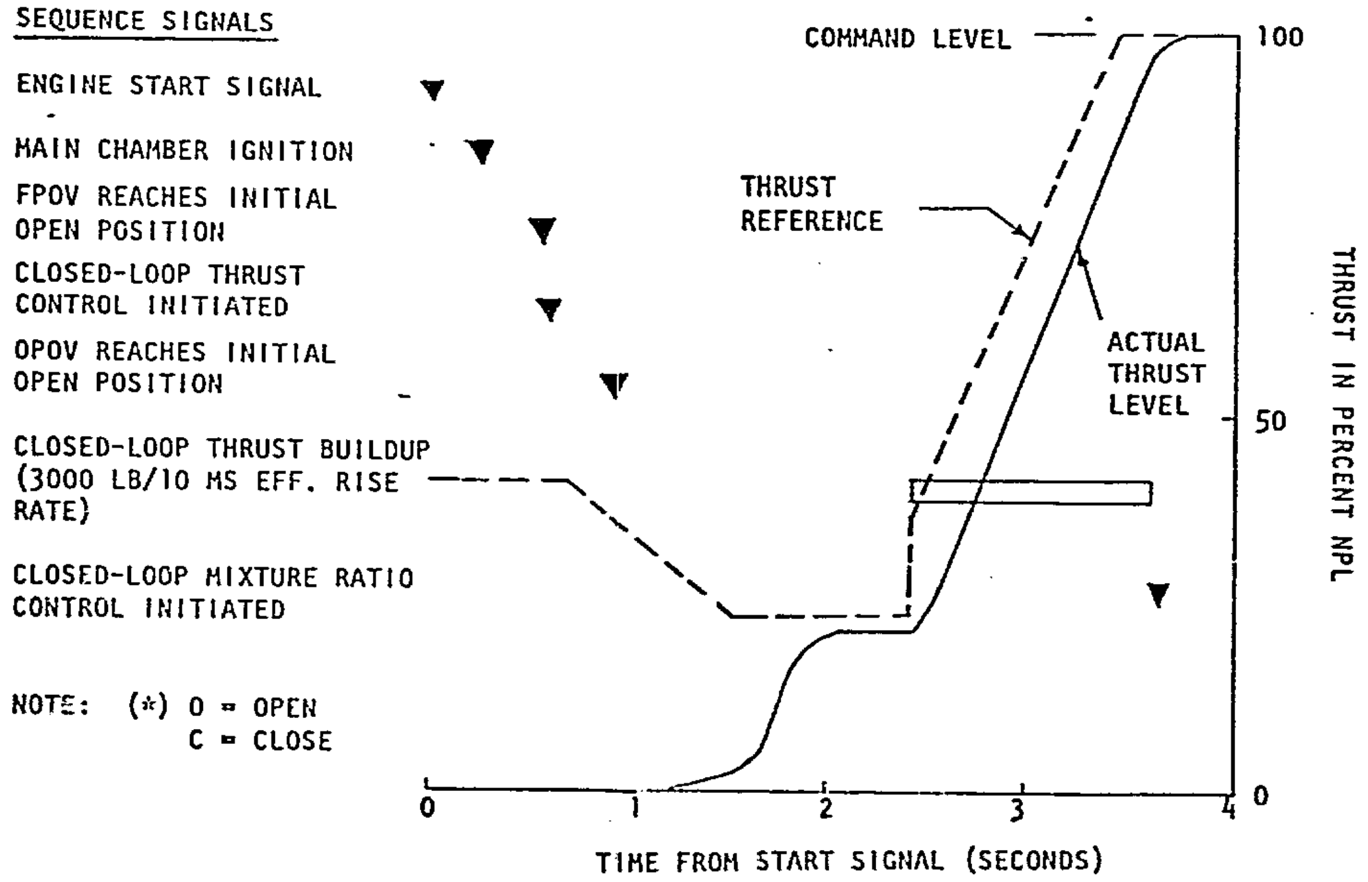

Figure 2. SSME Start Sequence to NPL

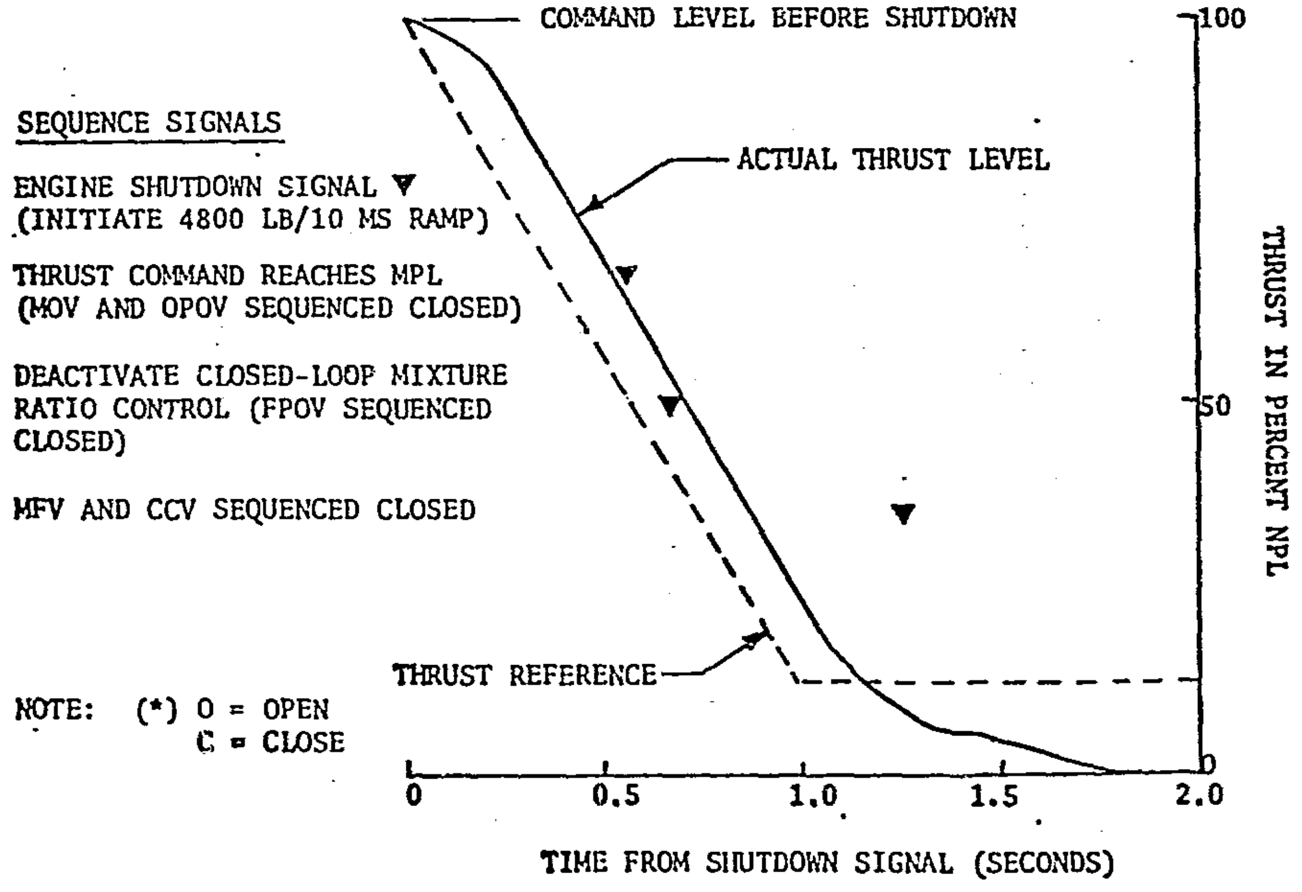

Figure 3. SSME Shutdown Sequence

Table 3. Engine Start and Shutdown Criteria

Prevent transient overshoots or undershoots.
Provide mixture ratio variations compatible with engine life and reliability.
Provide repeatable engine start characteristics to rated power levels.
Provide thrust accelerations within customer specification.
Provide thrust accelerations required to minimize side loads at sea level.
Provide start transients insensitive to vehicle and mission operation requirements.
Provide shutdowns without detrimental pump speed and turbine temperature transients.
Provide shutdowns with combustion of all fuel and oxidizer residuals without damaging mixture ratio transients.

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

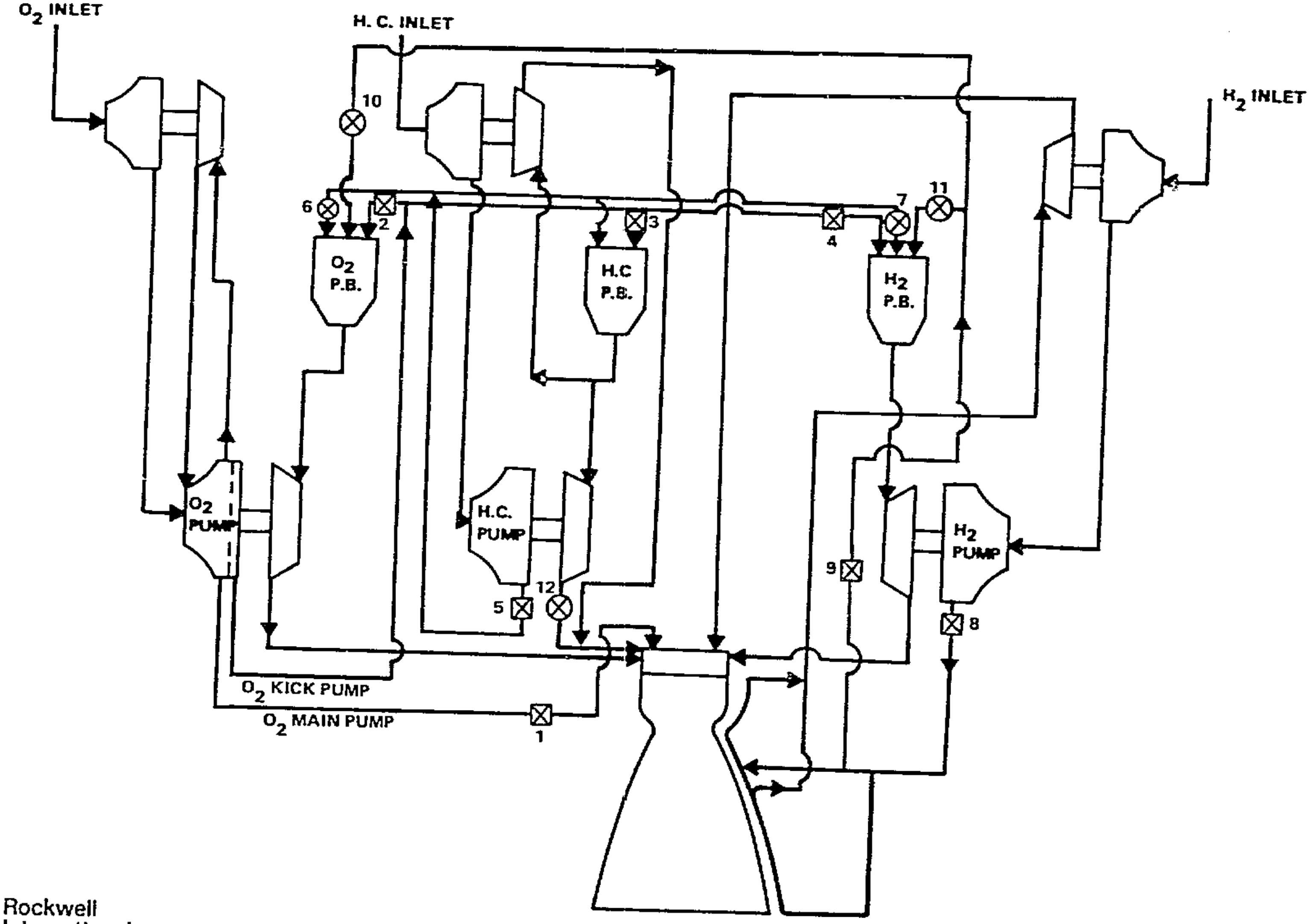

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Figure 4

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

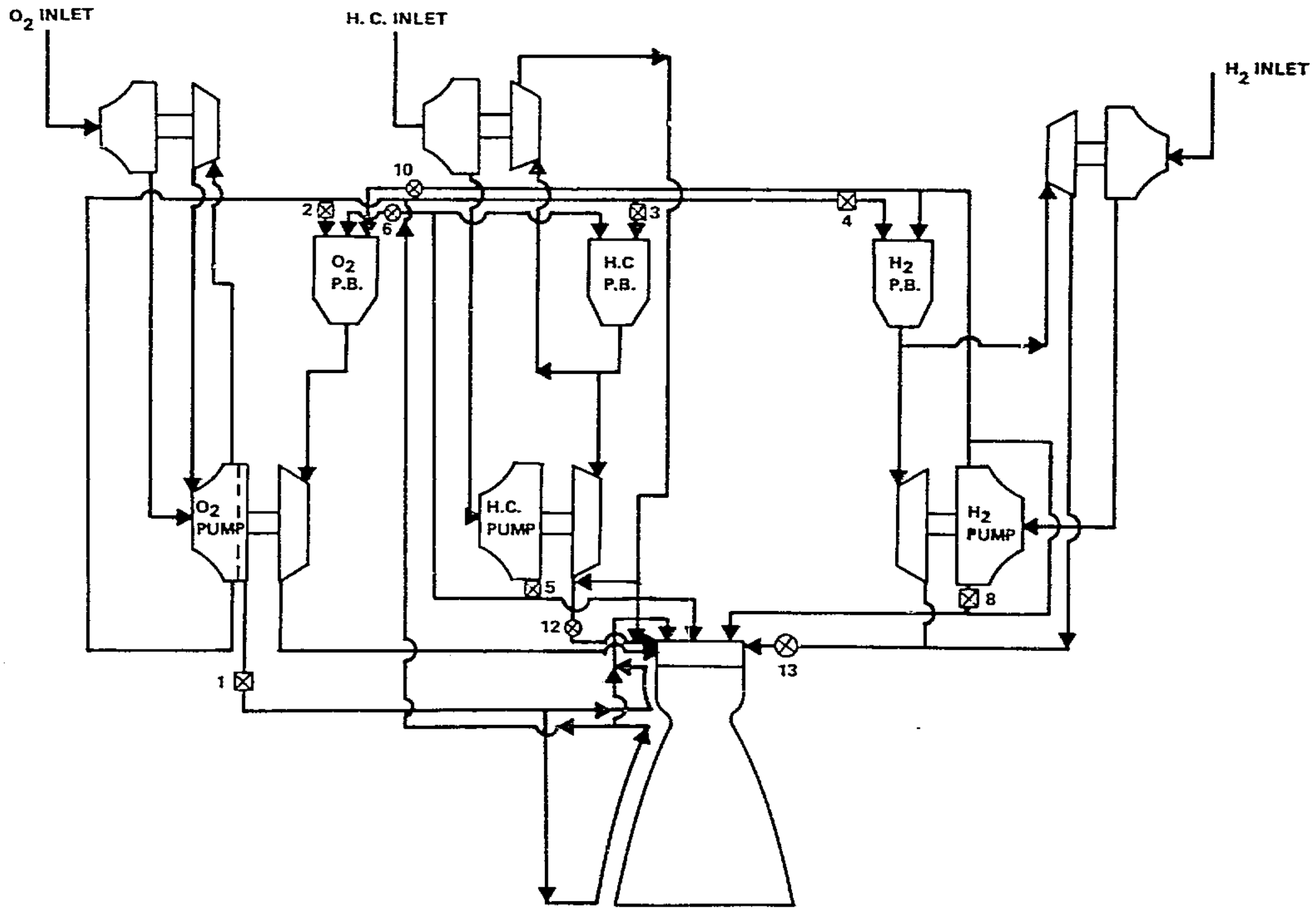

Figure 5

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

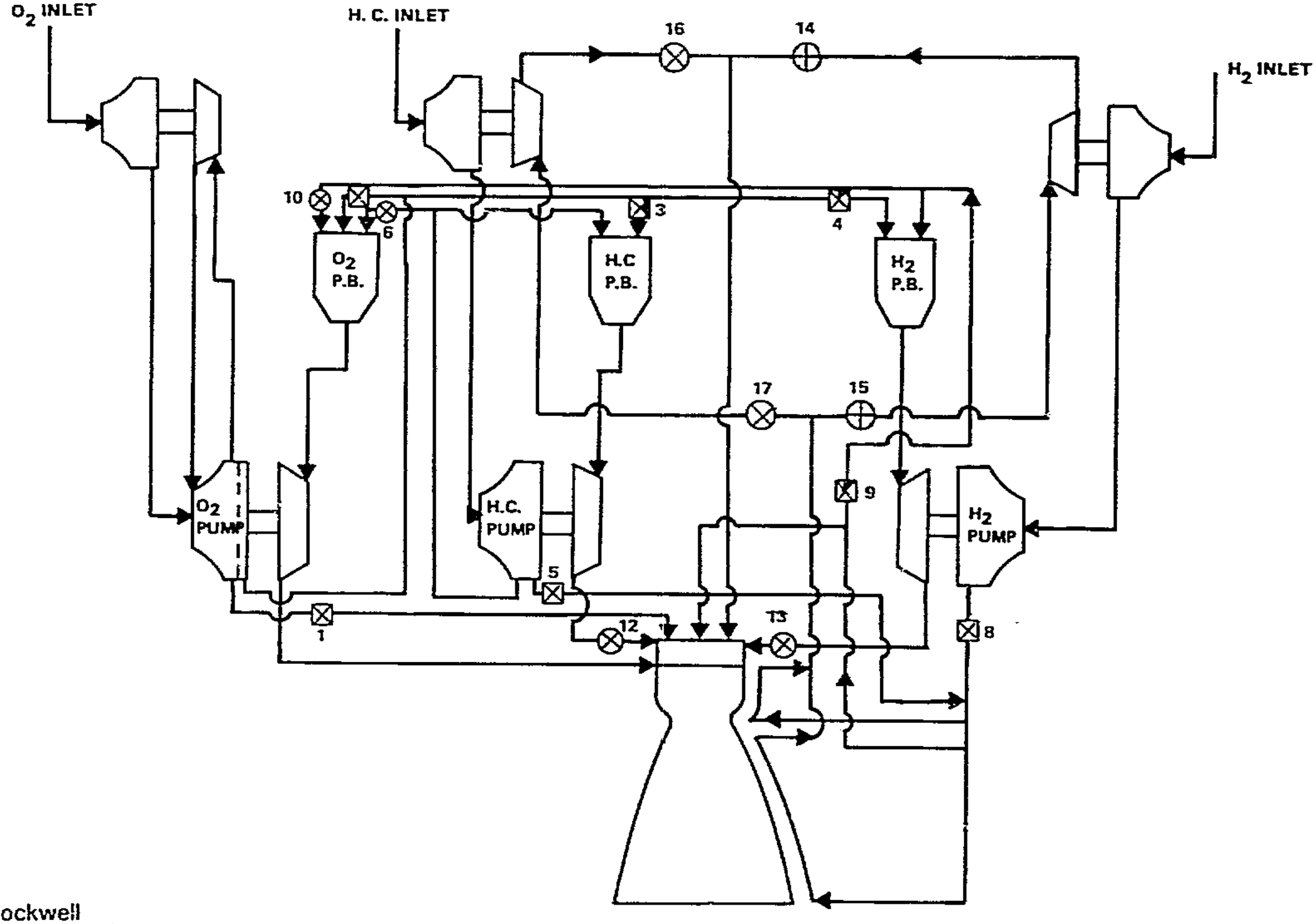

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Figure 6

Open-Loop Control Mode. Start is initiated by a command from the vehicle. (Prestart procedures provide for removal of all vapor from engine passages above the main propellant valves and above the oxidizer preburner valves and inerting of propellant feed manifolds and coolant jackets.)

The start sequence (Fig. 7) starts with actuation of the main hydrogen valve (Valve No. 8 in Fig. 4) to the full-open position and the preburner and main chamber hydrogen igniter valve. This establishes flow under tank pressure to systems downsream of the valve for priming, including the main combustors, preburners, and ignition system. Upon priming of the fuel systems, the main oxidizer valve (1)* the oxidizer preburner oxidizer valve (2), and the hydrocarbon fuel preburner oxidizer valve (3), and the hydrogen preburner oxidizer valve (7) begin to open, retracting the valve ball seats. Before main flow begins to build up from these valves, igniter element oxidizer flows past the valve ball-seat and into the preburners, and main combustion chamber. Seal retraction of the oxidizer valves establishes hydrogen propellant flow in the igniter systems.

Propellant flow (hydrogen and oxygen) to the main chamber and preburner ignition units is ignited by a spark igniter units at the main chamber and preburner, producing a hot-gas core for main (Mode 1) propellant ignition at the injector approximately 300 milliseconds after the start signal is actuated. Initiation of LOX/H_2 pilot combustion early in the sequence assures that the main hydrocarbon propellants of the main chamber and preburners ignite safely and that no raw propellants are dumped into the vehicle boattail during start.

Actuated a fraction of a second after the main hydrogen valve the main oxidizer valve continues to open to approximately 60 percent of its full travel. Hydrocarbon, oxygen and hydrogen preburner oxidizer valves are then ramped open to their intermediate 50 percent position. Immediately after, the hydrocarbon main valve (5) is ramped to fully open position. This initiates preburner power buildup of the hydrocarbon turbomachinery, with the oxidizer turbomachinery power lagging slightly behind the hydrocarbon.

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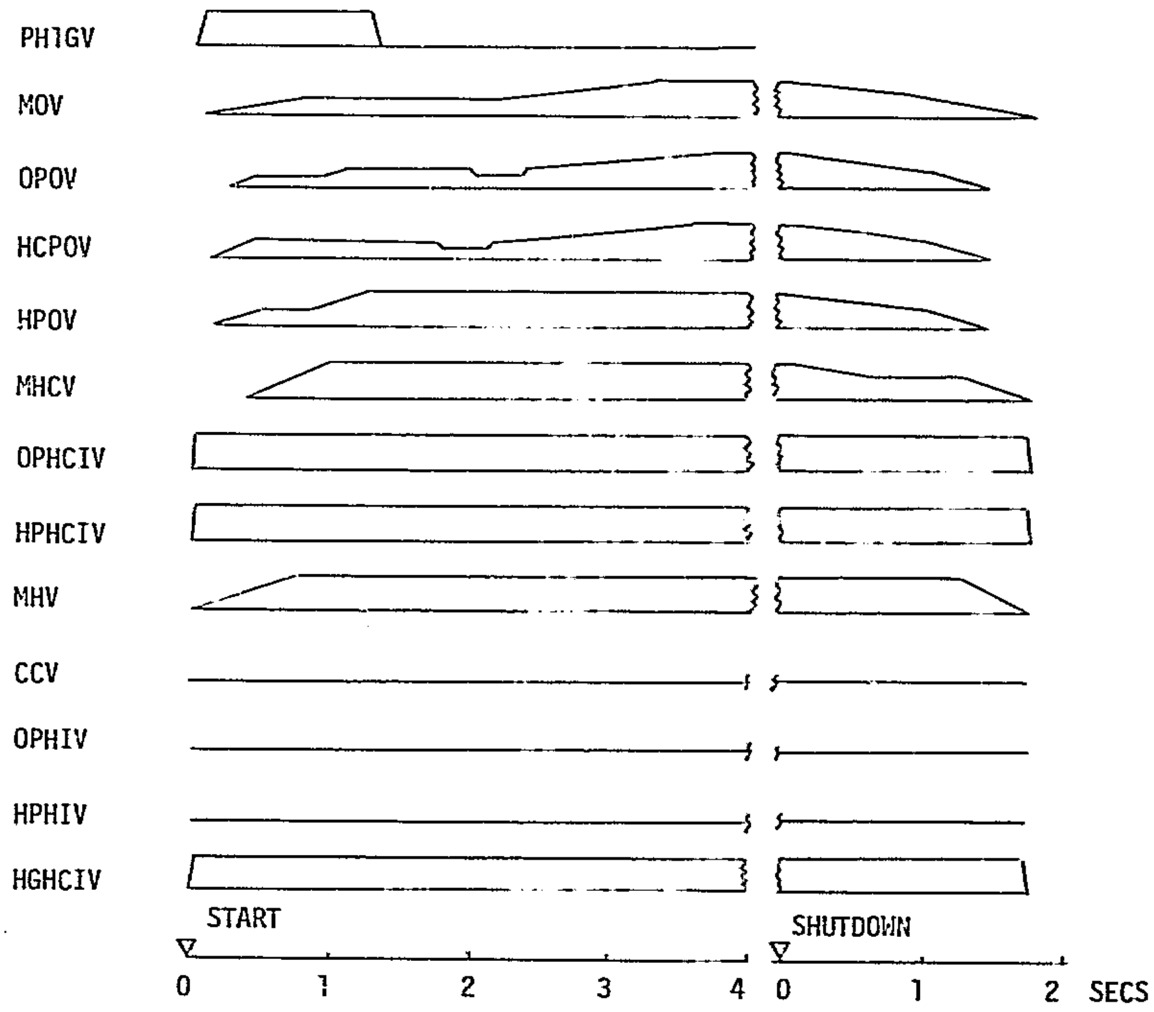
* Numbers in parenthesis refer to valve number on appropriate schematic

START AND SHUTDOWN SEQUENCE, CONCEPTS 1-6, 10-13*, MODE I



* Concepts 10 & 11: No HPHCIV, HPHIV, CCV
Concepts 12 & 13: No HPHCIV, HPHIV
MHV Closed

Figure 7

Hydrocarbon isolation valves on the oxidizer (6) and hydrogen (7) preburners are opened with the activation of the start signal and remain open during mode 1 operation, as well as the thrust chamber hot-gas hydrocarbon isolation valve (12). The oxidizer (10) and hydrogen (11) preburner isolation valves and the coolant control valves (5) remain closed during mode 1 operation. The first two valves prevent hot-gas hydrocarbon products from entering the hydrogen flow system during mode 1 operation.

Propellant flow to the main chamber and preburner ignition units is ignited by a spark igniter producing a hot-gas core for main propellant ignition at each injector 250 milliseconds after the engine start signal is actuated. Initiation of LOX/H_2 combustion early in the sequence provides assurance that no raw propellants are dumped into the vehicle boattail during start and that the main hydrocarbon propellants of the main chamber and preburners ignite safely.

Actuated at a fraction of a second after the main hydrogen valve the main oxidizer valve continues to open to 62 percent of their travel. Shortly after, the hydrocarbon preburner oxidizer valve is ramped to the intermediate open position of 52 percent. Immediately after, the hydrocarbon main valve is ramped to fully open position. This initiates preburner power to the intermediate open position of 52 percent. Immediately after, the hydrocarbon main valve is ramped to fully open position. This initiates pre-burner power buildup of the hydrocarbon turbomachinery.

The valve positions established by approximately one second set the engine power level at approximately 25 percent of rated power level. The transient to this thrust level provides preburner and main combustion chamber mixture ratio variations which do not degrade component life and reliability. The engine continues in this operating mode until 2.0 seconds. At this time, all engines start transients, including the slowest systems under the worst operating conditions, will have reached 25 percent of rated power level. When the thrust is increased from 25 percent to the final thrust level, all engine systems, regardless of environment will respond in the same manner and with the same characteristics. The pre-established thrust acceleration rates conform with customer specifications and provide for minimization of side loads for seal level starts.

Closed-Loop Mode. Start buildup to the commanded thrust and mixture ratio levels is performed under closed-loop control. At approximately 3/4 second into the start transient the oxidizer and fuel preburner oxidizer valve positioning controls are turned over to closed-loop thrust control. This procedure is selected to maintain the engine mixture ratio between the proper limits in the high-impulse range during the major portion of the thrust buildup. The commanded thrust level is achieved in approximately four seconds. This method achieves repeatable start characteristics with commanded thrust and mixture ratio achieved in the same time on every start.

Startup procedures are similar for concepts 1-6, 12, 13 except for a few non-consequential steps. The main hydroven valve (7) remains closed during mode 1 operation since the engine is hydrocarbon cooled in mode 1. Hydrogen for the ignition system is obtained from upstream of the hydrogen valve. No hydrogen preburner hydrocarbon isolation valve (7) or hydrogen preburner hydrogen isolation valve (11) are required since the hydrogen preburner operates only once during the cycle.

During mode 1, the heated hydrogen isolation valves (14 & 15) remain closed while the heated hydrocarbon isolation valves (16 & 17) are open. With the main fuel valve closed a portion of the hydrocarbon provides thrust chamber and power for the low pressure pump cooling turbine before flowing into the thrust chamber injector.

Since concepts 10-11 utilize oxygen cooled thrust chambers no coolant control valves (9) have been included. As in concepts 12-13 the hydrogen preburner operates only once during the cycle and therefore does not require preburner isolation valves, hydrogen (7) hydrocarbon (11). Also no isolation valves (14-17) are required in the coolant circuits. Except for the above the start procedures during mode 1 are identical to those of concepts 1-6.

Engine Shutdown. The engine achieves shutdown functions with the same elements used for start and mainstage control. The shutdown sequence (Fig. 7) by employing closed-loop and open-loop elements, provides repeatable shutdown transients which are insensitive to vehicle and mission operation requirements.

Mode 2 Operation. Mode 2 operation of the tripropellant engine is in the LOX/ H_2 mode which is identical to SSME operation. Start and shutdown transients are as shown in Figs. 2 and 3. Valve sequencing and scheduling are as shown in Fig. 7. All the hydrocarbon valves (3, 5, 6, 7, 12, 16, 17) remain closed while all the hydrogen valves are operative.

Control Valve Requirements. Control valves required in the staged combustion cycles are summarized in Table 4 according to the three thrust chamber cooling concept groups. The least number of valves (10) is required by the oxygen cooled concepts 10 and 11 and the largest number (15) is required by concepts 12 and 13 which use both fuels sequentially for cooling the thrust chamber. This sequential use of fluids requires an increased number (3) of isolation valves over the all-hydrogen cooled concepts (1-6). Isolation valves are used whenever a component such as the preburner, main thrust chamber, coolant jacket, or turbine is required to operate sequentially with two fluids. The respective isolation valve presents the fluid in use from entering and contaminating the inactive circuit of the fluid not in use. In most cases these isolation valves are simple one-way on-off valves while in the case of isolation valves which handle hot-gas they can become large in size and intricate in design if nearly zero leakage is a requirement.

The principal system valves are used for coarse or fine control of fluid flow and are of design similar to the SSME valves. These are the main fuel and oxidizer valves, the preburners oxygen valves and the coolant control valves. Though the SSME type valve designs can be adopted in all cases for mode 1 tripropellant engine valves, the specific SSME hardware cannot be utilized in some cases because of differences in flowrate and pressure requirements between the SSME and the tripropropellant engine (Table 5). The applicability of SSME control valves to the staged combustion tripropellant engine is indicated in Table 6. Because of flowrate restrictions (Table 5) the SSME OPOV cannot be used for the tripropellant engine OPOV (Table 6). Flowrate restrictions again preclude use of some of the SSME oxidizer valve candidates to the tripropellant engine HCPOV and HPOV (Table 6). There are no propellant isolation valves used in the SSME, therefore, no candidates for the tripropellant engine isolation valves.

Table 4
CONTROL VALVE REQUIREMENTS
STAGED COMBUSTION CYCLES

VALVE NAME	SYMBOL	CONCEPTS 1-6 (H_2 Cooled)	CONCEPTS 12 & 13 (HC/H_2 Cooled)	CONCEPTS 10 & 11 (O_2 Cooled)
MAIN OXIDIZER VALVE	MOV	1	1	1
OXIDIZER PREBURNER OXIDIZER VALVE	OPOV	2	2	2
H.C. PREBURNER OXIDIZER VALVE	HCPOV	3	3	3
H_2 PREBURNER OXIDIZER VALVE	HPOV	4	4	4
MAIN H.C. COOLANT ISOLATION VALVE	MHCV	5	5	5
OXIDIZER PREBURNER H.C. ISOLATION VALVE	OPHCIV	6	6	6
H_2-PREBURNER H.C. ISOLATION VALVE	HPHCIV	7	-	-
MAIN H_2 & COOLANT ISOLATION VALVE	MHV	8	8	8
COOLANT CONTROL VALVE	CCV	9	9	-
OXIDIZER PREBURNER H_2-ISOLATION VALVE	OPHIV	10	10	10
H_2-PREBURNER H_2 ISOLATION VALVE	HPHIV	11	-	-
T/C H.G. H.C. ISOLATION VALVE	HGHCIV	12	12	12
T/C H.G. H_2 ISOLATION VALVE	HGIV	-	13	13
HEATED H_2 ISOLATION VALVES	HH2IV	-	14,15	-
HEATED H.C. ISOLATION VALVES	HHCIV	-	16,17	

Table 5. Flow and Pressure Requirements, Staged Combustion Cycle System Control Valves

VALVE FUNCTION	SSME	CONCEPT NUMBER									
		1	2	3	4	5	6	10	11	12	13
MOV, LB/SEC PSI	965 4788	1045 4123	1045 4123	1085 4123	1085 4123	1064 4123	1064 4123	1090 4123	1090 4123	1128 4123	1101 4123
OPOV, LB/SEC PSI	32.4 8038	285.1 7331	385.1 7331	448 7331	448 7331	446 7331	446 7331	604 7331	604 7331	369 7331	328 7331
HCPOV, LB/SEC PSI	- -	50.8 7331	182 7331	56.3 7331	316 7331	63.2 7331	260 7331	51.7 7331	161 7331	291 7331	448 7331
HPOV, LB/SEC PSI	85.8 8038	42.9 7331	166 7331	29.5 7331	182 7331	40 7331	182 7331	85.8 8038	85.8 8038	85.8 8038	85.8 8038
MHV, LB/SEC PSI	161 6831	34 4000	34 4000	34 4000	34 4000	34 4000	34 4000	148 6206	148 6206	148 6206	148 6206
CCV, LB/SEC PSI	66.5 6534	62 5700	62 5700	62 5700	62 5700	62 5700	62 5700	62 5700	62 5700	62 5700	62 5700
MHCV, LB/SEC PSI	- -	300 4123	300 4123	252 4123	252 4123	287 4123	287 4123	389 4123	389 4123	322 6064	367 6064

Table 6. Control Valve Availability Staged Combustion Cycles

VALVE NAME	SYMBOL	STAGED COMBUSTION CONCEPTS									
		1	2	3	4	5	6	10	11	12	13
Main Oxidizer Valve	MOV	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME
Oxidizer Preburner Oxidizer Valve	OPOV										
H. C. Preburner Oxidizer Valve	HCPOV	SSME HPOV		SSME HPOV		SSME HPOV		SSME HPOV			
H_2 Preburner Oxidizer Valve	HPOV	SSME		SSME		SSME		SSME	SSME	SSME	SSME
Main H.C. Coolant Isolation Valve	MHCV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV
Oxidizer Preburner H.C. Isolation Valve	OPHCIV										
H_2-Preburner H.C. Isolation Valve	HPHCIV										
Main H_2 and Coolant Isolation Valve	MHV	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME	SSME
Coolant Control Valve	CCV	SSME	SSME	SSME	SSME	SSME	SSME	-	-	SSME	SSME
Oxidizer Preburner H_2-Isolation Valve	OPHIV										
H_2-Preburner H_2 Isolation Valve	HPHIV										
T/C H.G. H,C. Isolation Valve	HGHCIV										
T/C H.G. H_2 Isolation Valve	HGIV										
Heated H_2 Isolation Valves	HH2IV										
Heated H.C. Isolation Valves	HHCIV										

Other Valve Requirements. In the case where components are operated with two propellants sequentially, purging of the component is required after use with the first propellant before use with the second can proceed. To minimize trajectory-performance losses purging must occur in the shortest possible time interval. The propellants in question are methane, propane, and RP-1 used as coolant in the thrust chamber jacket, and as propellant in the main injector during mode 1 followed by hydrogen coolant during mode 2. Because the hydrogen enters the system at its normal boiling point of 37R, the possibility exists that any of the hydrocarbon residuals may freeze. The lowest melting point is that of methane (154R), the highest is that of RP-1 (405R). Gaseous purging is required to reduce the concentration of these propellants and will be especially effective in the case of methane and propane. In the case of RP-1 (a liquid) purging effectiveness will depend on orientation of engine, location of vents, and geometry of the coolant passages. Experimental evaluation is required in this area. Purge valves and fluids are required therefore at the coolant jackets and at the injector manifolds for concepts 12 and 13. Concepts 1-6 require fuel system purge valves at the oxidizer preburner and at the hydrogen preburner. Concepts 10 and 11 require purge valves at the oxidizer preburner for the same reasons as stated above.

Gas Generator Cycle Concepts

The gas generator cycle cooling options are: all-hydrogen cooled, and hydrocarbon cooled in mode 1 with hydrogen cooling during mode 2. Only one gas generator is used in both concepts, thus necessitating an injector capable of burning LOX/hydrocarbon and LOX/hydrogen sequentially. Start and shutdown procedures are described below.

Mode 1 Operation. Criteria for start and shutdown are the same as outlined in Table 3. Schematics of the four engine concepts are categorized according to the two cooling options and are depicted in schematic form in Fig. 8 and 9 .

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

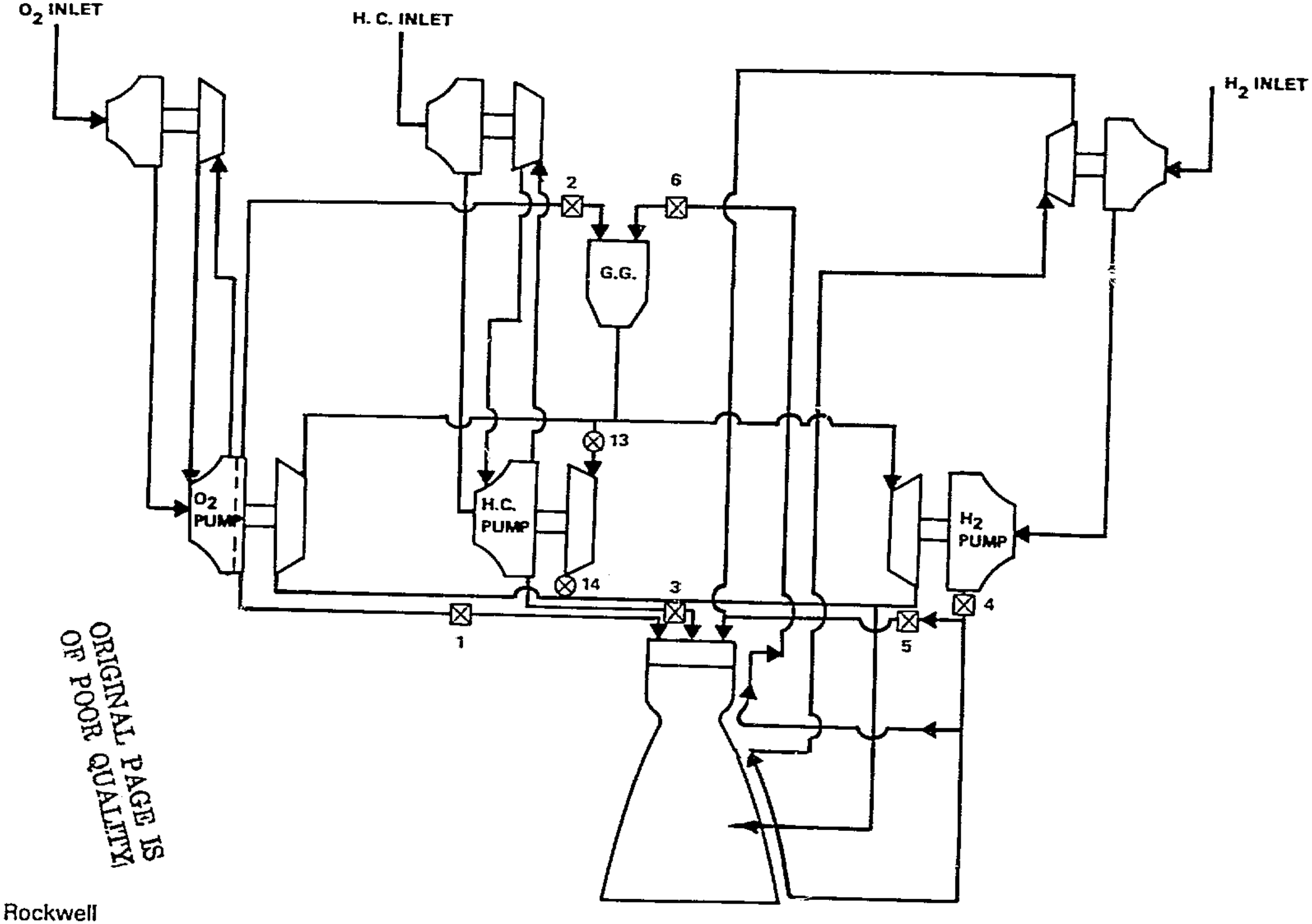


Figure 8

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

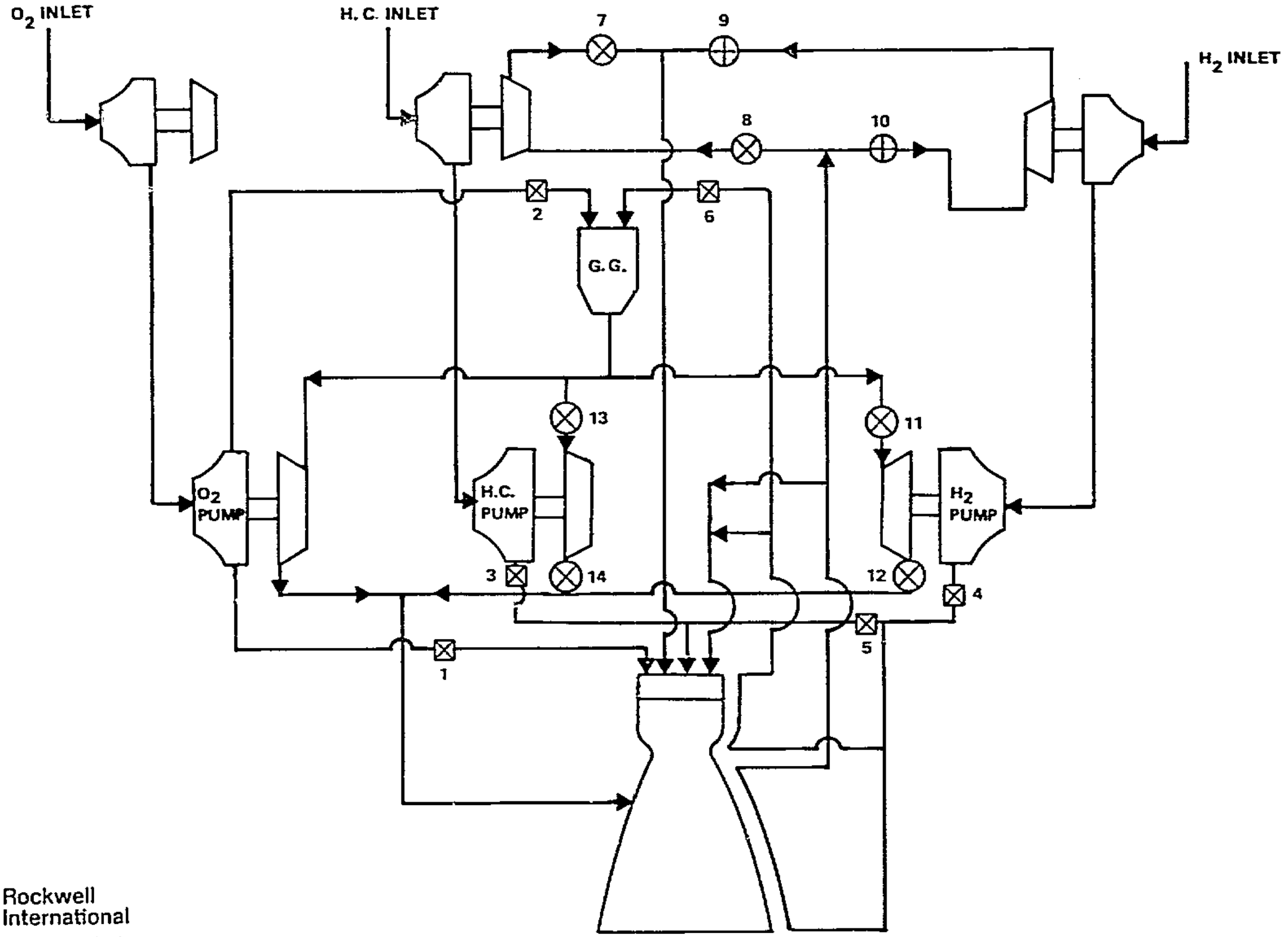


Figure 9

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Start and shutdown procedures for both engine cooling categories are similar and will be discussed jointly.

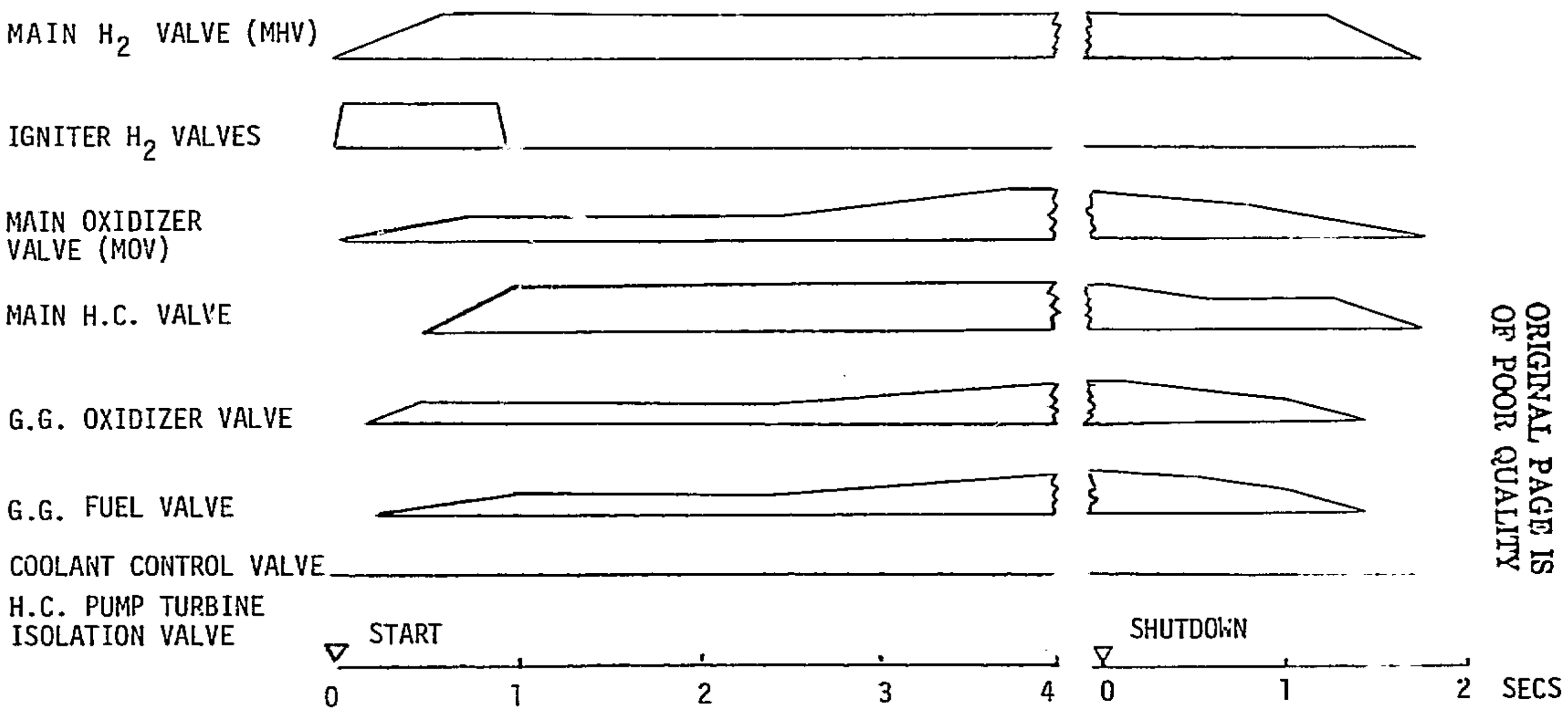
Start valve sequencing is shown in Fig. 10. The start signal causes the main hydrogen valve (4) and the igniter hydrogen valves in the gas generator and thrust chamber to open allowing priming of coolant jackets and hydrogen lines and initial igniter units hydrogen flow to start in the case of concepts 7, 8, and 9. Shortly after, the main oxidizer valve (1) and the gas generator oxidizer valve (2) are actuated allowing initial unseating of ball valve seals and allowing oxidizer flow to the igniter units. Ignition of LOX/H_2 propellants is then initiated in the gas generator and thrust chamber augmented spark igniters. In the case of concepts 14 and 15 (schematic in Fig.9) the igniter hydrogen flow is obtained from upstream of the fuel valve which remains closed during mode 1 operation. The gas generator fuel valve (6) is then sequenced open (hydrogen in the case of concepts 7, 8, and 9). Main propellant ignition occurs then in the gas generator. Ignition is caused by the hot stream of combusting LOX/H_2 in the gas generator igniter. The main hydrocarbon valve (3) is then actuated which causes main propellant ignition to occur in the thrust chamber upon contact with the main chamber igniter LOX/H_2 combustion products.

The engine then enters a close loop control phase wherein the thrust is first increased to a 25 percent plateau with mixture ratio control and after approximately 1/2 second ramped to 100 percent rated thrust at prescribed ramp rates. This action produces start transients similar to those of the SSME (Fig.2).

As in the staged combustion cycle concepts, closed loop control prevents start transients overshoots or undershoots of any of the parameters that may affect engine life. It also provides for the uniformity of start transient behavior between engines.

Shutdown is effected with the same components and in a closed-loop control mode to minimize detrimental transients in turbine temperatures and pump speeds.

START & SHUTDOWN SEQUENCE, CONCEPTS 7, 8, 9, 14, 15*, MODE 1



*Concepts 14&15: HHCIV, HCPTIV, Valves Open; HH2IV, HPTIV Closed, MHV Closed

Figure 10

Control Valve Requirements. The valve requirements for the gas generator cycles are shown in Table 7. Concepts 14 and 15 require 6 isolation valves more than concepts 7, 8, and 9. This is caused by the dual nature of the coolant fluid, i.e., hydrocarbon in mode 1 and hydrogen in mode 2. The hydrogen circuits need isolation during the hydrocarbon phase (valves 9 and 10) and vice-versa during mode 2 (valves 7 and 8. The hydrogen pump turbine requires isolation during the mode 1 with valves 11 and 12. During mode 2 valves 13 and 14 isolate the hydrocarbon flow system from hot gases entering through the hydrocarbon pump turbine.

In addition to the six main control valves (1-6) concepts 7, 8, and 9 require hydrocarbon pump turbine isolation valves (13 and 14) during mode 2 operation.

Other Valve Requirements. For dual fuel operation purging of the thrust chamber coolant jacket, injector manifolds and feed lines is required immediately after the hydrocarbon phase and before the hydrogen can be introduced in the circuits. Purging has to be performed to a degree such that no hydrocarbon residuals capable of freezing and obstructing flow passages or forming explosive mixtures remain. Other purge and inerting operations are as required by standard prelaunch or preactivation procedures.

Control Valve Availability. Flowrate and operating pressure requirements for the gas generator cycle main control valves is indicated in Table 8 . Also shown are flows and pressures for applicable SSME main control valves. In Table 9 the applicability of SSME valve functions is indicated.

Table 7

CONTROL VALVE REQUIREMENTS

GAS GENERATOR CYCLES

VALVE NAME	SYMBOL	CONCEPTS 7, 8, 9	CONCEPTS 14 & 15
MAIN OXIDIZER VALVE	MOV	1	1
GAS GENERATOR OXIDIZER VALVE	GGOV	2	2
MAIN H.C. & COOLANT ISOLATION VALVE	MHCV	3	3
MAIN H_2 AND COOLANT ISOLATION VALVE	MHV	4	4
COOLANT CONTROL VALVE	CCV	5	5
GAS GENERATOR FUEL VALVE	GGFV	6	6
HEATED H.C. ISOLATION VALVES	HHCIV		7, 8
HEATED H_2 ISOLATION VALVES	HH2IV		9, 10
H_2 PUMP TURBINE ISOLATION VALVES	HPTIV		11, 12
H.C. PUMP TURBINE ISOLATION VALVES	HPTIV	13, 14	13, 14

Table 8 . Flow and Pressure Requirements, Gas Generator Cycle System Control Valves

VALVE FUNCTION	SSME	CONCEPTS				
		7	8	9	14	15
MOV, LB/SEC	965	1056	1084	1058	1102	1074.5
PSI	4788	5106	5106	5106	5106	5106
GGOV, LB/SEC	(OPOV) 32.4	13.9	15.8	14.7	28.6	33.6
PSI	8038	5106	5106	5106	5106	5106
MHV, LB/SEC	161	34	34	34	-	-
PSI	6831	6084	6084	6084	-	-
GGFV, LB/SEC	(HPOV) 85.8	-	-	-	66.5	76.4
PSI	8038	-	-	-	5466	5107
MHCV, LB/SEC	-	335.7	277	314	373	423.3
PSI		5106	5106	5106	5106	5106

Table 9. Control Valve Availability Gas Generator Cycles

VALVE NAME	SYMBOL	CONCEPTS				
		7	8	9	14	15
Main Oxidizer Valve	MOV	SSME	SSME	SSME	SSME	SSME
Gas Generator Oxidizer Valve	GGOV	SSME OPOV	SSME OPOV	SSME OPOV	SSME OPOV	SSME OPOV
Main H.C. and Coolant Isolation Valve	MHCV	SSME MOV	SSME MOV	SSME MOV	SSME MOV	SSME MOV
Main H_2 and Coolant Isolation Valve	MHV					
Coolant Control Valve	CCV	SSME	SSME	SSME	SSME	SSME
Gas Generator Fuel Valve	GGFV				SSME HPOV	SSME HPOV
Heated H.C. Isolation Valves	HHCIV					
Heated H_2 Isolation Valves	HH2IV					
H_2 Pump Turbine Isolation Valves	HPTIV					
H.C. Pump Turbine Isolation Valves	HCPTIV					

TASK V - SSME COMPONENT ADAPTABILITY

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 established a relationship between the required operating conditions, for the tripropellant feed systems being evaluated, and the operational capability of the SSME turbines. Those turbines 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 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

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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.

The gas turbine analyses utilized the working fluid available energy data and the operating parameters. Turbine velocity ratios (U/C_{oR}) 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 turbine 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. A summary of the study conclusions is presented in Table 10.

Candidate engines 1 and 2 utilize LOX/RP-1 turbine working fluid in a staged combustion cycle installation. The 28,660 design horsepower of the HPOT turbine is not exceeded by the required 22,100 horsepower of these candidate engines. The required 25,800 rpm turbine speed can be achieved. The analysis indicates the LO_2/RP-1 velocity ratio, (U/C_{oR}) is 0.624, this is in an unfavorable off design operating region; the HPOT turbine design U/C_{oR} is 0.296. The oxidizer turbine required turbine gas path area is larger than the physical areas existing in the turbine nozzles and blading. The area difference is too large, and modification of the existing gas path elements is not practical. The required flow area(s) is approximately three times larger than available in the existing turbine. Use of the HPOT turbine in those applications is not recommended.

Candidate engines 3 and 4 use LO_2/CH_4 turbine working fluid in a staged combustion cycle configuration. The 23,200 required turbine horsepower in these candidate engines doesn't exceed the HPOT turbine design power, and turbine speed can be achieved for these candidate designs. Turbine

Table 10

TURBINE EVALUATION

T/M COMPONENT			FIRST STAGE NOZZLE		COMMENTS
CANDIDATE	TURBINE	APPLICATION	FLUID SPECIFIC VOLUME ft^3/lb	FLOW AREA REQUIRED IN^2	LIMITING PARAMETER
1	HPOT	Full Flow Lox	0.198	9.17	Turbine Flow Area Not Adequate.
2	HPOT	Full Flow Lox	0.198	9.17	↓
3	HPOT	↓	0.203	12.57	
4	HPOT		0.203	12.57	
5	HPOT		0.200	12.20	
6	HPOT		0.200	12.20	
7	HPOT		4.038	2.23	New Nozzles and Blading May Satisfy Requirements.
8	HPOT		4.038	2.33	↓
9	HPOT		4.038	2.28	
10	HPOT		-	-	Turbine Horsepower Requirements Exceeds Design. HP design = 28,658 HP required = 39,300
11	HPOT		-	-	
12	HPOT		0.203	12.57	Turbine Flow Area Not Adequate.
13	HPOT		0.201	13.26	" " " " "
14	HPOT		-	-	Requires at Least One Additional Turbine Stage
15	HPOT		-	-	" " " " "

Design Nozzle Flow Area = 2.94 Sq. In.

Design Nozzle (First Stage) Specific Volume = 1.066 ft^3/lb

velocity ratio U/C_{oR} is 0.684; this is in the off design operating range of the turbine. In addition a large difference exists between the gas path area(s) required for these candidate applications and the flow area(s) available in the HPOT turbine. This is exemplified by the 12.57 sq. in. area required in the first stage nozzle for the LO_2/CH_4 working fluid; the current design area for this gas path element is 2.94 squ. in. The difference between these turbine gas path areas is too large, and it is impractical to consider modifying the existing turbine design to accommodate operations for the LO_2/CH_4 - staged combustion candidates.

The LO_2/C_3H_8 turbine performance and flow constraints for number 5 and 6 candidate engines, are approximately the same as found in the staged combustion candidates 1 through 4. The 0.683 off design velocity ratio (U/C_{oR}) in these candidate designs reduces the turbine efficiency to 55.7 percent. The 22,600 horsepower can be achieved, at a speed of 26,100 rpm; this requires a turbine mass flow rate of 508 lb/sec.

Candidate engines 7,8 and 9 utilize LO_2/H_2 turbine working fluid in a gas generator engine cycle. The study results indicate the required turbine powers and speeds can be achieved, To accomplish this, 29 lb/sec turbine mass flow rate is required with the designated turbine pressure ratio of 20:1. The gas path of the HPOT turbine was designed for a pressure ratio of 1.57 for a staged combustion engine cycle. Therefore, to satisfy the required power requirements the analysis indicates the turbine should be modified with new nozzle(s) and rotor blading designs in these candidate engines. A typical redesigned turbine gas path will contain two stages, with a pressure ratio of 5 across the first stage. The resultant 55 percent stage efficiency is influenced principally by the low 0.155 velocity ratio (U/C_{oR}) in which the turbine will operate. The turbine performance can be improved with adjustments in the design speed, pressure ratio, and turbine inlet temperature. The required first stage nozzle areas for the existing reaction turbine design and for the redesigned gas generator cycle, turbine nozzle are approximately equal.

The horsepower requirements in the staged combustion, candidate engines number 10 and 11 exceed the design power of the HPOT turbine, and therefore eliminates its use in these applications. The required turbine power is 39, 300 horsepower, whereas the existing turbine was designed to develop a maximum of 28,658 horsepower. A redesign of the turbine to accommodate the increased power requirement is not practical. The complexity of modifying the existing configuration, coupled with the cost and time required to achieve this type of change, eliminates use of the HPOT turbine in these candidate engines.

LO_2/CH_4, and LO_2/C_3H_8 turbine working fluid are respectively used in the staged combustion candidate engine 12 and 13. The power and speed required in these applications are within the design limits of the HPOT turbine. The turbine velocity ratio(s) (U/C_{oR}) are 0.69 at the 24,000 rpm speed range, and 1.6 turbine pressure ratio. This places the turbine in an off design operating range, and therefore the performance is penalized; the predicted turbine efficiency is 55 percent in each of these candidate engine systems. The turbine required mass flow is 555 lb/sec and 553 lb/sec respectively in engines 12 and 13. The initial sizing of the gas path details indicates the existing turbine nozzle area is too small to accommodate flow for the new application. The 2.94 sq. in. nozzle design area is approximately one-fourth the area required for the 555 lb/sec turbine mass flow rate in candidates 12 and 13. The use of the HPOT turbine is eliminated on the basis of low turbine performance, and too large a mismatch in gas path area to effectively implement a gas path modification.

Candidate engines 14 and 15 require turbine designs, which respectively operate with O_2/CH_4 and O_2/C_3H_8 working fluids, in gas generator installations. The HPOT, turbine design speed and horsepower are within the design requirements for these candidate engines. Matching the gas path conditions, at the 20 to 1 turbine pressure ratio to the 1.57 HPOT design pressure ratio configuration, reduced the velocity ratio range in which the turbines operate. The respective single stage velocity ratios

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(U/C_{oR}) for these candidates are 0.118 and 0.133; these were calculated with a 5 to 1 pressure ratio in the first stage. The data indicated the use of a 2-stage HPOT turbine was pressure ratio limited, and therefore new nozzles and blading were considered. The performance of a typical redesigned 2-stage configuration is penalized because of the velocity ratio range in which it will operate. The proper design for these candidate engines would contain three turbine stages, or perhaps a three-row design could be developed to efficiently utilize the working fluid available energy. For these reasons, the use of the HPOT turbine was determined not suitable for these candidate applications. A redesign to a three turbine rotor configuration for the HPOT turbopump is too complex and costly. A new turbopump design is recommended.

TASK VI - TEST PLANS

The objective of this task is to identify critical areas for experimental component evaluation based on the results of Tasks I through V. Based on this information, test plans will be generated for additional testing to complement the current NASA test plans for 40K hardware with LOX/RP-1. This task effort is just beginning and is scheduled to be completed in mid-May. Since the tripropellant engine studies have not identified any SSME components that would have direct applicability to a tripropellant engine, these test plans will not be directed toward verifying component adaptability but will be geared toward more general technology questions that arose during the course of these studies. The results of the proposed testing would therefore have a more general usefulness in that they would answer questions pertaining to the design of an all new dual mode tripropellant engine or a single mode LOX/hydrocarbon booster engine.

NASA has already planned a comprehensive test program using the 40K SSME subscale hardware with LOX/RP-1 propellants and the test plans developed in this study are to be in addition to or complement the current NASA plans. At this point no additional test objectives can be identified for

LOX/RP-1 propellants. Also, the results of this study have shown that CH_4 offers some significant advantages for a dual mode tripropellant engine or in any LOX/hydrocarbon booster engine system. Therefore the test plans to be studies in this task will be primarily for LOX/CH_4 propellants. However some of the tests would be of equal importance with any hydrocarbon fuel being considered. A list of topics to be considered in developing these test plans is presented below. A short discussion follows to describe the approach to be used in developing the test plans.

1. Low mixture ratio LOX/hydrocarbon gas properties.
2. Oxidizer-rich preburner demonstration.
3. Hydrocarbon cooling.
4. Dual fuel operational transition.
5. Turbine drive gas temperatures greater than 2000R.
6. Staged combustion with LOX/CH_4.
7. Fuel rich and oxidizer rich preburners feeding a main chamber.

Low Mixture Ratio Gas Properties

Previous experience in the F-1 and H-1 engine programs has shown that considerable difference exists between the low mixture, low temperature hot combustion (LOX/RP-1) gas properties observed experimentally and those predicted with current free-energy performance codes. This is believed to be primarily due to the high amount of carbon formed in the very fuel rich combustion process. This comparison has only been demonstrated at low combustion pressures ($<$1000 psia) and the effect is unknown at higher pressures and is therefore a subject for an experimental test program. It is anticipated the LOX/C_3H_8 will behave much like LOX/RP-1 but that the LOX/CH_4 system may not exhibit this discrepancy between experimental and theoretical predictions of mixture ratio vs temperature. A theoretical study is in progress to investigate these effects for LOX/C_3H_8 and LOX/CH_4. The possibility of conducting an experimental program using the 40K preburner with an expansion nozzle is also being investigated. By making hot

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gas pressure and temperature measurements, the pertinent gas properties can be derived.

Oxidizer-Rich Preburner

Staged combustion LOX/hydrocarbon engine system power balances at chamber pressure levels of interest have shown that insufficient energy (fuel flowrate) is available to drive the turbines with all fuel rich preburners. One alternative is to operate one or more preburners oxidizer rich since there is considerably more LOX available. This brings up numerous questions concerning the design and operation of a preburner capable of operating in a very high mixture ratio, low combustion temperature mode. Little experience is available and a test program would provide the much needed information in this area. A test plan will be proposed with the objective of providing some of these answers.

Hydrocarbon Cooling

Little information is available pertaining to experience with any of the hydrocarbon fuels as regenerative coolants. Analytical predictions indicate that the RP-1 is poor coolant and there is less interest in demonstrating its chamber cooling capabilities. However CH_4 appears to be an attractive candidate for future LOX/hydrocarbon booster engine systems and a hot firing cooling demonstration would provide valuable information in the further study and comparison of the candidate systems and in the actual design of a chamber. It is expected that this regenerative cooling demonstration could be conducted with the 40K hardware in conjunction with an injector/combustion process demonstration. The approach would be to first perform calorimeter chamber tests to determine the heat flux profile in the main chamber with LOX/CH_4 combustion. With this information, predictions for wall temperatures and coolant temperatures for the regenerative cooled chamber could be improved. A subsequent test with the channel wall regeneratively cooled chamber would finally demonstrate the CH_4 cooling capabilities and provide valuable design information necessary to design a full scale engine. The regenerative cooling tests could be conducted using only the 40K main chamber by supplying LOX and CH_4 to the injector as in a gas generator cycle or by using the preburner as in a staged combustion cycle. Preliminary studies indicate that the existing injectors can be used with only minor modifications in either the gas generator or staged combustion configurations as long as the CH_4 is heated prior to injection. If the CH_4 is to be injected as a liquid a new injector will be necessary. With the current facility coolant water supply pressure (1500 psia) the calorimeter chamber would be limited to approximately 1800 psia. If the previously available higher pressure water coolant tank were available, a higher chamber pressure could be achieved with the calorimeter chamber. An analysis of the channel wall chamber has shown that a 3000 psia chamber pressure can be cooled with 30 lb/sec of CH_4 with a maximum hot gas wall temperature of 1000F and a coolant pressure drop of less than 500 psia. This chamber can therefore be used for a regenerative cooling demonstration. More details of the injector and cooling analysis will be presented along with the overall test plan in the next report.

Dual Fuel Operational Transition

One of the biggest questions that arises in the tripropellant engine concept concerns the transition from a hydrocarbon fuel during mode 1 to H_2 in mode 2. It is certain that some intermediate purging of the injector, manifold and cooling circuit will be required to prevent freezing of the residual hydrocarbon by the entering LH_2. The feasibility of this demonstration with the 40K hardware will be investigated during the next report period.

Higher Turbine Drive Gas Temperatures

The engine cycle balances conducted during this study for the staged combustion cycle have shown that to achieve an engine balance with all preburners fuel rich, turbine inlet gas temperatures exceeding 2000R are required. This requires that the preburner operate at higher mixture ratios than the current SSME design and that it must be able to withstand the additional heat load. The higher temperature turbine inlet gases will also have a significant impact on the turbine operational limits. The feasibility of a meaningful demonstration of the increased turbine drive gas temperatures with the 40K hardware will be evaluated in this study task.

Staged Combustion with LOX/Hydrocarbon

A 40K demonstration of a staged combustion system using LOX/hydrocarbon propellants would provide information concerning ignition, carbon formation, stability of this system. These test objectives could possibly be achieved in conjunction with the hydrocarbon cooling and injector testing.

Combined Fuel and Oxidizer Rich Preburners

One of the alternatives for achieving adequate turbine drive gas energy for the LOX/hydrocarbon staged combustion systems is to operate the fuel preburner fuel rich and the oxidizer preburner oxidizer rich. This concept requires a new main injector to accommodate the two hot gas streams. The current NASA plans already call for the fabrication of new fuel rich and oxidizer rich preburners of the 40K size. These preburners could be used in conjunction with the available 40K main chamber and a new main chamber injector provide all of the hardware necessary for this demonstration.

All of these test objectives will be studied further to determine their feasibility with regard to the 40K hardware and to determine if several of these test objectives can be achieved in a single test program. Results of the injector analysis and heat transfer studies for the 40K hardware will be presented along with the capability of the available NASA test facility.

TRIPS AND MEETINGS

A mid-contract review meeting was held on January 12, 1978 at the Marshall Space Flight Center to review the study progress and results.

PROGRAM PERFORMANCE AND EXPENDITURES

Program performance and expenditures as of 1 February 1978 are as shown in Table 11 .

Table 11 . Program Expenditures, Tri-Propellant Engine Study

Month Ending January 1978
NAS8-32613
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Total Cumulative Cost-to-Date	ETC	EAC	Percent Complete
31.0K	10.9K	41.9K	74