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ADVANCED PROJECTS
LARGE ENGINES
LAP 67-473

THE AEROSPIKE ROCKET ENGINE (u)

CONCEPT, PERFORMANCE, DESIGN, AND OPERATION DATA

LIQUID OXYGEN - LIQUID HYDROGEN PROPELLANTS

250- TO 500-KLBF VACUUM THRUST CLASS [redacted]

PREPARED BY

ROCKETDYNE, A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION

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7 November 1967

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NORTH AMERICAN ROCKWELL CORPORATION
SPACE DIVISION

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THE BOEING COMPANY
AEROSPACE DIVISION

7 November 1967

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THE AEROSPIKE ROCKET ENGINE

INTRODUCTION

The Aerospike rocket engine is the outstanding candidate for new rocket-powered vehicle systems. It achieves high performance and embodies many unique features which enhance the performance and operation for the vehicle. The Aerospike engine concept has been demonstrated in extensive NASA-, Air Force- and company-sponsored programs.

A review of the Aerospike rocket engine concept, and a description of the performance, design, weight and operation for Aerospike engines in the 250 - to 500-klbf vacuum thrust class using liquid oxygen-liquid hydrogen propellants is presented. The Aerospike performance, design and operation data are based upon the AF ADP* program results, the NASA AEA** engine investigation and supplementary studies.

Information from these programs has been consolidated to provide a working document applicable to an Aerospike engine in the 250- to 500-klbf vacuum thrust class.

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* "Advanced Cryogenic Rocket Engine Program, Aerospike Nozzle Concept", Air Force Contract Number AF04(611)-11399.

** Advanced Engine Design Study (Aerospike)", NASA Contract Number NAS8-20349.

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THE AEROSPIKE ENGINE CONCEPT

CONCEPT DESCRIPTION

The Aerospike engine general design configuration is shown in Fig. 1. The aerospike nozzle (Fig. 2) is a truncated, annular spike nozzle (radial inflow type) which utilizes a small amount of secondary flow introduced into the nozzle base region. This nozzle has been successfully tested (cold-flow models and hot firing) in Air Force-, NASA-, and company-sponsored programs.

The primary flow (high-pressure gases) which produces the major portion of the engine thrust is exhausted from an annular-type combustion chamber and expands against the metal surface of the center truncated-spike nozzle (Fig. 2). The characteristics of the primary flow field upstream of the base region are determined by the annular throat geometry, the nozzle wall contour, and the ambient pressure. The annular primary flow continues to expand beyond the nozzle surface and encloses a subsonic, recirculating flow field in the base region. The pressure acting upon the nozzle base contributes additional thrust to the nozzle.

When a small amount of secondary flow is introduced into the base (added to the recirculating flow), the base pressure is further increased. As the secondary flow is increased, the overall nozzle efficiency (considering the additional flow) increases because of the increase in base pressure. There is a limit to this gain in efficiency, and an optimum secondary flow exists for each configuration.

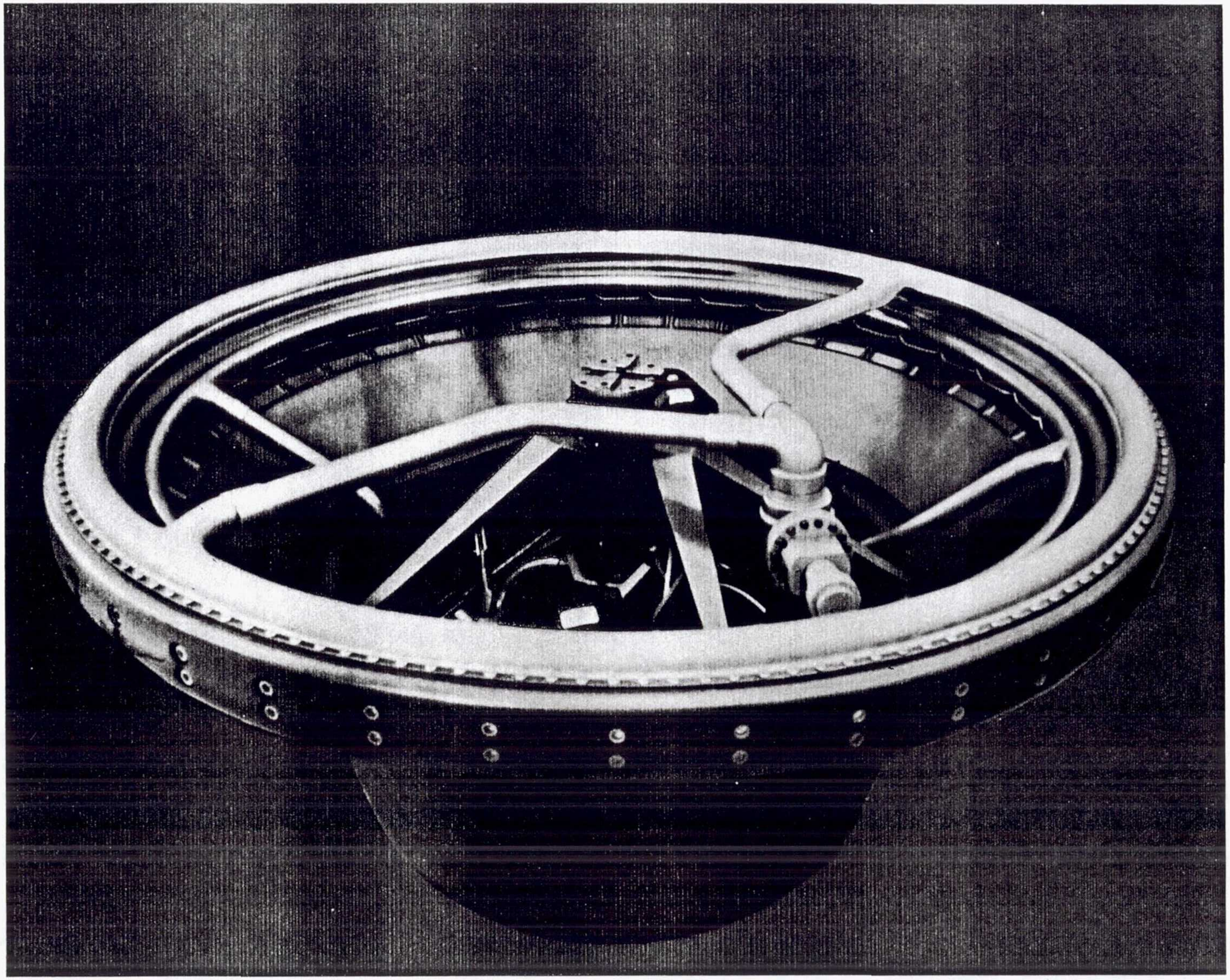

Fig. 1 Aerospike Rocket Engine

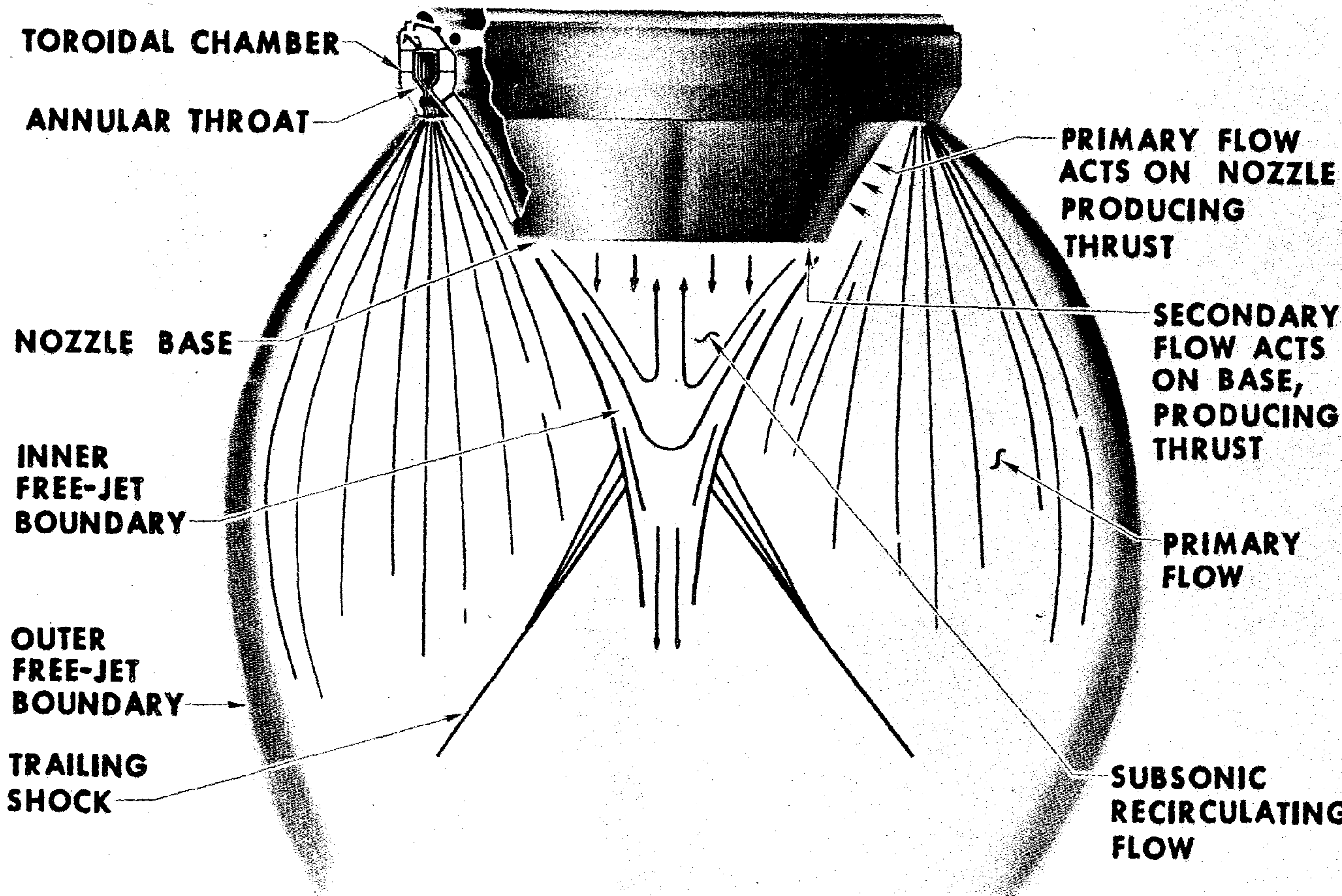

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Figure 2. Toroidal Combustor, Aerospike Nozzle, Thrust Chamber and Flow Fields

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ALTITUDE COMPENSATION

The outer surface of the annular primary flow is a free-jet boundary, which is influenced by ambient pressure. This ambient pressure influence on the primary nozzle flow provides this type of nozzle with altitude compensation. In operation at high-pressure ratios (i.e., altitude conditions), the outer free-jet boundary of the primary flow is governed by the Prandtl-Meyer turning angle at the throat. At low-pressure ratios (i.e., sea level operation), the relatively higher ambient pressure compresses the primary flow field. This compression increases the static pressure on the nozzle wall and partially offsets the negative effect of the higher ambient pressure on the back side of the nozzle. The base pressure is also increased with increased ambient pressure because the compressed primary flow field, which influences the base pressure, has higher static pressures. This combination of flow-field effects provides the altitude compensation inherent in the aerospike nozzle.

The effect of ambient pressure on the free-jet boundary and the flow fields is shown in the Schlieren photographs of Fig. 3. This ambient pressure influence causes the performance to be near an "ideal" variable-area-ratio nozzle at all chamber pressure to ambient pressure ratio (P_c/P_a) values; this effect is called altitude compensation.

ENGINE OPERATION - THE TAPOFF CYCLE

The tapoff power cycle for the toroidal combustor, aerospike nozzle engine is illustrated schematically in Fig. 4. Basically, this cycle is a simplification of the gas generator cycle.

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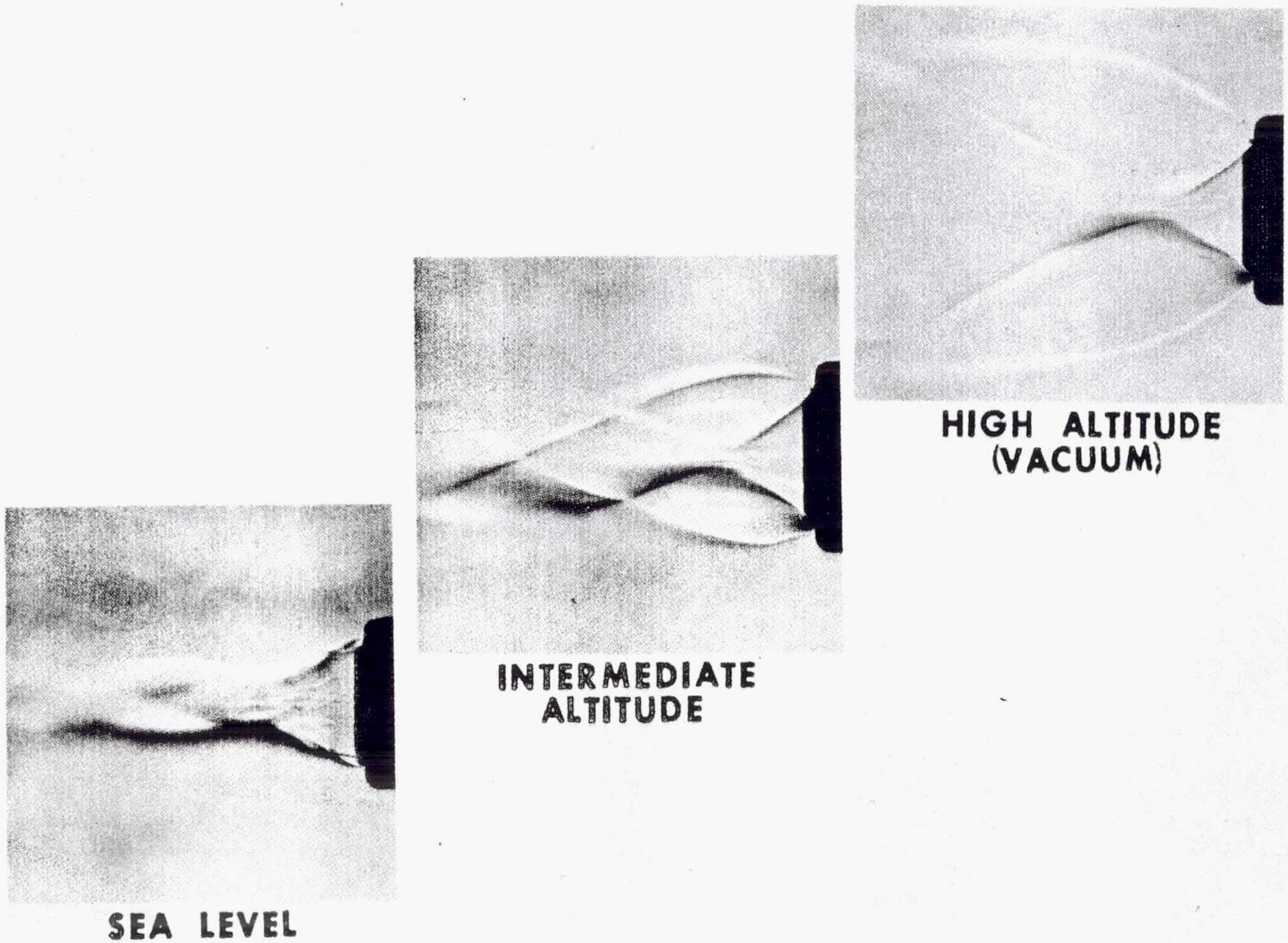

Figure 3 . Schlieren Photographs of Aerospike Nozzle
Cold-Flow Tests

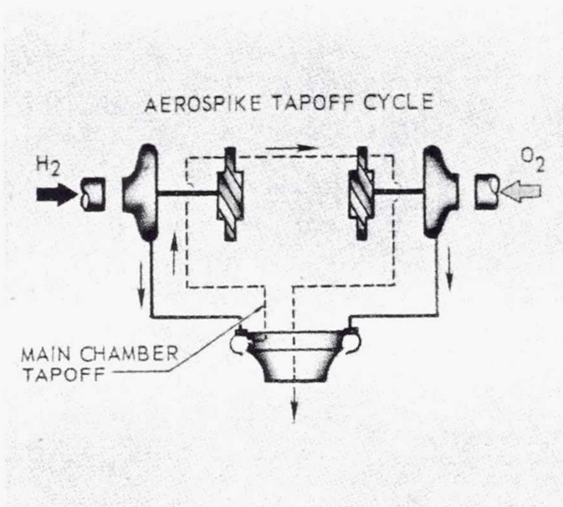

Fig. 4 Aerospike Tapoff Cycle

In this system, the combustion of the propellants takes place in the main, annular-type combustor and the major portion of the combustion gases (i.e., the primary flow) expands along the aerospike nozzle and generates thrust. A small portion of the gases is tapped from the main combustor and used to drive the engine turbopumps. The turbine drive gas after expanding through the turbines, provides the secondary flow to the base region of the nozzle which increases the base pressure and thrust. This use of the turbine drive gas results in high nozzle performance and a very high overall engine efficiency.

THRUST CHAMBER COOLING

The thrust chamber is regeneratively cooled with hydrogen fuel flowing through the contoured thrust chamber walls. Liquid hydrogen is introduced into the regenerative cooling circuit from the fuel turbopump through an annular manifold at the nozzle exit plane. After completing the cooling circuit, the hydrogen is delivered to the injector to be subsequently combusted with liquid oxygen in the toroidal combustor.

The use of regenerative cooling permits a maximum in thrust chamber performance to be achieved. Supplementary film or transpiration cooling - which degrades the overall system performance through (1) noncombustion or nonmixing of the film coolant with the main stream gases, and (2) by resulting in a higher mixture ratio and lower performance for the main stream propellants because of the bleed-off of the hydrogen coolant - is not required.

ENGINE CONFIGURATION

The combination of the annular combustor and the aerospike nozzle provides an inherently short-length, compact engine. The turbopumps, duct, controls, and thrust structure are packaged compactly and accessibly within the central cavity of the thrust chamber, enclosed by the nozzle. The two propellant turbopumps are separate units mounted 180 degrees apart with axes parallel to the engine axis. The aerospike nozzle is 25 percent the length (or less) of an equivalent 15-degree half-angle conical nozzle. The nozzle, the packaging arrangement, plus the short thrust structure, make it possible to provide a high-performance engine that is at least 75 percent shorter than an equivalent engine with a conventional bell nozzle.

Engine thrust loads are transmitted through an efficient combination cone and radial-beam thrust structure to a single, spherical-bearing gimbal block located on the engine axis. The radial beams also provide the primary mounting structure for the turbopumps and the gimbal actuators.

The engine gimbal, which provides thrust vector control (TVC), is located in the longitudinal plane of maximum engine diameter; thus, a gimbal deflection can be accomplished without increasing the engine envelope. This permits the engine to fill the available envelope completely, thereby allowing a higher area ratio nozzle to be used in the design compared to an engine with a nozzle which must be designed to an envelope physically smaller than the available envelope to allow for gimbaling (Fig. 5).

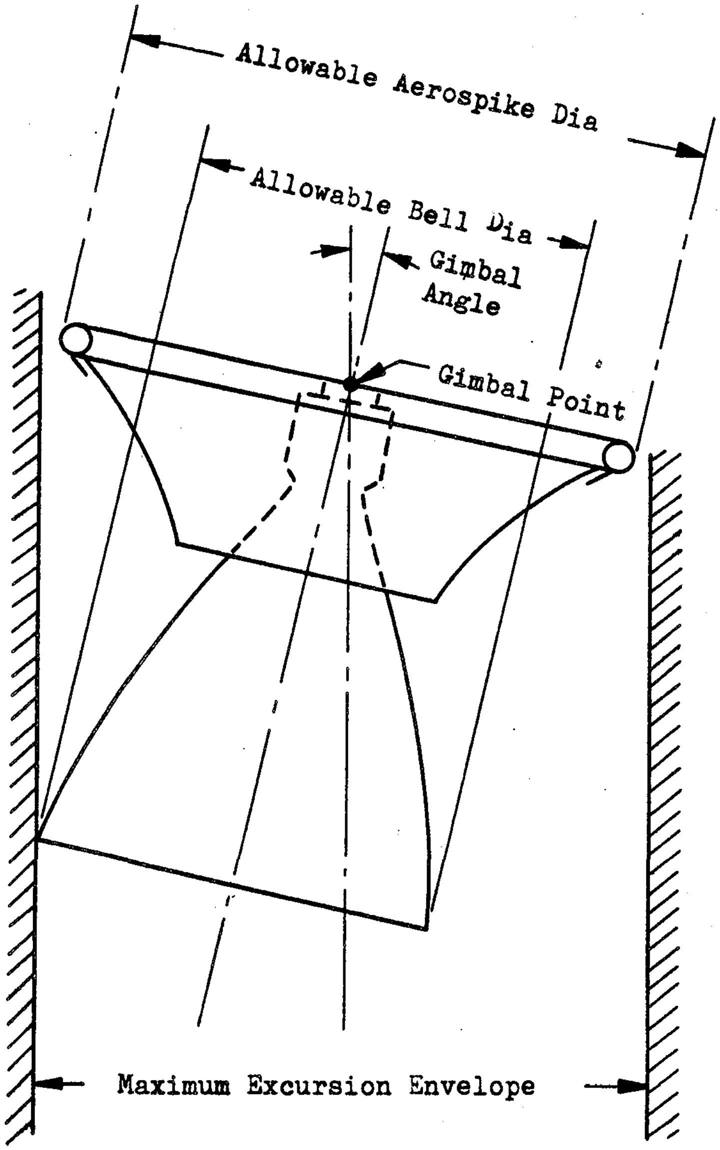

Figure 5. Envelope Limits for Bell and Aerospike Engines

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AEROSPIKE ENGINE PERFORMANCE AND OPERATION

MAIN STAGE PERFORMANCE

Parametric main stage vacuum specific impulse data for Aerospike engines operating at a mixture ratio of 6:1 as a function of engine dynamic diameter from 75 to 100 inches for thrust of 200- to 500-klbf is presented in Fig. 6 . (In reference to Fig. 5 , the dynamic diameter of the Aerospike engine is the envelope diameter required for engine gimbaling. With the gimbal in the plane of maximum physical diameter, the two dimensions are the same). The Aerospike engines are designed for chamber pressure operation at 1500 lbf/in^2 and employ liquid oxygen and liquid hydrogen as propellants. The engine is designed for nominal operation at a mixture ratio of 6:1 but is capable of operating over a range of mixture ratios from 5:1 to 7:1. Parametric main stage vacuum specific impulse and thrust data as a function of mixture ratio (5:1 - 7:1) is provided on Figs. 7, 8 and 9 for the subject thrust range. Vacuum specific impulse and thrust data from Figs. 7, 8 and 9 are cross plotted on Fig. 10 for engine diameter values of 75, 100, and 125 inches (mixture ratio = 6:1). Engine specific impulse data as a function of altitude is presented in Figs. 11, 12, and 13 for vacuum thrust levels of 250-, 350-, and 450-klbf, respectively.

The operating range (thrust versus mixture ratio) for an Aerospike engine designed to have a 5:1 throttling capability is presented in Fig. 14; (This operating range is based on design studies conducted for the AF ADP Aerospike engine). Based upon optimization studies of vehicle payload and engine performance, constant chamber pressure (1500 lbf/in^2) main stage operation over the 5:1 to 7:1 engine mixture ratio range was specified. This operation results in a slight gain in thrust, over 250-klbf for the 7:1 mixture-ratio operation, and a reduction in thrust for 5:1 mixture-ratio range. A constant thrust over this mixture ratio range can be accomplished, if desired, by small changes in chamber pressure; i.e.,

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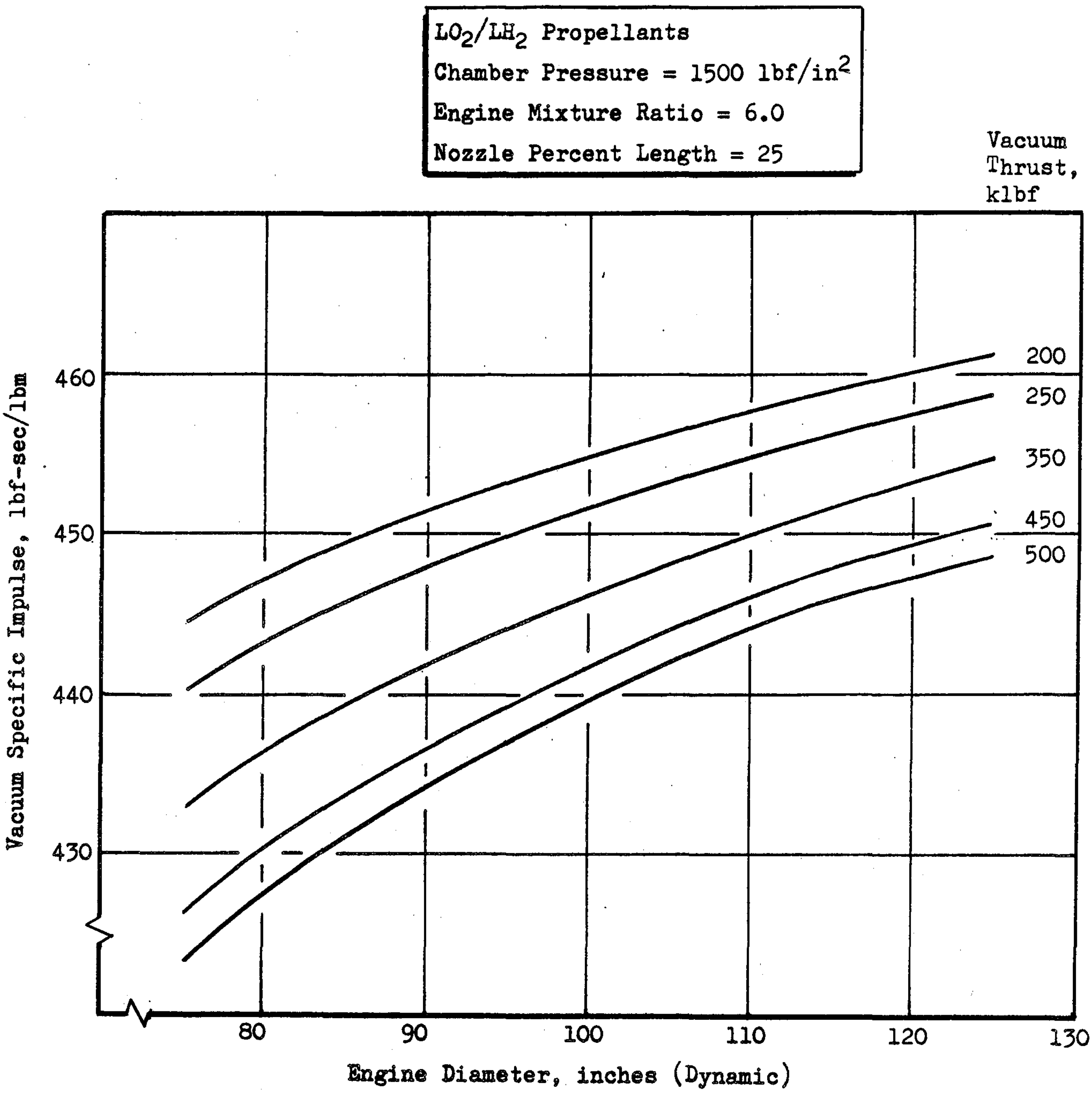

Figure 6 . **Aerospike Engine Vacuum Specific Impulse vs Engine Diameter.**

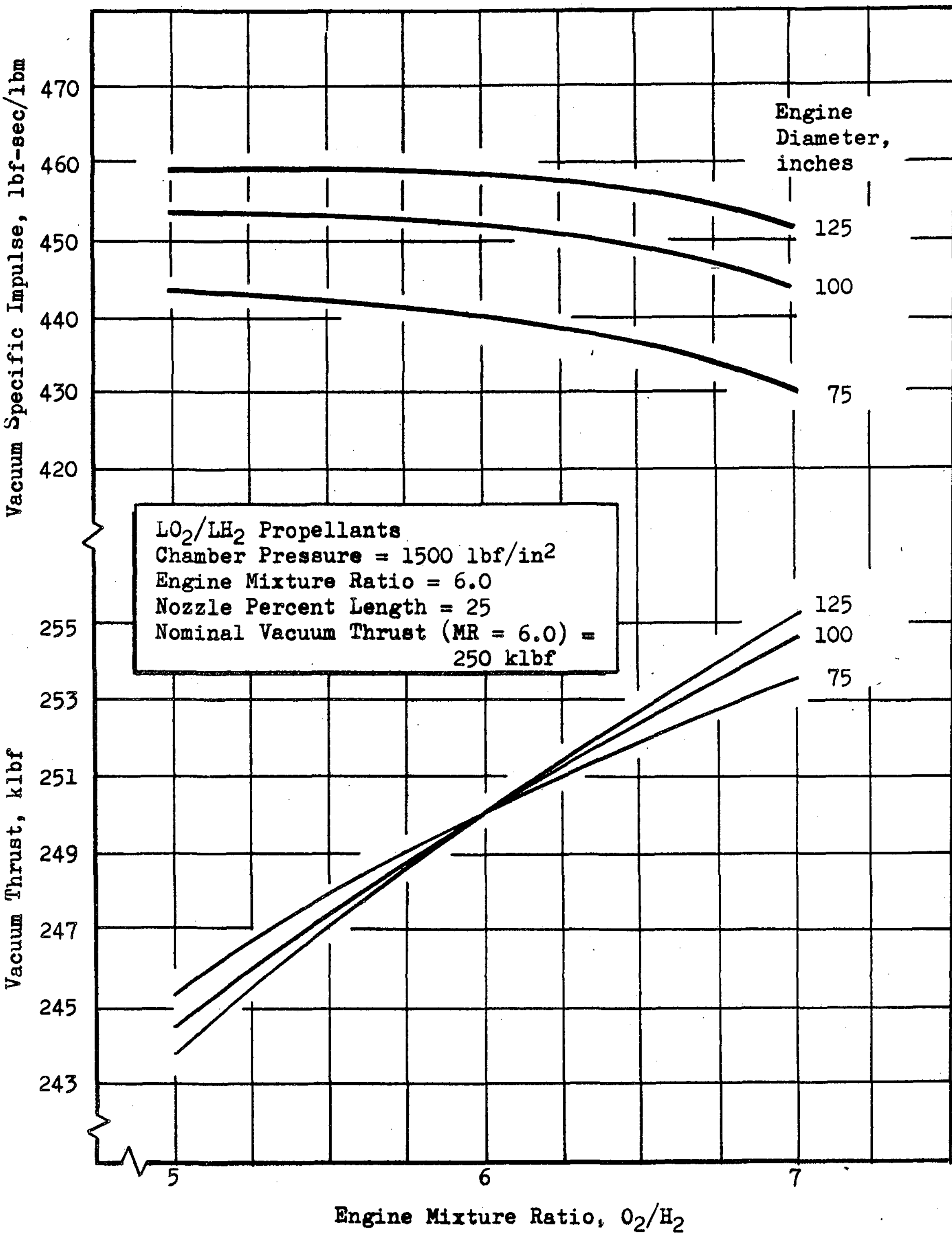

Figure 7. Aerospike Engine Vacuum Specific Impulse and Thrust vs Engine Mixture Ratio.

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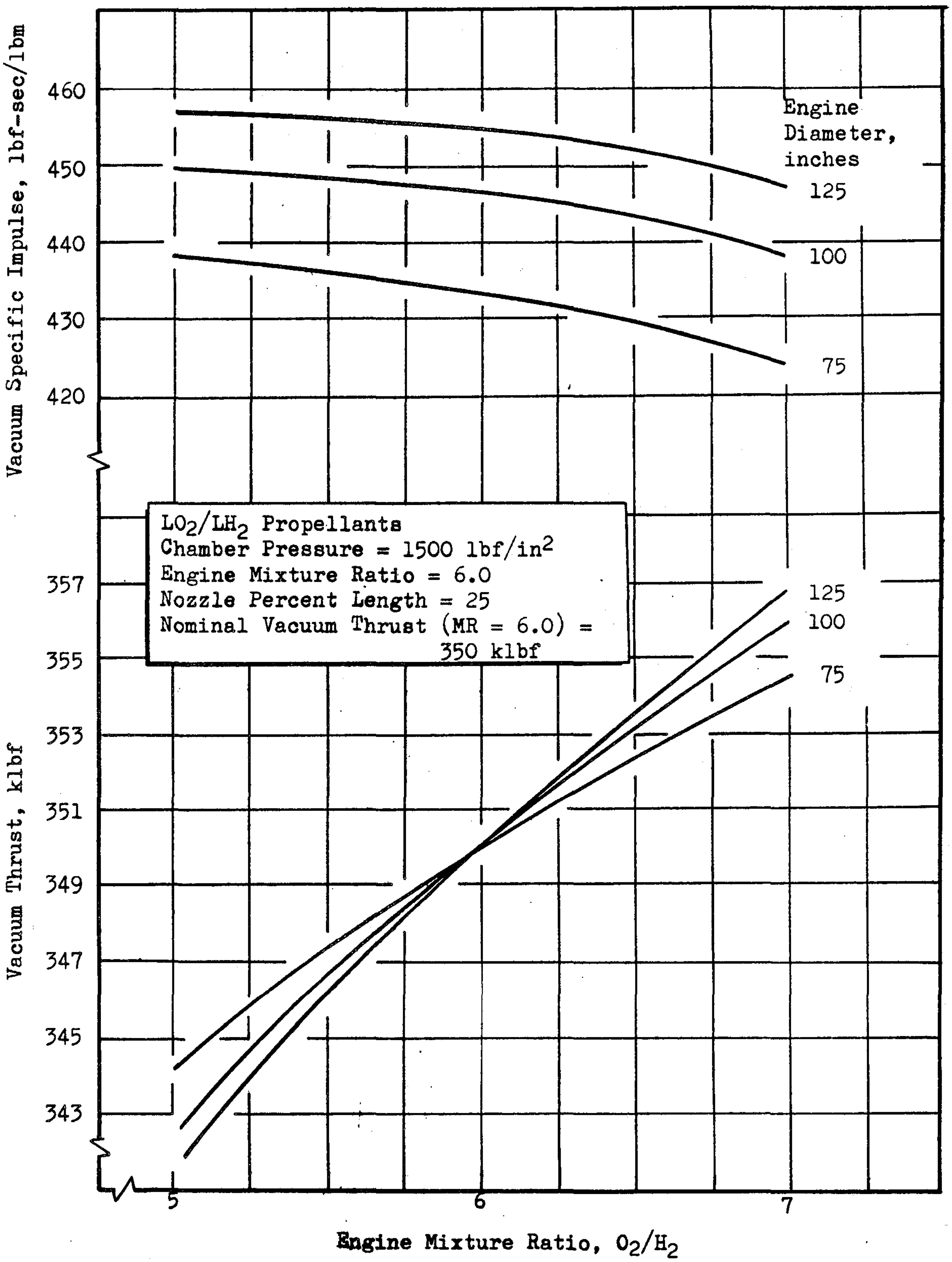

Figure 8. **Aerospike Engine Vacuum Specific Impulse and Thrust vs Engine Mixture Ratio.**

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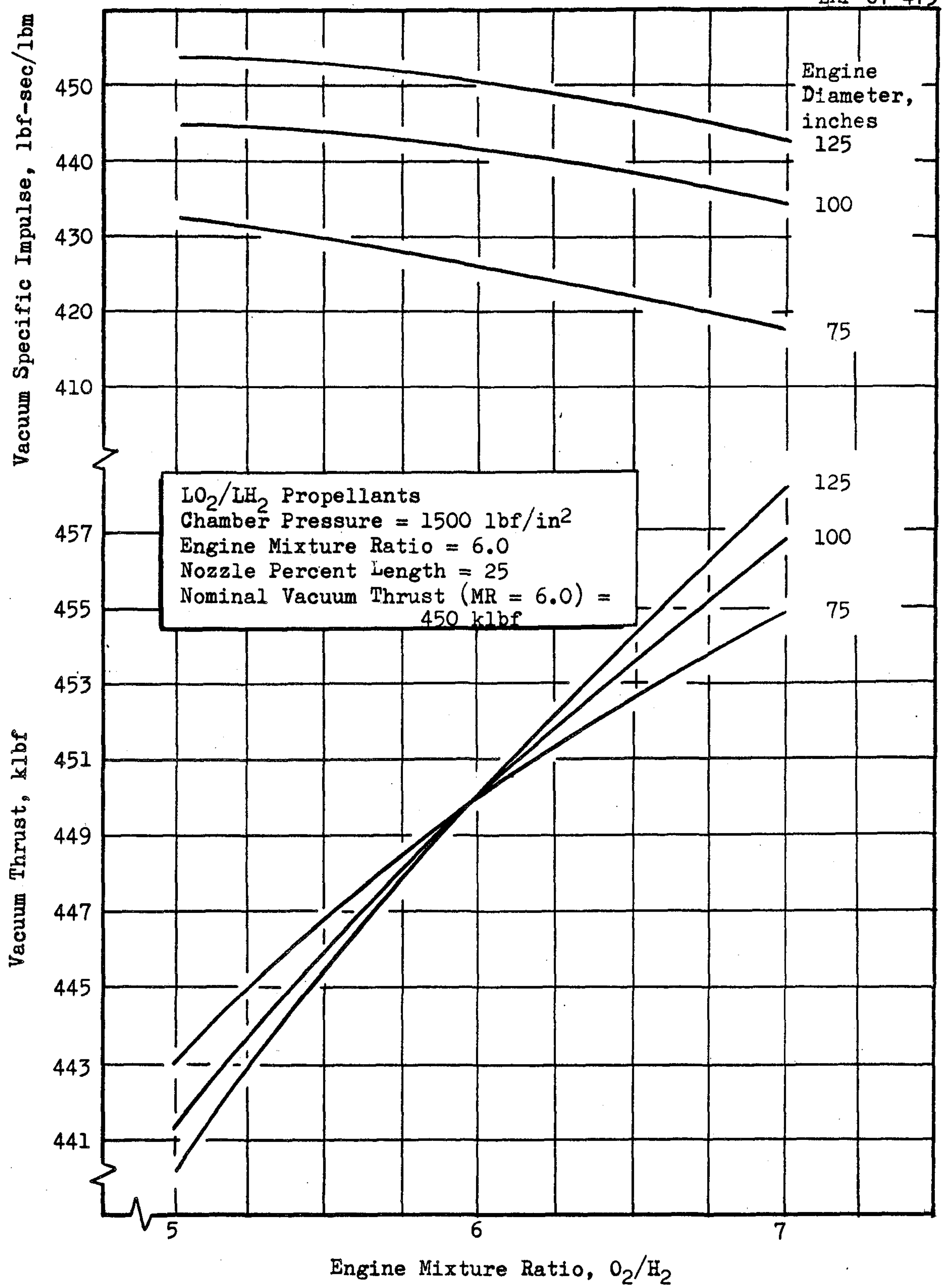

Figure 9 . Aerospike Engine Vacuum Specific Impulse and Thrust vs Engine Mixture Ratio.

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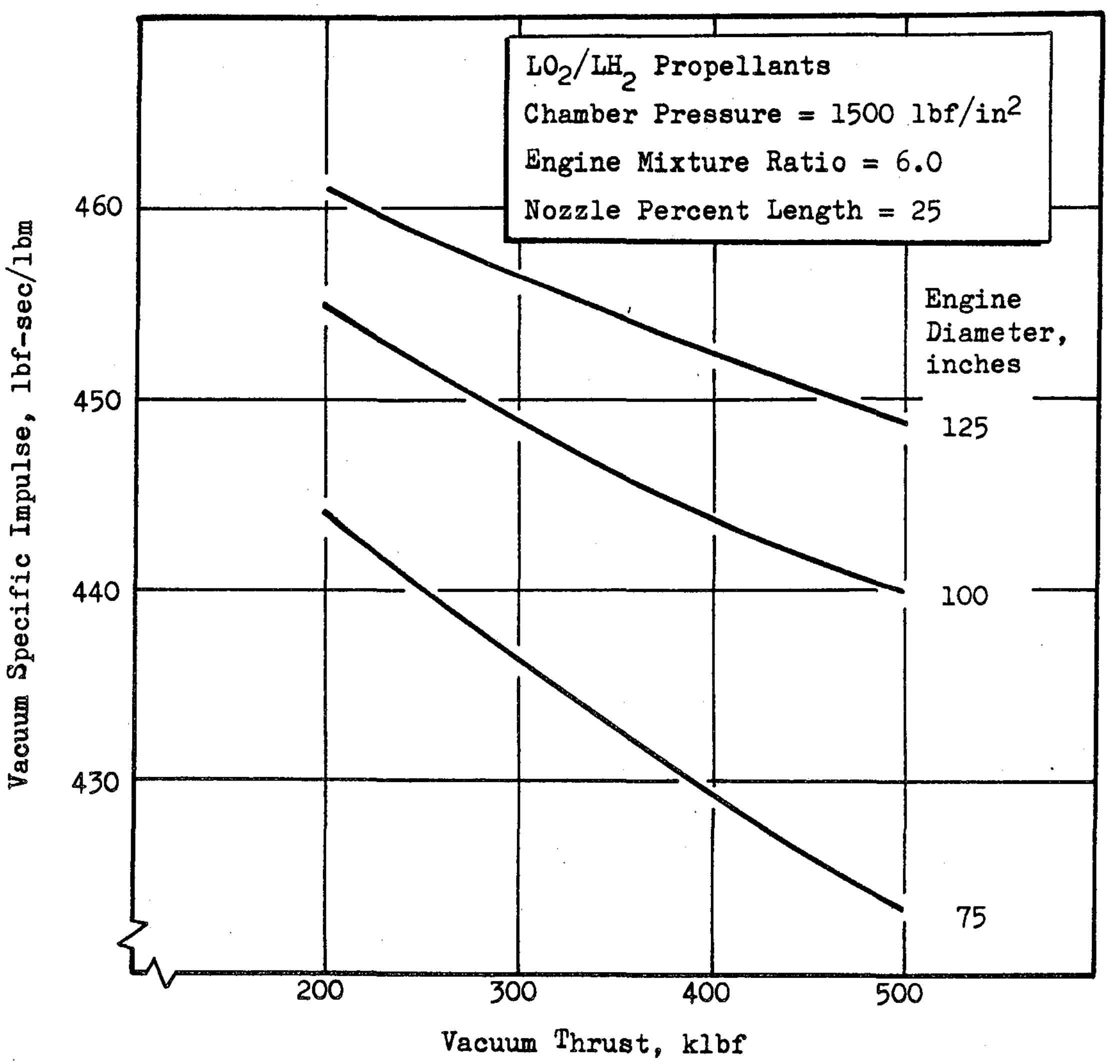

Figure 10. Aerospike Engine Vacuum Specific Impulse vs Vacuum Thrust.

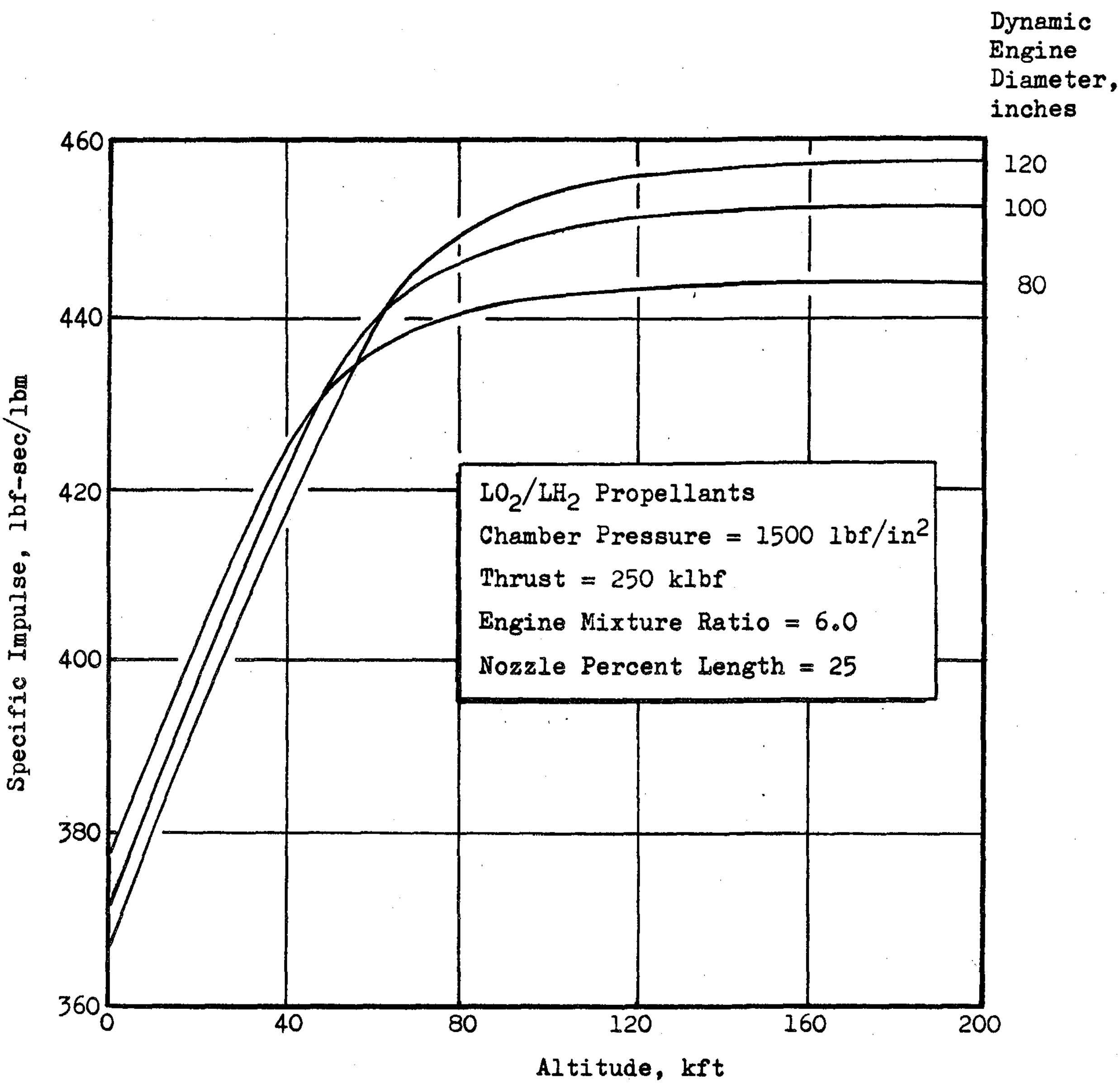

Figure 11. Toroidal Aerospike Engine Specific Impulse vs Altitude.

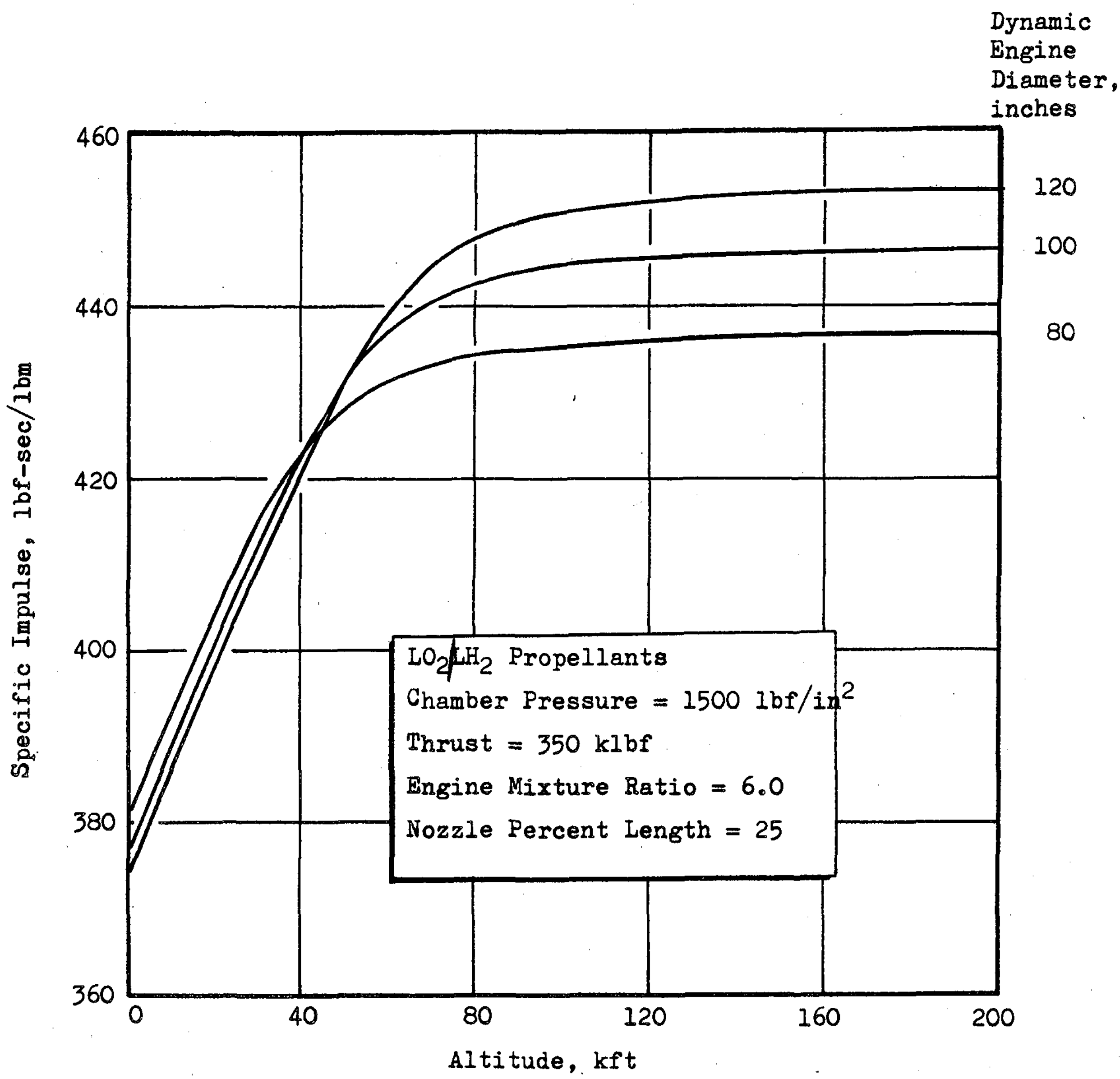

Figure 12. Aerospike Engine Specific Impulse vs Altitude.

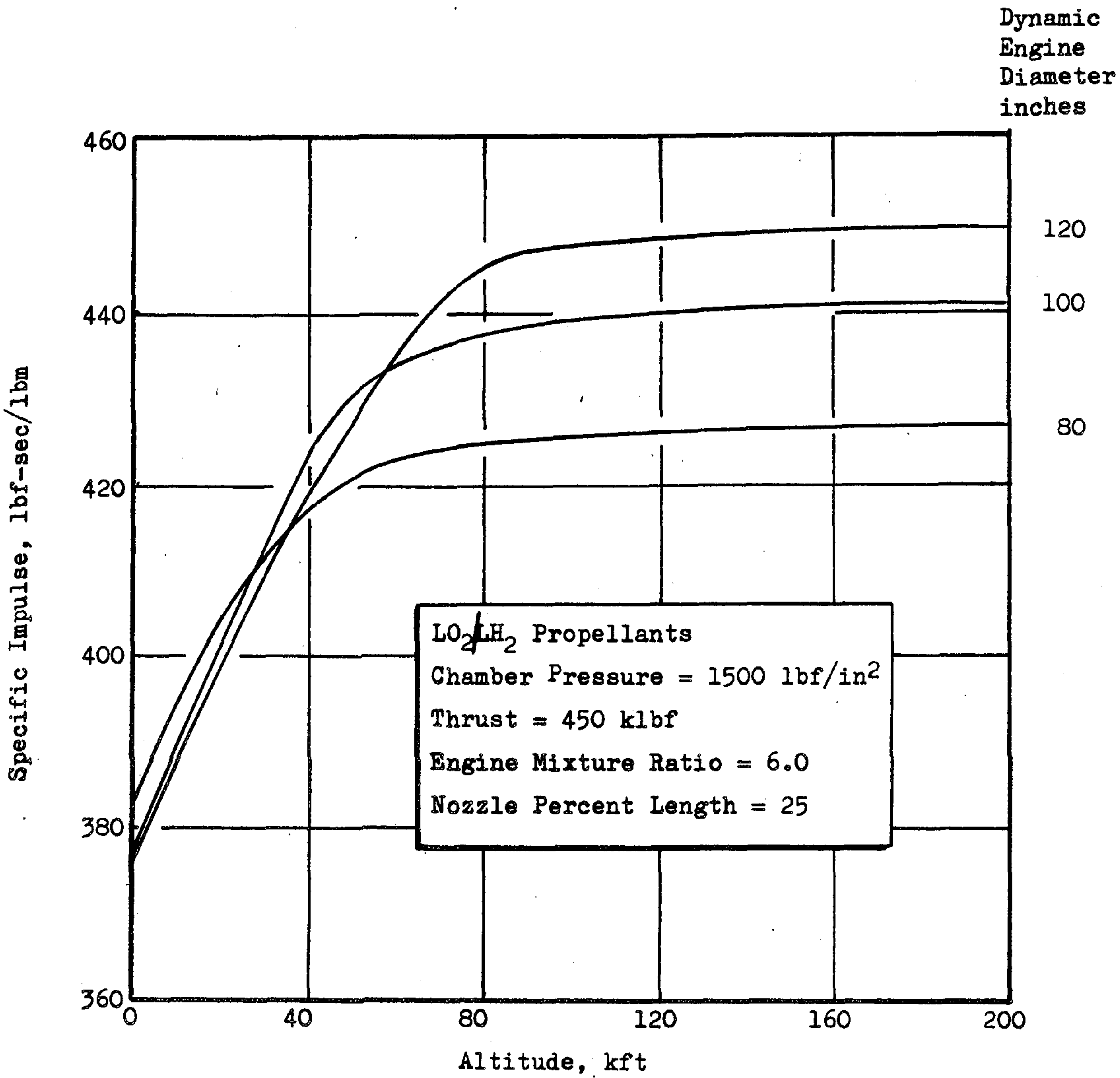

Figure 13. Aerospike Engine Specific Impulse vs Altitude.

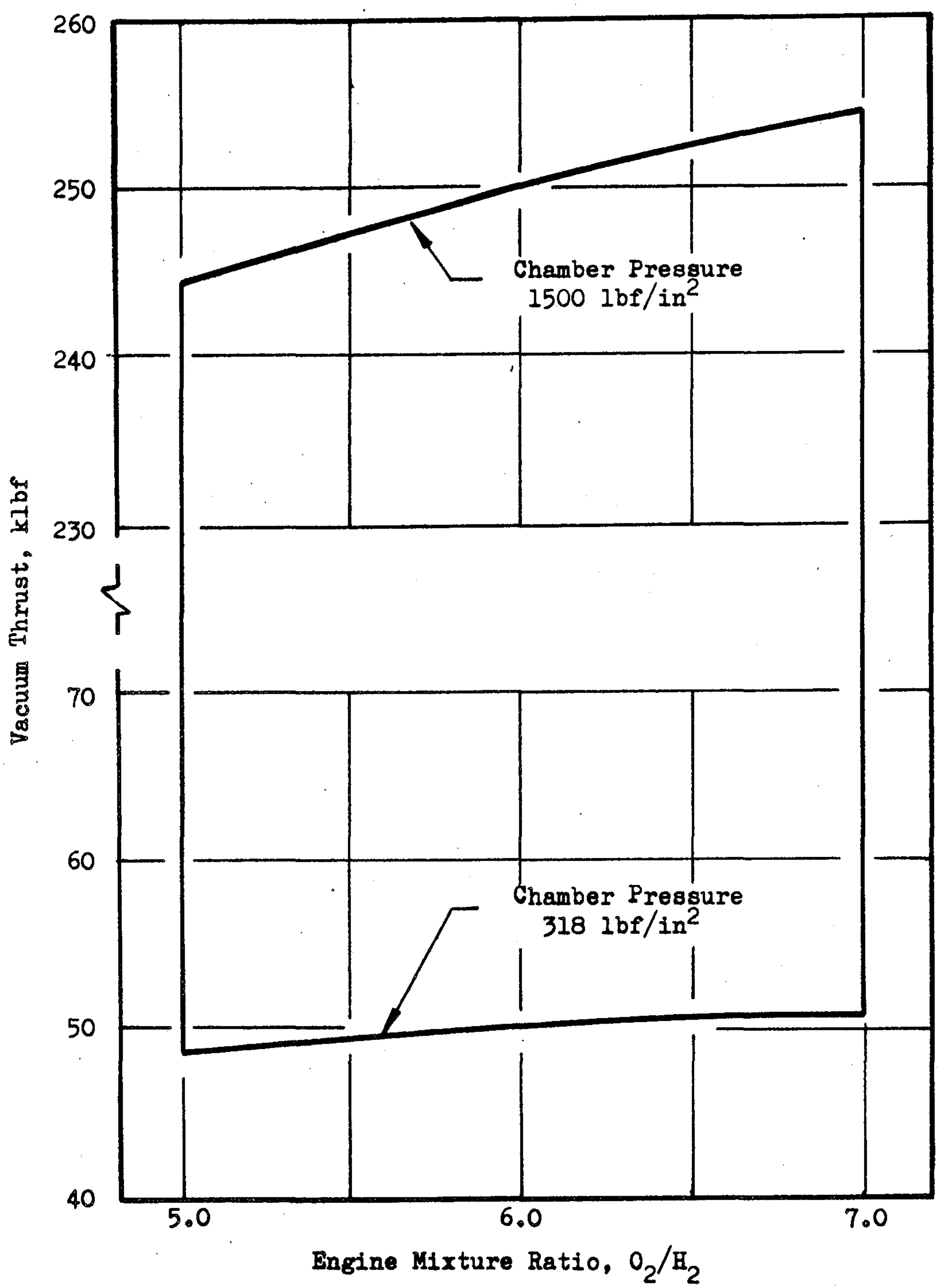

Figure 14. Aerospike Engine Operating Range for 5:1 Throttling Capability

slightly higher at the 5:1 mixture ratio and slightly lower at the 7:1 mixture ratio. The result of providing constant thrust over the mixture-ratio range rather than constant chamber pressure has virtually no effect upon specific impulse.

An Aerospike engine control system designed for and calibrated to maintain thrust and mixture-ratio accuracy to $\pm$ 3 percent at the rated thrust was investigated in detail in the AF ADP Aerospike engine studies and found to be completely feasible. This accuracy is typical for engines in the 250- to 500-klbf thrust class.

ENGINE INFLUENCE COEFFICIENTS (MAIN STAGE OPERATION)

Engine influence coefficients (gain factors), i.e., the influence upon engine performance resulting from a change in the propellant inlet conditions, are presented in Table 1 for a representative 250-klbf vacuum thrust Aerospike engine system. The engine control system is designed to maintain chamber pressure and mixture ratio at prescribed conditions. The specific impulse gain factors presented result from changes in the engine power balance with changes in the propellant inlet conditions. The thrust gain factor is the result of changes in engine balance resulting in change in primary and secondary flows, which change the overall engine thrust, and the effect of propellant enthalpy changes. These gain factors are typical for Aerospike engines in the subject thrust range using a chamber pressure/mixture-ratio control system.

ENGINE OPERATION AND TRANSIENT PERFORMANCE

The flow schematic for the basic Aerospike engine is illustrated in Fig. 15 . The tapoff lines, main propellant valves, control valves, turbopumps, thrust chamber and ignition systems are all indicated. The turbopumps are driven in parallel by the combustion chamber tapoff gases. Both the fuel and oxidizer pumps have centrifugal-flow impellers.

Based on this typical Aerospike engine schematic (Fig. 15), a discussion of the engine start and shutdown transient operation is presented in the following

TABLE 1

ENGINE INFLUENCE COEFFICIENTS

Independent Variables

1. LH_2 Temperature, Pump Inlet: 41.3 R
2. LO_2 Temperature, Pump Inlet: 175.6 R
3. Engine Inlet LH_2 Pressure: 35.0 lbf/in^2
4. Engine Inlet LO_2 Pressure: 40.0 lbf/in^2

A one-percent increase in any one of the independent variables (above) causes the following percent change in any one of the dependent variables (below).

		Independent Variable			
Dependent Variable	Nominal	1	2	3	4
Engine Thrust, klbf	250.0	0.0036	0.0022	-0.0002	-0.0001
Engine I_{sp}, lbf-sec/lbm	451.9	-0.0034	-0.0019	0.0002	0.0001
Engine LH_2 Flow, lbm/sec	78.9	0.0070	0.0041	-0.0004	-0.0001
Engine LO_2 Flow, lbm/sec	474.1	0.0070	0.0041	-0.0004	-0.0001

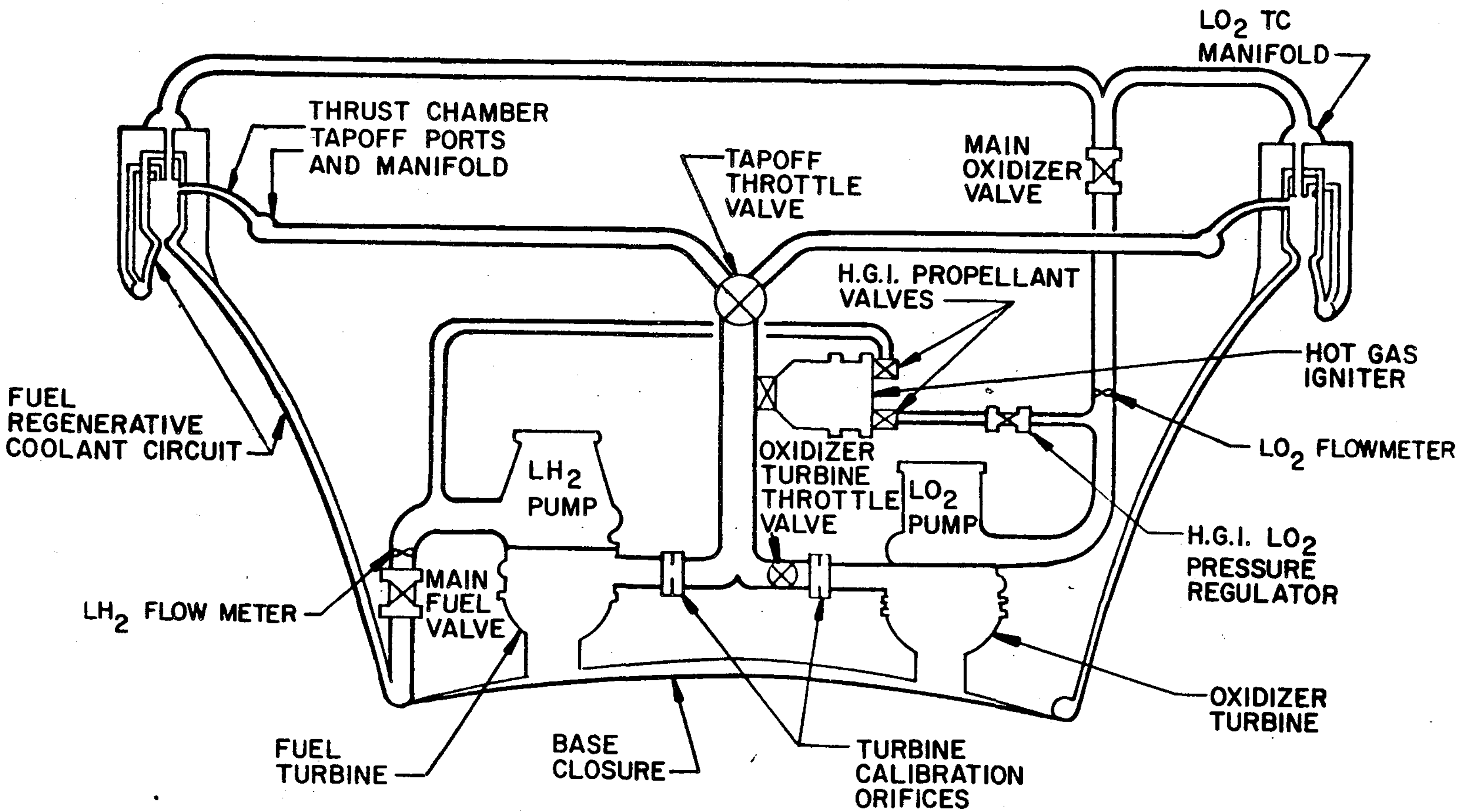

Fig. 15 Basic Aerospike Engine Schematic

paragraphs. Representative data on thrust and total impulse generated during transient operation are also provided.

Start

Prior to start, the main fuel and oxidizer valves are closed; the start is based upon liquid propellants available at the main valves (Fig. 16).

Ignition of propellants in the main thrust chamber is obtained from a hot-gas igniter (HGI), which is located within the engine module. The ignition system utilizes the hot-gas tapoff ducts and manifold to distribute and inject the ignition gases. During start, the hot-gas igniter functions to augment the available tank head pressure to drive the turbopumps; propellants for the igniter are supplied under tank head pressure. An isolation valve, integral with the igniter, prevents the turbine drive gases from backing up into the igniter during main stage operation. The start is initiated (Fig. 17) by opening the oxidizer and fuel HGI (hot-gas igniter) valves and the main fuel valve. Chilldown of the tube jacket is accomplished, ignition flow (from the HGI) is stabilized (Fig. 18), the main oxidizer valve then opens (in a two-step procedure) and main stage operation results (Fig. 19). The valve sequencing for engine start is summarized on Fig. 20 . The Aerospike engine is restartable without start system recharging or engine conditiong in flight. (For example, analytical results indicate that the thrust chamber tube jacket will cool, with normal start flow, in approximately 1.2 seconds. This is the time delay between HGI ignition and the main fuel valve opening).

Liquid propellants are required for start at the engine main valves. A vehicle propellant inlet duct and propellant conditioning system (i.e., an idle-stage phase to chill down the propellant inlet ducts and consume low-quality propellants) can be used, if required, for engine start following an extended space coast.

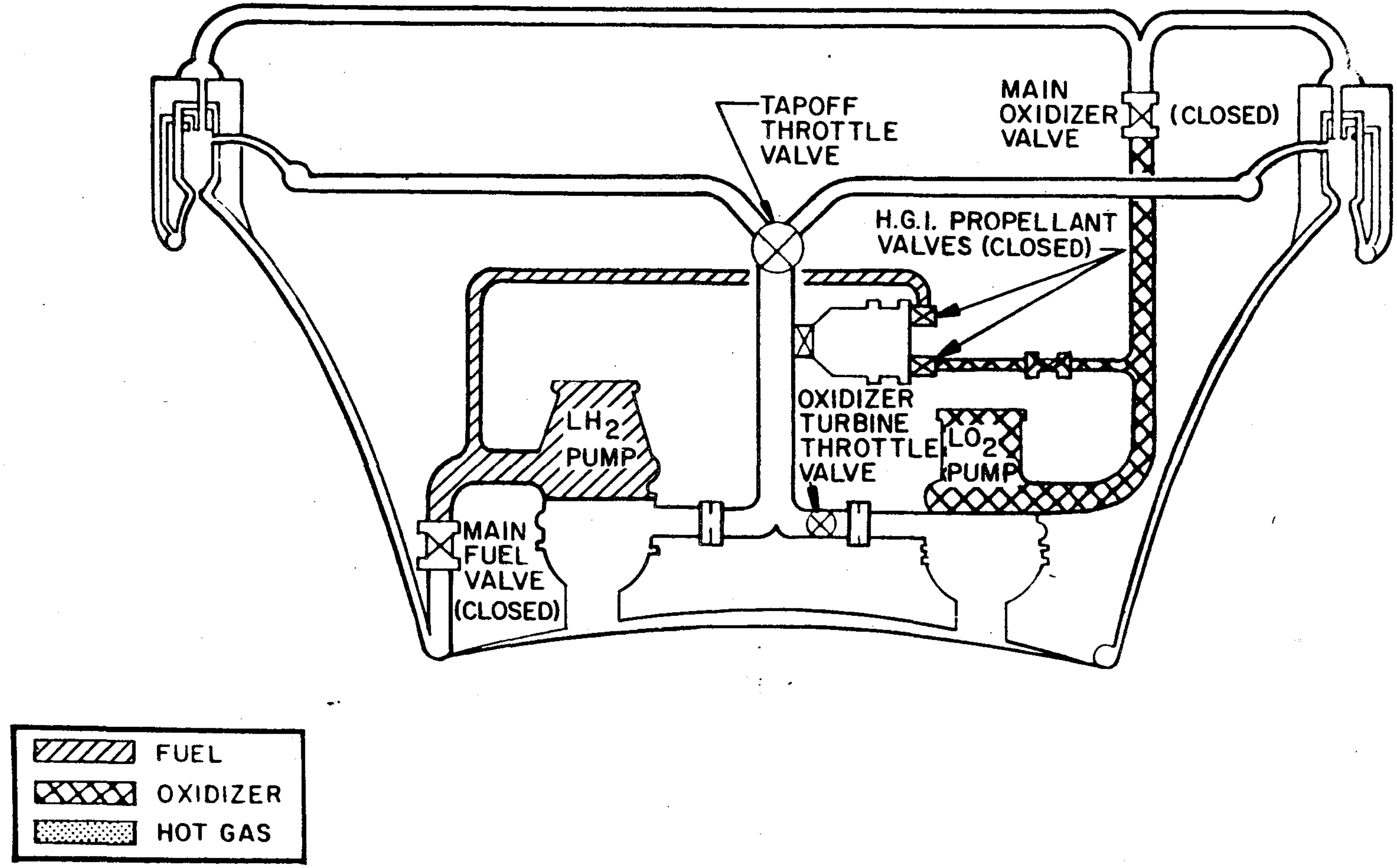

Fig. 16 Aerospike Engine Start Sequence Schematic - Time Zero

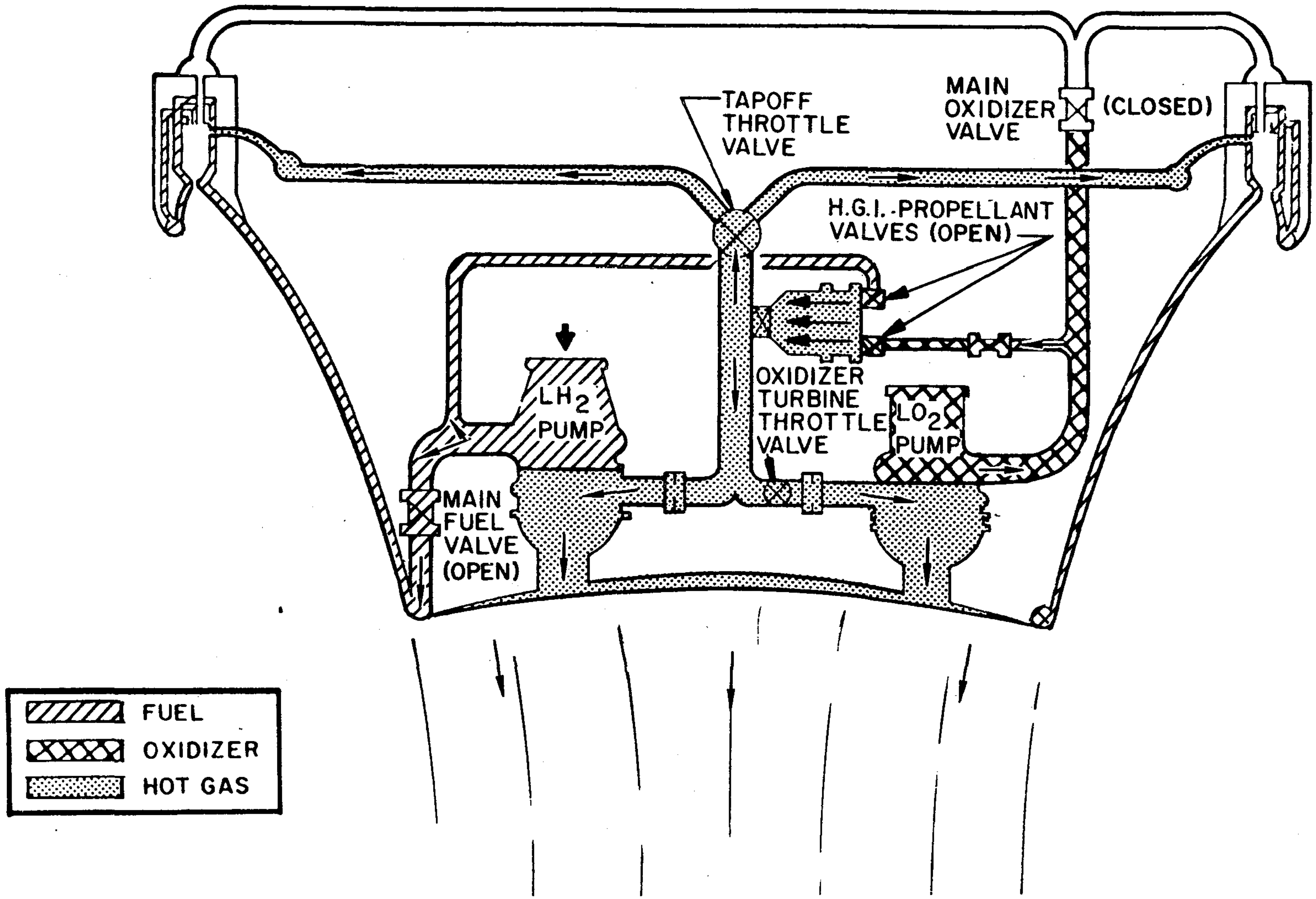

Fig. 17 Aerospike Engine Start Sequence Schematic - Start Initiated

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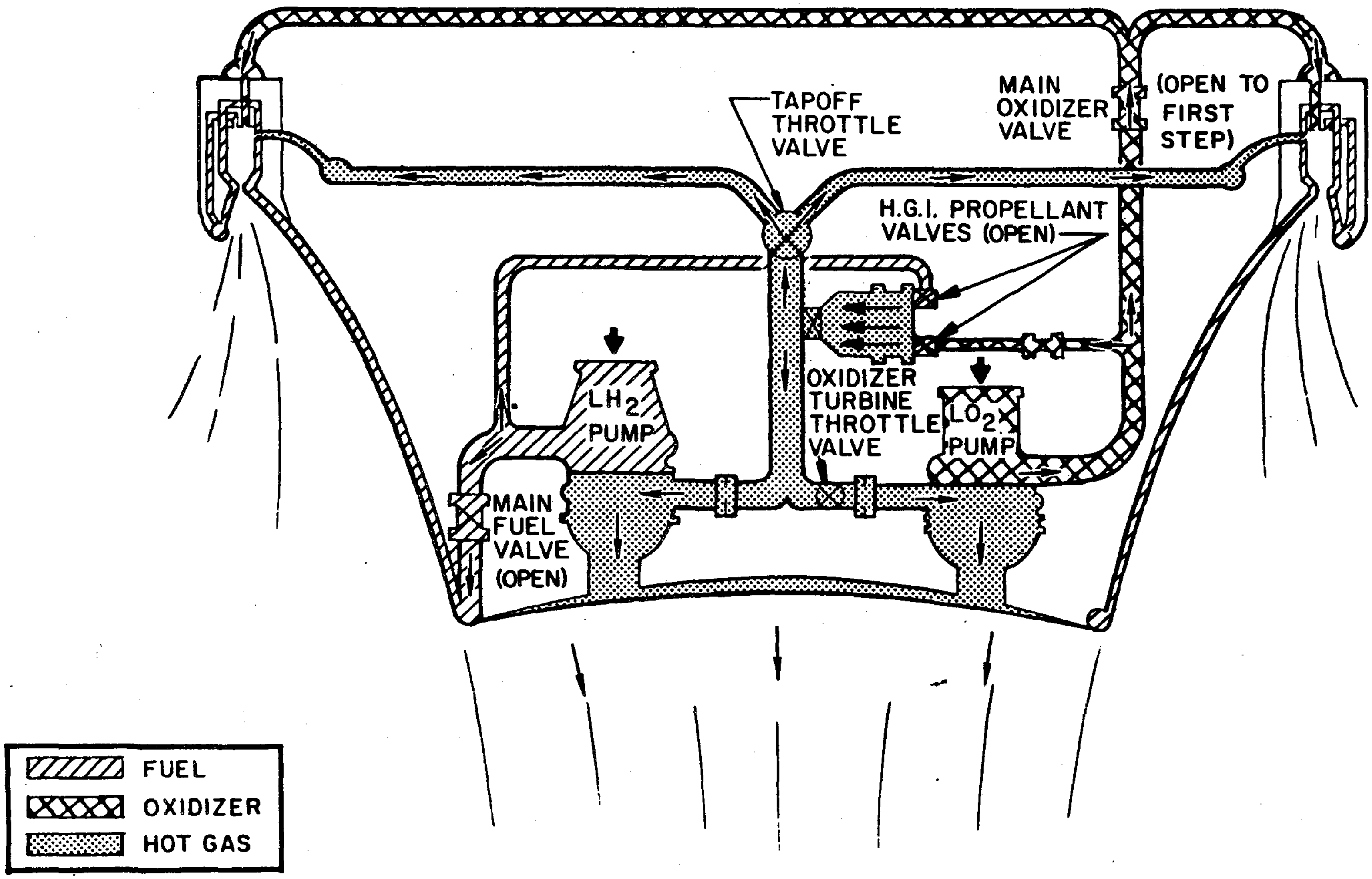

Fig. 18 Aerospike Engine Start Sequence Schematic - Ignition

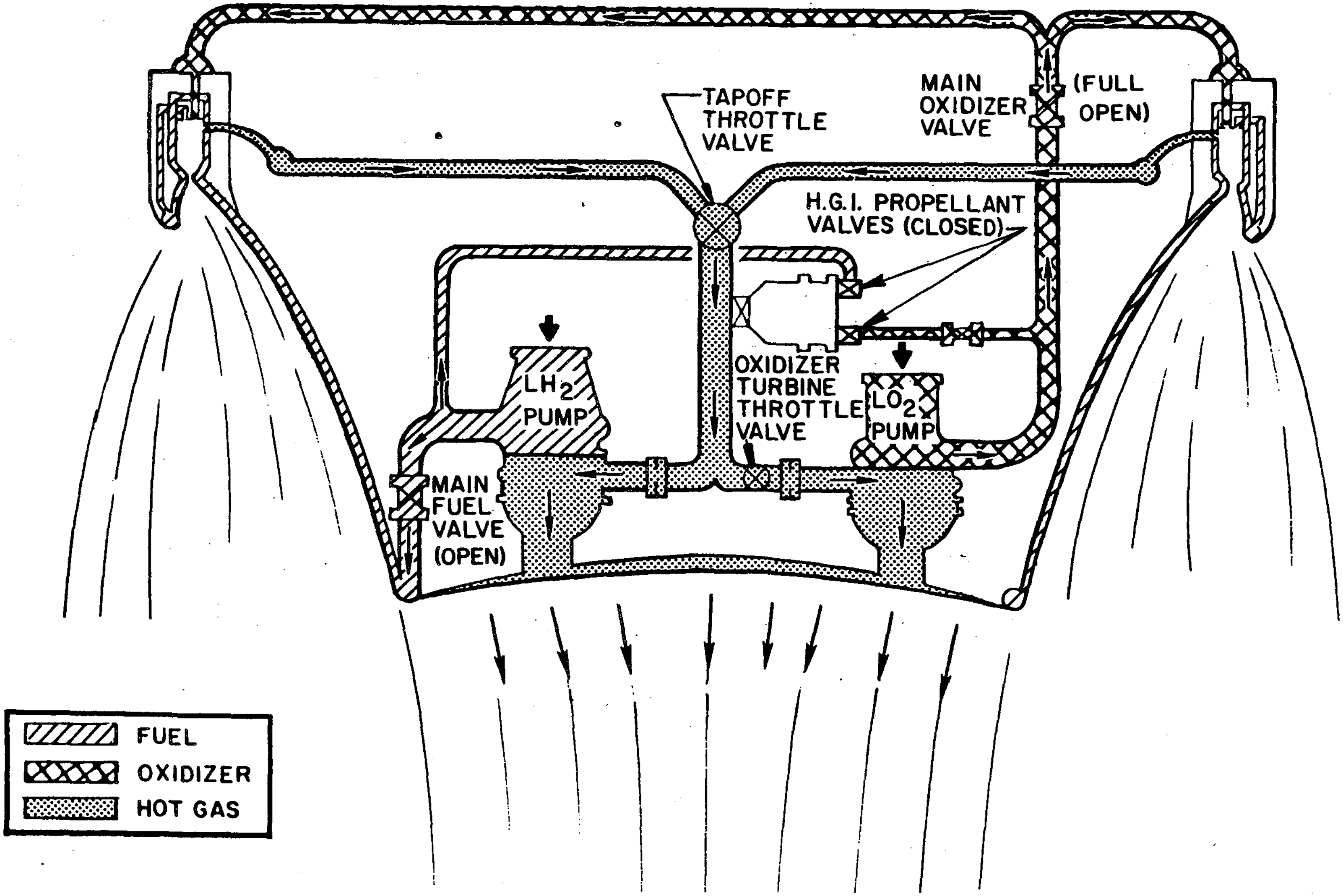

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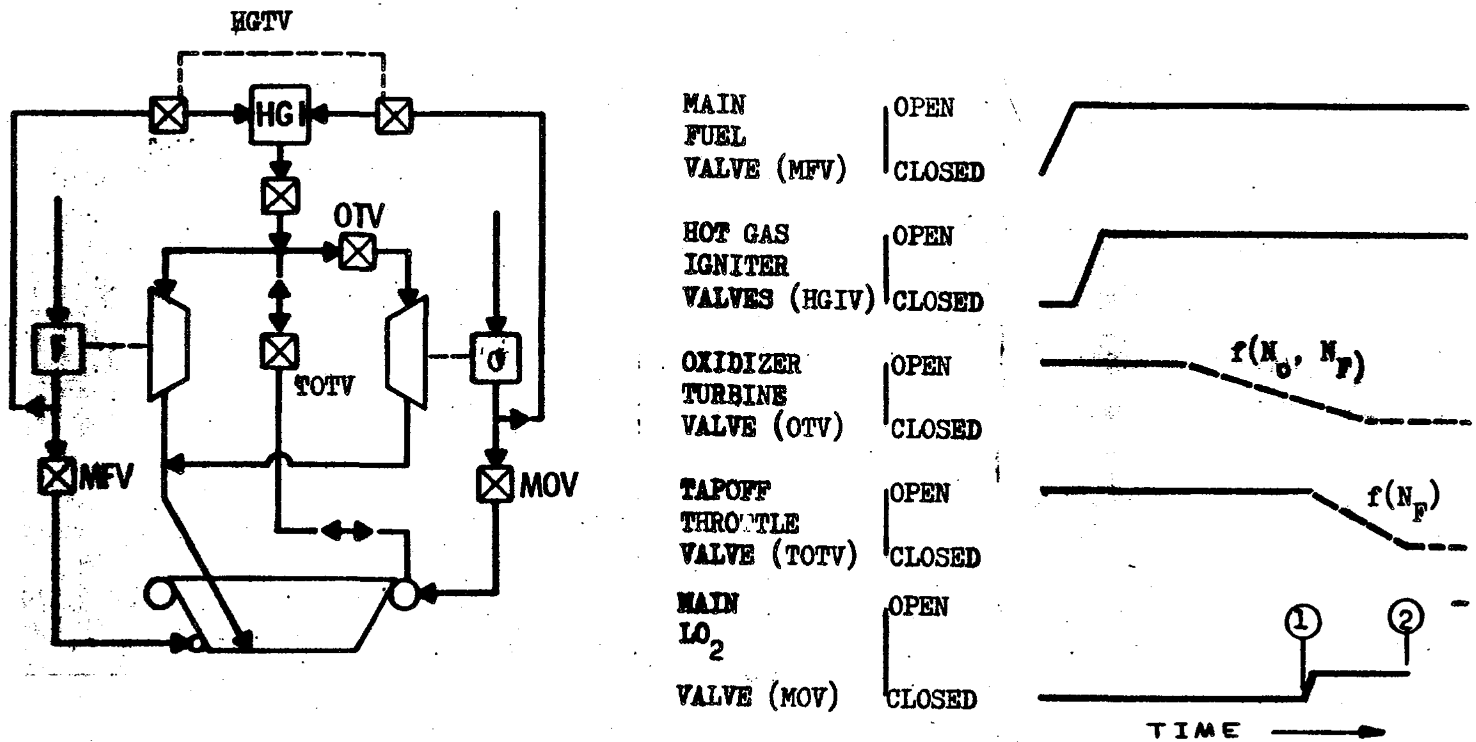
Fig. 19 Aerospike Engine Start Sequence Schematic - Main Stage



1 FUEL PUMP DISCHARGE, PRESSURE = 200 Lbf/in^2

2 LO_2 FEED SYSTEM PRIME
N_O = LO_2 PUMP SPEED
N_F = FUEL PUMP SPEED

Fig. 20 Aerospike Engine Valve Sequencing for Start

Engine start transient data, based upon a 250-klbf Aerospike engine dynamic investigation are provided on Fig .21. The thrust buildup trend, and the total impulse trends are shown, respectively. The approximate values of propellant consumed during start, total impulse, and total impulse tolerances (from zero to 97-percent thrust) are as follows:

Fuel Consumed	122 lbm	(to 4.5 seconds)
Oxidizer Consumed	663 lbm	(to 4.5 seconds)
Total Impulse (vacuum)	318 klbf-sec	(to 4.5 seconds)
Estimated Total Impulse Tolerance (Run-to-Run)	$\pm$19-klbf-sec	

(The fuel consumption indicated includes a hydrogen lead prior to HGI ignition which has an approximate 0.5- to 1.0-second duration at a flowrate of about 1.0 lbm/sec.).

The total impulse generated during engine start for Aerospike engines is approximately proportional to thrust. Thus for higher thrust engines, start total impulse has been approximated and is shown in Fig. 22. Total engine start time will be approximately the same for all engines in the thrust range of 250- to 500-klbf. If changes in engine start time should occur as a result of vehicle requirements, the engine-start total impulse will be affected. For changes in start time between 10 and 90 percent main stage thrust, the change in total impulse generally would be directly proportional to the change in this time. Between 0 and 10 percent, the effect would be almost negligible. Between 90 and 100 percent, the effect would be an increment of impulse equal to the product of main stage thrust and additional increment of time.

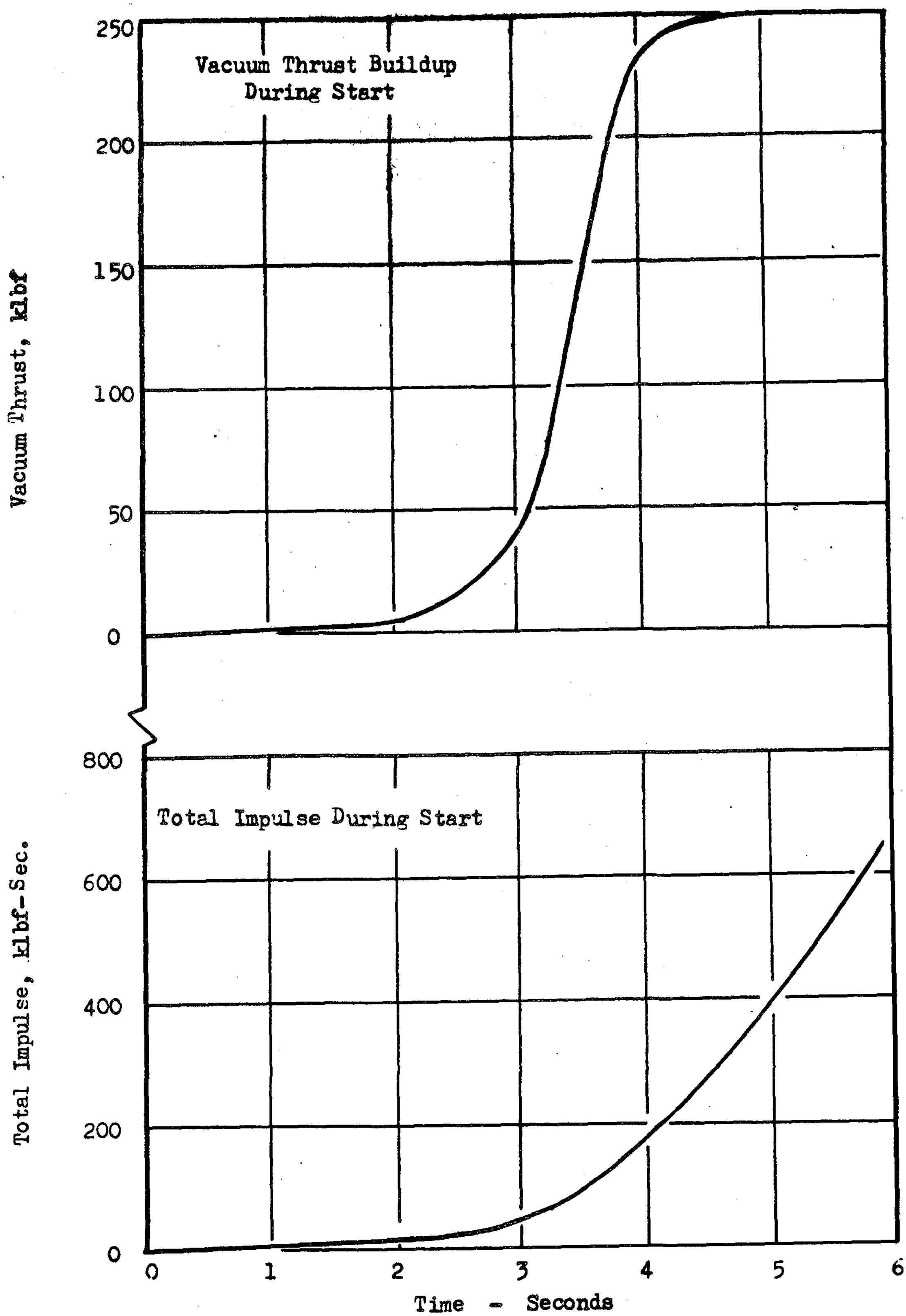


Figure 21. Aerospike Engine Start Characteristics.

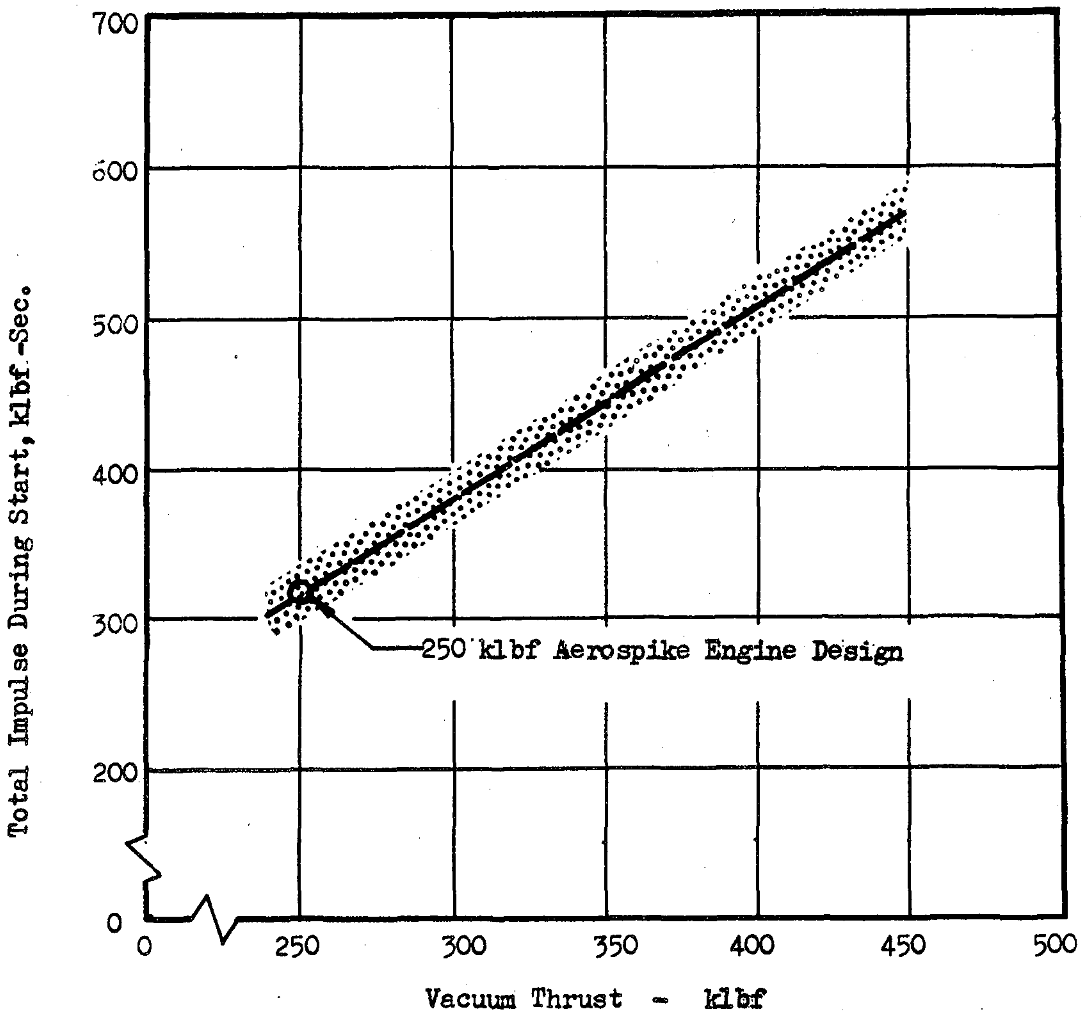


Figure 22. Aerospike Engine Total Impulse During Start (Effect of Thrust)

[redacted]

Shutdown

Engine shutdown is accomplished by closing, in sequence, the main oxidizer and main fuel valves and the oxidizer turbine valves. Operation to oxidizer depletion is an anticipated capability.

Preliminary estimates of engine shutdown transient data presented in Fig. 23 for thrust decay and total impulse values during the shutdown transient (from 100 - 3 percent thrust) for the 250-klbf Aerospike engine are based on the following:

Fuel Consumed	130 lbm	(to 3.0 seconds)
Oxidizer Consumed	100 lbm	(to 3.0 seconds)
Total Impulse Vacuum	83 klbf-sec	(to 3.0 seconds)
Estimated Total Impulse Tolerance (run-to-run)	± 8 klbf-sec	(to 3.0 seconds)

The total impulse generated during engine shutdown is approximately proportional to thrust (providing the main oxidizer valve closing time remains unchanged); estimates for higher thrust Aerospike engines are shown in Fig. 24. If a change in engine shutdown time is required, the engine shutdown impulse will change proportionally to this change in shutdown time.

Throttling Operation and Performance

Throttling, i.e., thrust control, is provided in the Aerospike engine designs Thrust control can be by either (1) a hot-gas throttle valve and an oxidizer turbine throttle valve, (2) throttleable main oxidizer and fuel valves, or (3) a combination of both. The control points for these systems are illustrated schematically in Fig. 25.

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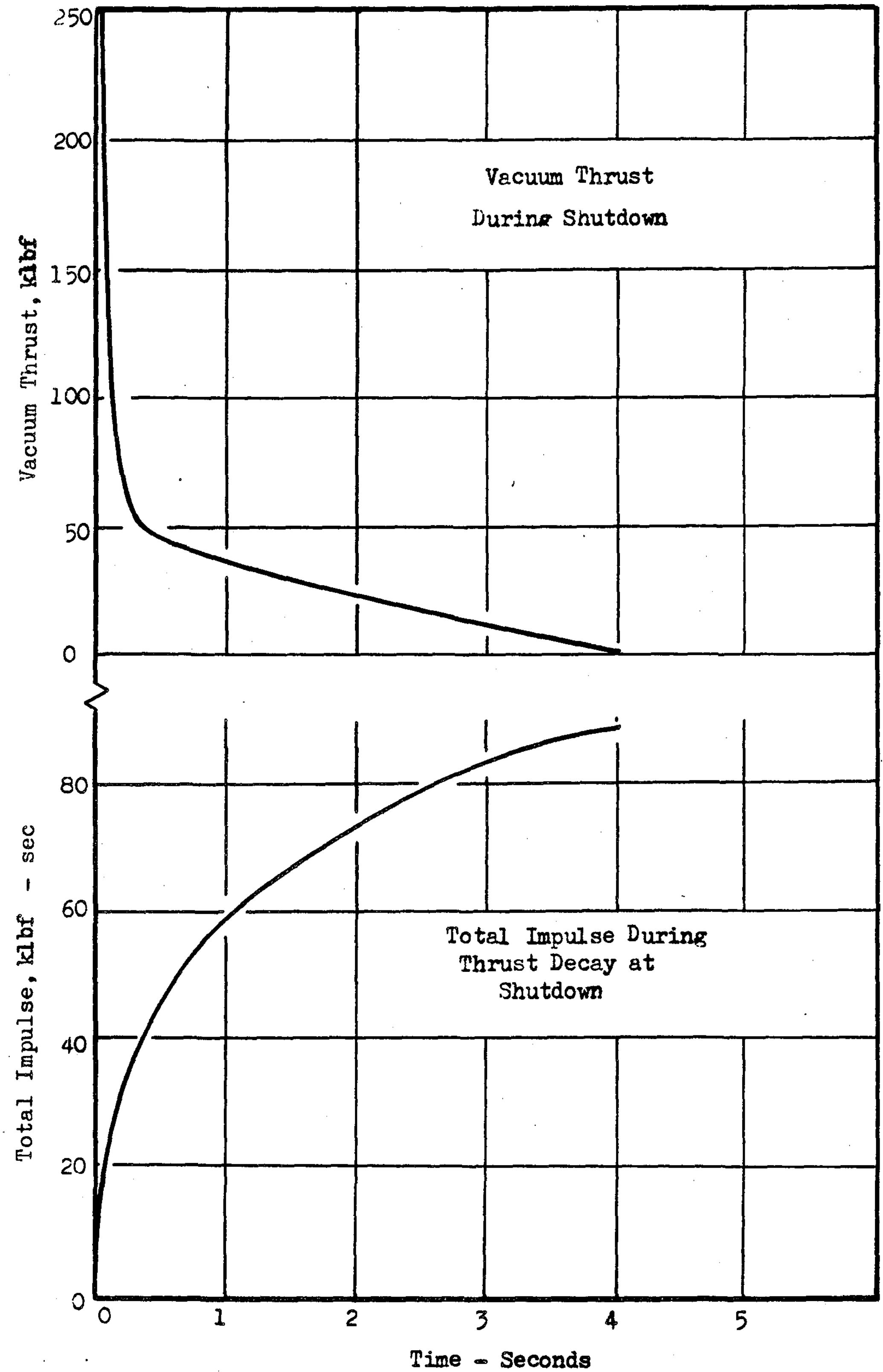

Figure 23. Aerospike Engine Shutdown Characteristics

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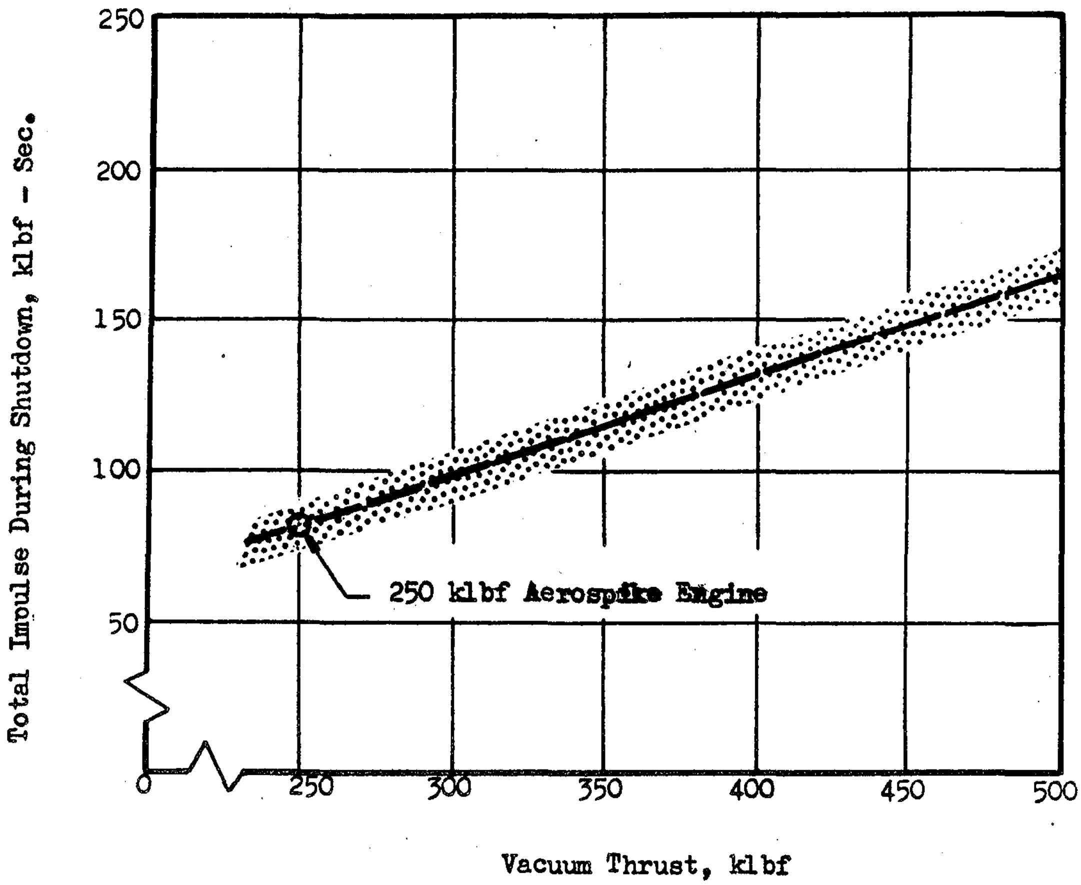


Figure 24. Aerospike Engine Total Impulse During Thrust Decay (Effect of Thrust)

[redacted]

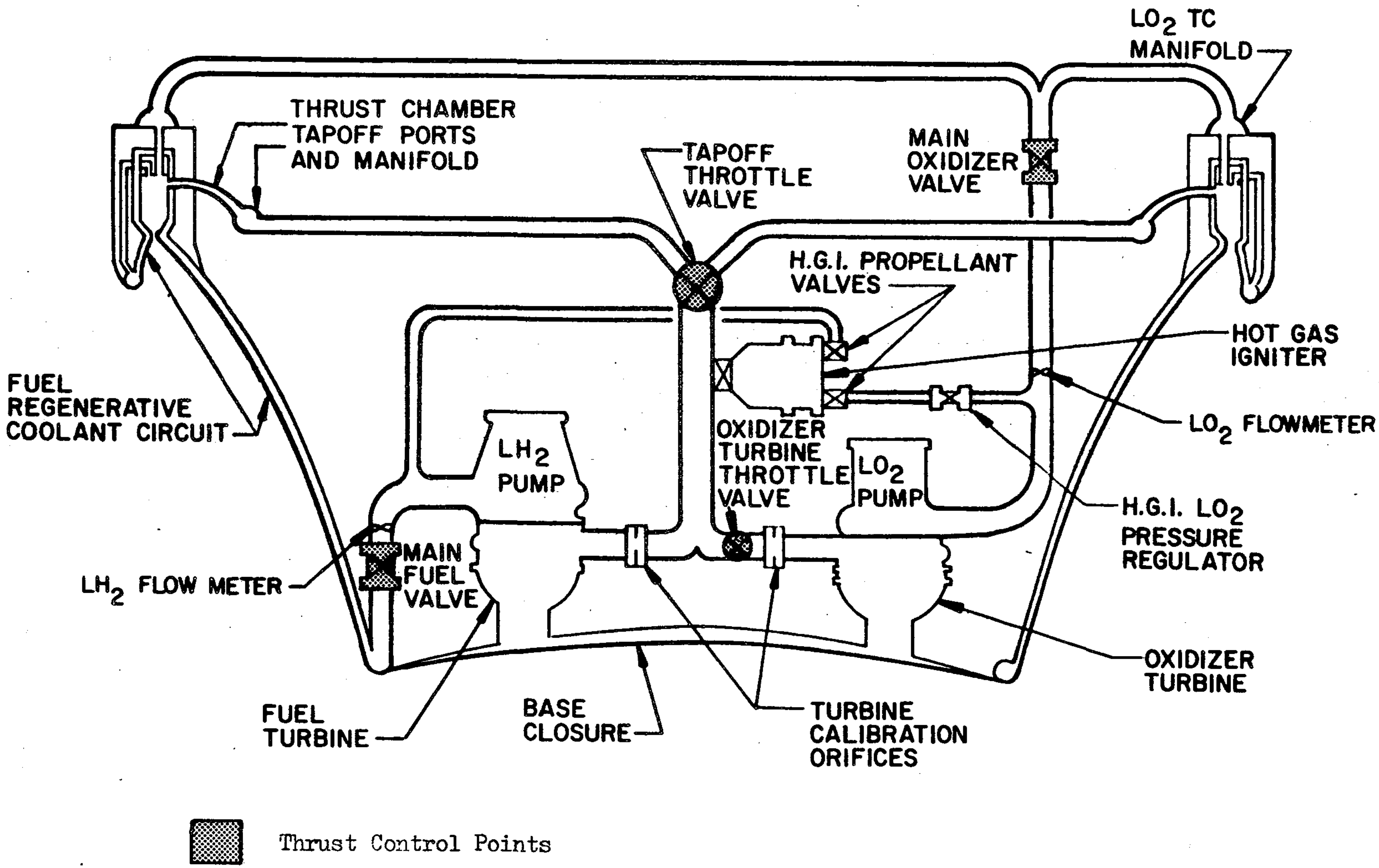


Fig. 25 Aerospike Engine Schematic - Thrust Control Point Summary

[redacted]

The response rate is influenced by the type of control system used, thus vehicle requirements are a prime factor in control system specification. The performance is influenced by the throttle control system during throttled operation. However, in any of the throttling control systems, pump power is inherently reduced during throttling; that is, because the chamber pressure is lower (i.e., throttled), the turbine power flow which is tapped from the main combustor is also reduced. Thus, the throttled engine flows are quite similar, and in general, independent from the throttle control system.

Engine throttled performance to 10-percent main stage thrust over an engine mixture ratio range of 5:1 to 7:1 is presented in Fig. 26 for a 250-klbf vacuum thrust Aerospike engine. This data is typical of Aerospike engines in the 250-to 500-klbf thrust range.

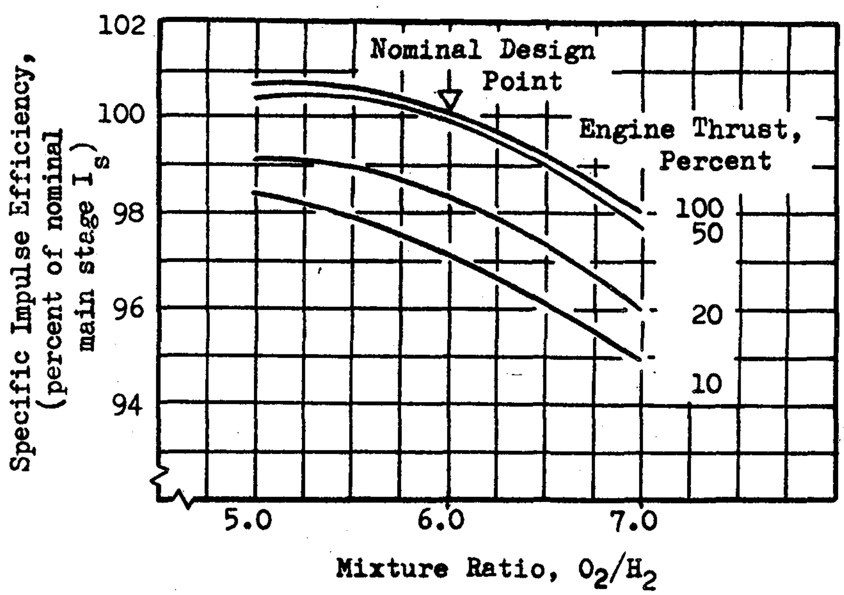


Figure 26. Aerospike Engine Specific Impulse Efficiency as a Function of Mixture Ratio Excursion Over a Throttling Range.

[redacted]

[redacted]

The 10:1 throttling capability can be provided in the Aerospike engines; tests have demonstrated high combustor performance and regenerative cooling throughout this throttling range. Complete capability of the engine controls for this throttling has been established from dynamic simulation of the engine.

Experimental engines at Rocketdyne using O_2/H_2 propellants - e.g., the X-8 and J-2X engines, - have demonstrated throttling capabilities significantly greater than 20:1 capability. Increased throttling capabilities (greater than 10:1) can be provided in the Aerospike engine with main combustor injector systems designed to provide high-combustion performance at the smaller, throttled propellant flowrates. Extremely deep throttling (greater than 33:1) can be obtained via idle stage operation.

Response. Dynamic analyses have been conducted for the various control systems. Use of liquid-line control (throttleable main oxygen and fuel valves) gives the fastest response. The potential response capability with this type of system for main stage thrust level is a 45-percent thrust change per second, i.e., from 100-percent thrust to 55-percent thrust in 1 second) for increasing or decreasing thrust.

Idle Stage. Detailed studies of this operating mode are in progress and this capability can be incorporated in any Aerospike flight-type engine. The schematic for an idle stage combustion mode of operation is illustrated in Fig. 27 ; the principal modifications to the basic schematic are the addition of a turbine bypass line and valve and a fuel turbine valve.

Essentially, idle stage operation can be employed for several basic vehicle-system operational objectives listed as follows:

[redacted]

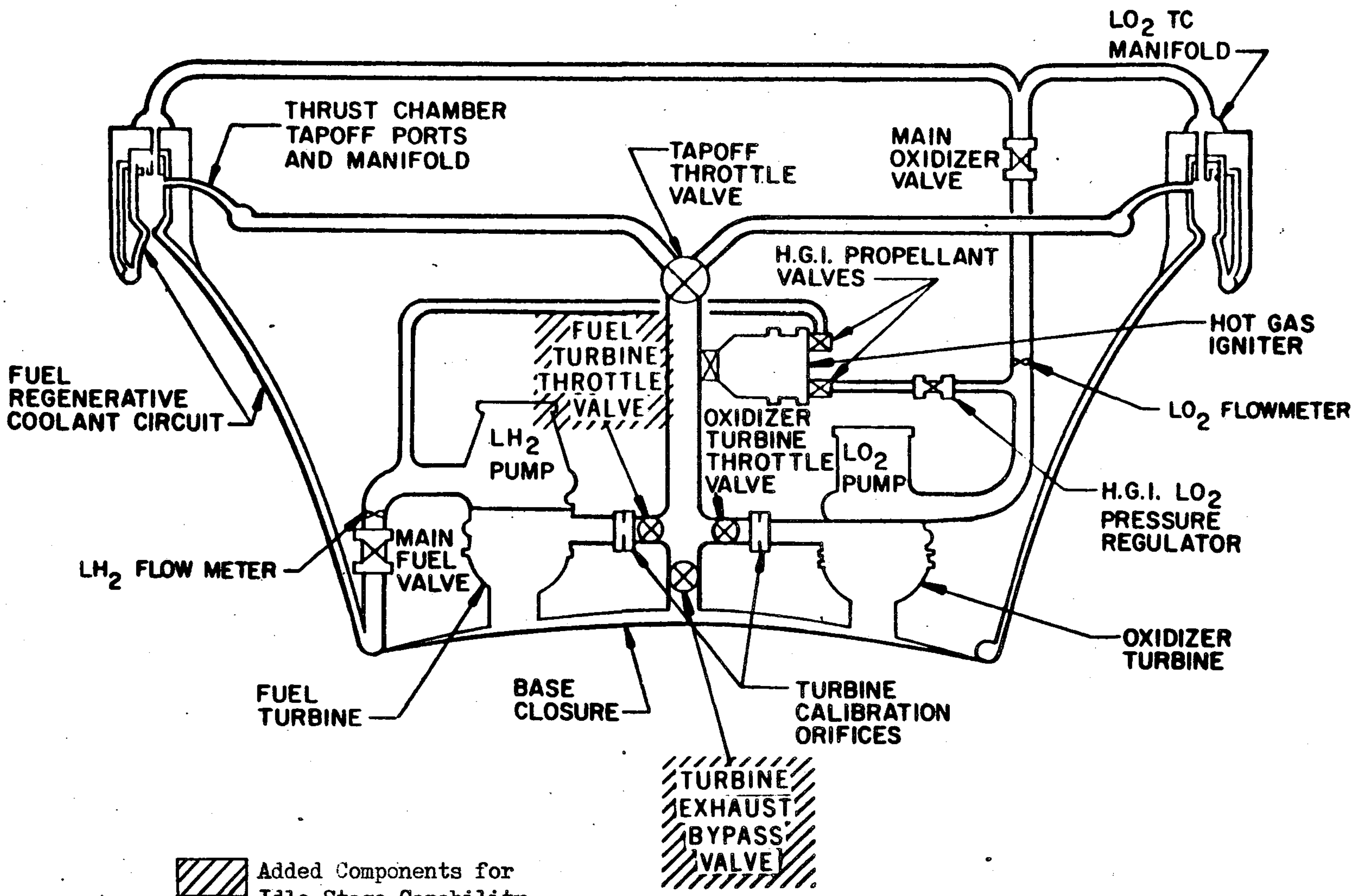


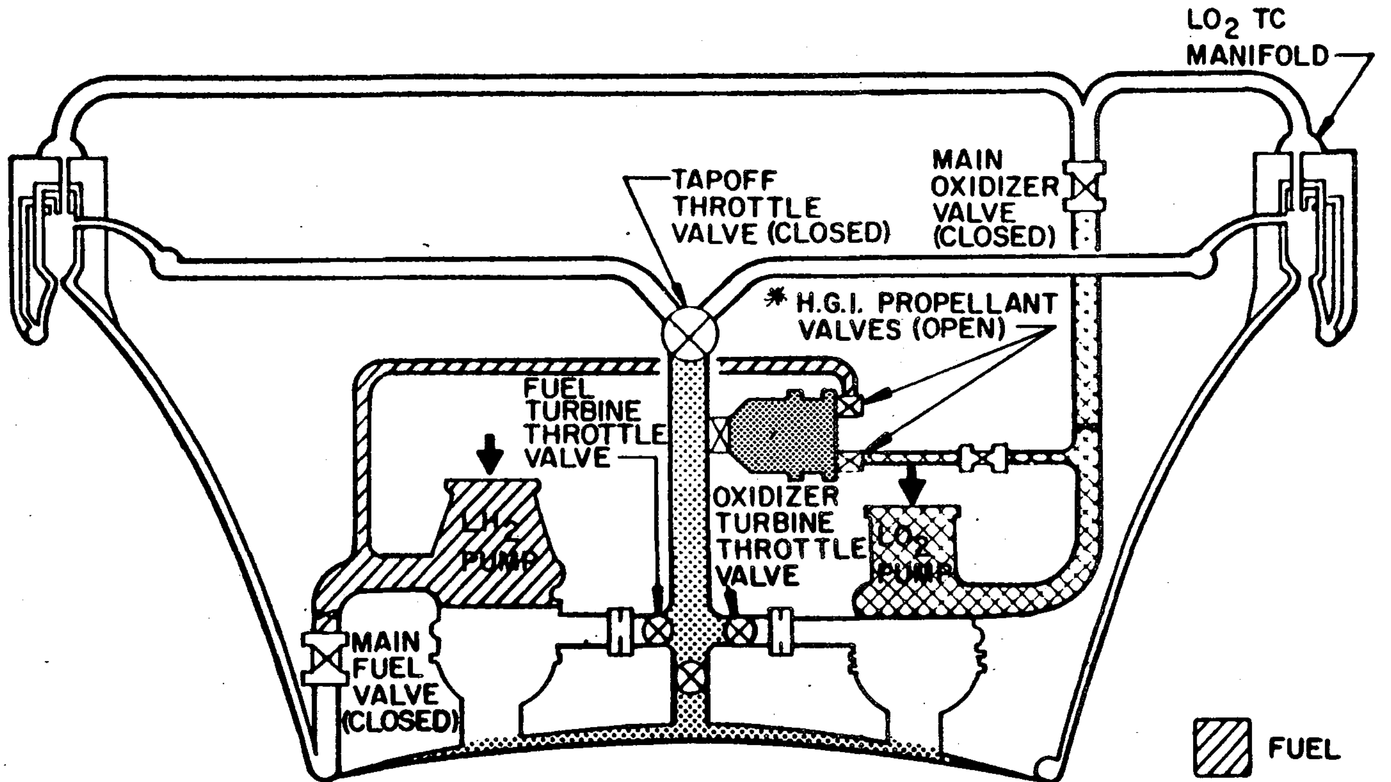
Fig. 27 Aerospike Engine Schematic - Idle Stage Capability

[redacted]

1. For low-thrust space maneuvers.
2. To settle propellants prior to start.
3. To precondition (purge and chill) the vehicle propellant lines to provide liquid propellant for the pumps at main stage start.
4. To provide heat source for propellant tank pressurization augmentation.

Considerable thrust versatility is accomplished by combining idle stage operation with the throttling capability of the primary combustor. Idle stage can be used to supplement main stage throttled thrust to provide an engine thrust capability from essentially zero thrust to 100 percent thrust. For very low-thrust, idle stage operation, a tank-head pressure-fed mode can be used (Fig. 28). In this tank-head idle stage, the main oxidizer and fuel valves remain closed. The fuel and oxidizer turbine valves are closed and the turbine bypass valve is open. The HGI operates as an idle stage combustor and its combustion gases are exhausted through the turbine bypass line to the base to provide the thrust force. The HGI can operate in this mode on mixed-phase or liquid propellants. Alternate thrust controls exist; control of thrust by tank pressure, the liquid valves, and if necessary, the HGI valves.

[redacted]



* The Hot Gas Igniter (HGI) is **redesigned** to be an Idle Stage Combustor (ISC) in the Idle Stage Mode

Fig. 28 Aerospike Engine Schematic - Idle Stage (Tank-head Operation)

[redacted]

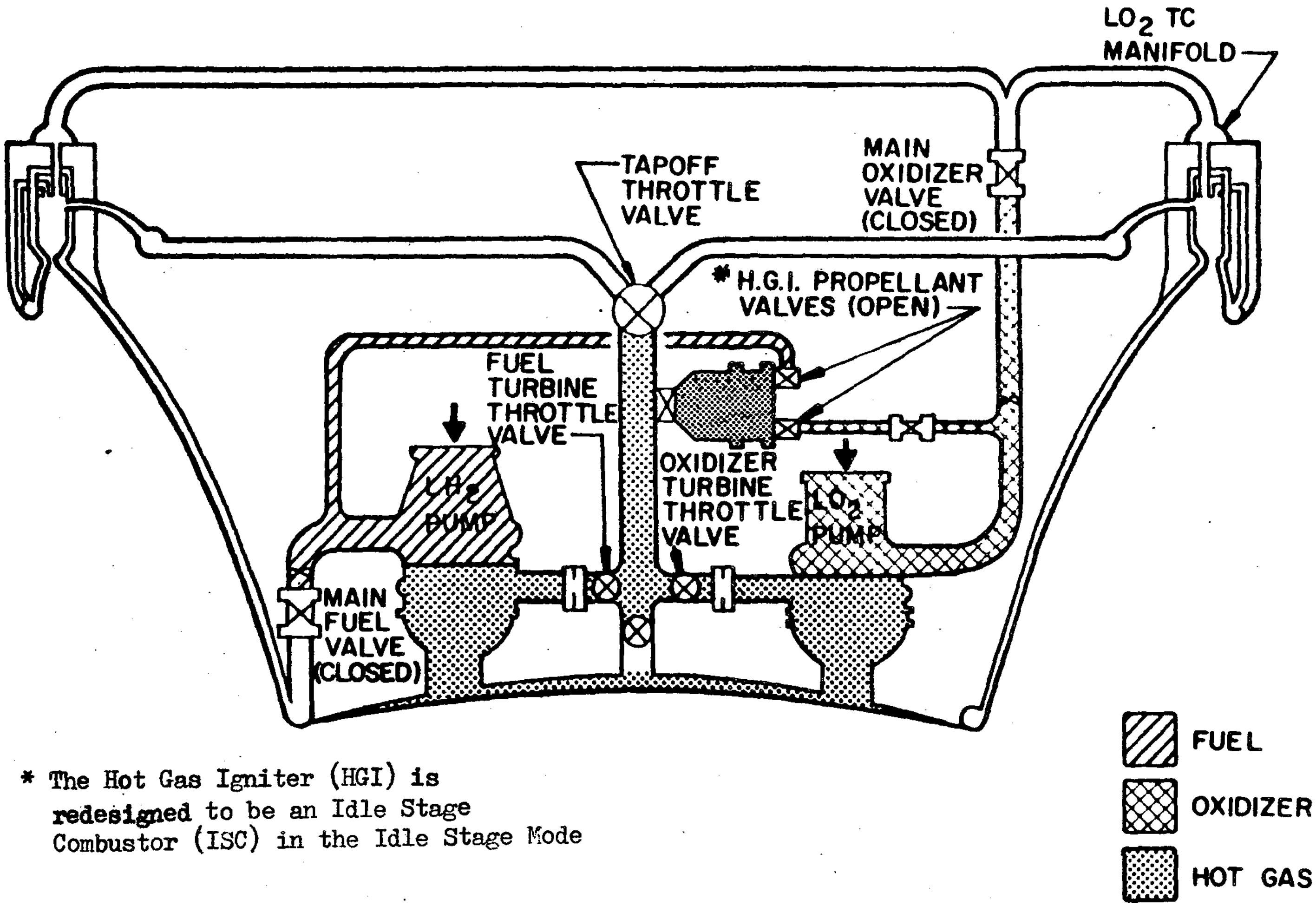
For higher thrust idle-stage-operation, the turbine bypass valve is closed and the oxidizer and fuel turbine valves are opened. This results in the pumps operating, i.e., a pump-fed idle stage operation (Fig. 29). Higher thrust can be achieved since higher HGI (or idle stage combustor) operating pressures can be maintained. Thrust control can be accomplished by the turbine valves or HGI valves, if required.

To achieve mainstage operation, the main fuel valve is opened to provide hydrogen flow through the jacket, and the tapoff throttle valve is opened to permit an igniter flow to the main combustor for ignition and operation to main stage then continues. In the sequence, the turbine bypass valve is closed just prior to the ignition phase.

Specific impulse for idle stage is anticipated to be in the 375- to 400-lbf-sec/lbm range.

Preliminary Aerospike engine thrust and mixture ratio operational limits in the 250- to 500-klbf thrust class are shown on Fig. 30; these data are based on NASA AEA system study results. The operational limit lines encompassing main stage and idle stage regions were generated by performing engine balances with a nonlinear model over wide ranges in thrust and mixture ratios. In the design mixture ratio range, the upper limit on thrust is based on the turbomachinery design capabilities. The result is limit line 3 in Fig. 30 which includes considerations of turbine drive gas properties and pump speed limits. Limit line 2 of Fig. 30 reflects the design point tapoff valve pressure drop. As engine mixture ratio is reduced at constant thrust, required turbine power increases because it takes more power to pump hydrogen than oxygen. The increased power must come from greater flowrate, hence higher fuel turbine inlet pressure. The tapoff valve must be opened to supply this pressure but, eventually, the point is reached where the required turbine inlet pressure is a maximum for a given chamber pressure, i.e., zero valve ΔP. At extremely low main stage thrust levels, the lower mixture ratio limit will be a flammability limit, at approximately 0.5 mixture

[redacted]



* The Hot Gas Igniter (HGI) is **redesigned** to be an Idle Stage Combustor (ISC) in the Idle Stage Mode

Fig. 29 Aerospike Engine Schematic - Idle Stage (Pump Fed Operation)

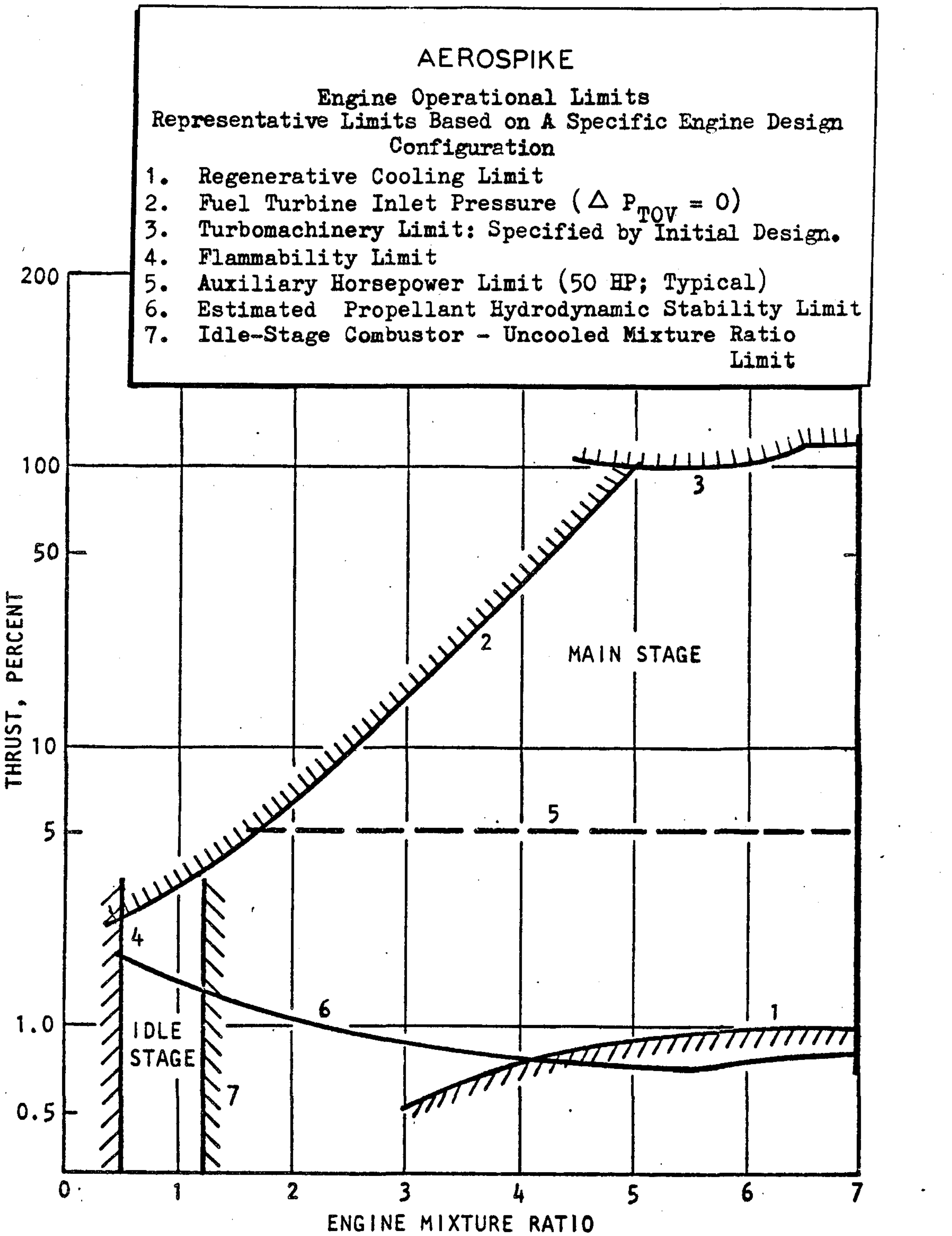


Figure 30. Aerospike Engine Operational Limits

ratio (line 4). Main chamber heat transfer considerations with regenerative cooling impose limits on high mixture ratio operation, and on low thrust operation. Limit line 1 of Fig. 30 represents the regenerative cooling limit for the specific design configuration used to illustrate the operation limits.

A requirement for auxiliary horsepower to be taken off the oxidizer turbine shaft changes the operational limits as indicated by the dashed line (5) in Fig. 30. Above this line, there is sufficient turbine power to supply 50 horsepower. The auxiliary power can be supplied below this point (5-percent thrust) with modifications to the control system and certain turbo-machinery parameter values. Lower thrust regions also are limited by the hydrodynamic flow stability of the oxidizer and fuel systems; this reflects the fact that the very low flowrates in the liquid regime may not fill the feed lines, the flow may not feed the manifolds resulting in nonuniform flow distribution, and control and measurement of these flowrates becomes extremely difficult (line 6).

The idle stage operational region utilizes both pressure-fed and pump-fed propellant supply techniques. Operating tank pressures, or NPSH requirements, for these modes of operation are provided in the NPSH discussion.

<u>Transient Impulse</u>. The Aerospike engine can be started and stopped without operating to full main stage thrust. That is, the engine can be started and can go into main stage with the throttle control system set at a prescribed throttled condition. Current analysis indicate that in the start, a thrust buildup to approximately 20-percent main stage thrust, prior to throttling to a lower thrust is desirable to ensure complete thermal stability of the engine. If a requirement for a lower initial thrust is required, minor changes in the design could provide the necessary capability.

The minimum impulse bit is governed by the thrust level desired, and whether transient thrust can be included in providing the vehicle impulse requirements. Also, idle stage may be useful in providing a small impulse, if a low thrust level is adequate. For preliminary data on minimum impulse, the response rate of 45 percent per second provides a means of determining minimum impulse bit and related thrust level and/or operating duration.

AEROSPIKE ENGINE DIMENSIONS, WEIGHT, AND MASS DISTRIBUTION

ENGINE DIMENSIONS

Engine dimensions in terms of engine diameter and length for the parametric thrust range considered are presented in Fig. 31.
It should be noted that for a specific engine diameter, engine length is essentially independent from thrust.

ENGINE WEIGHT

Engine weight trends (dry engine weight) for Aerospike engines are presented in Fig. 32 . The dry engine weight includes the combustion chamber, nozzle, base-closure assembly, turbopump, and mounting, propellant feed ducting and valves, ignition system, thrust mount, thrust vector control system, tapoff system, electrical controls, and associated structural members. Estimated weights for engine accessories, i.e., heat exchanger, inlet flex lines, and power takeoff are presented in Table 2. The incremental weight values between wet, dry, and burnout are presented in Table 2 . Engine wet weight values should be used in determining loads during flight, gimbaled engine loads, etc. Burnout weight includes the engine dry weight and the weight of the fluids trapped at burnout; propellant downstream of the main valves is consumed during engine shutdown.

MASS DISTRIBUTION

A tabulation of engine center-of-gravity (cg) location as a function of engine module diameter and thrust is presented in Table 3 for 250- ,

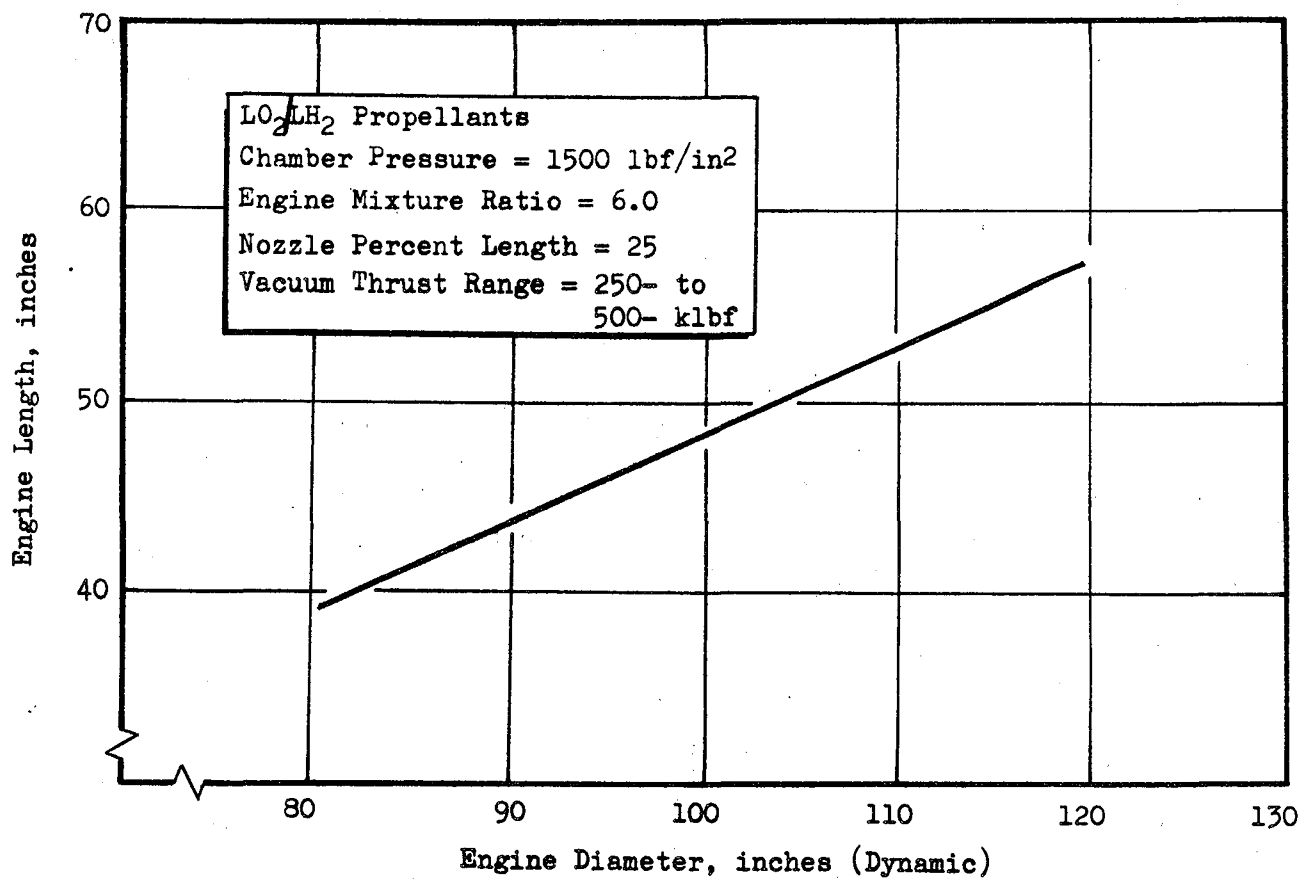


Figure 31. Aerospike Engine Length vs Engine Diameter.

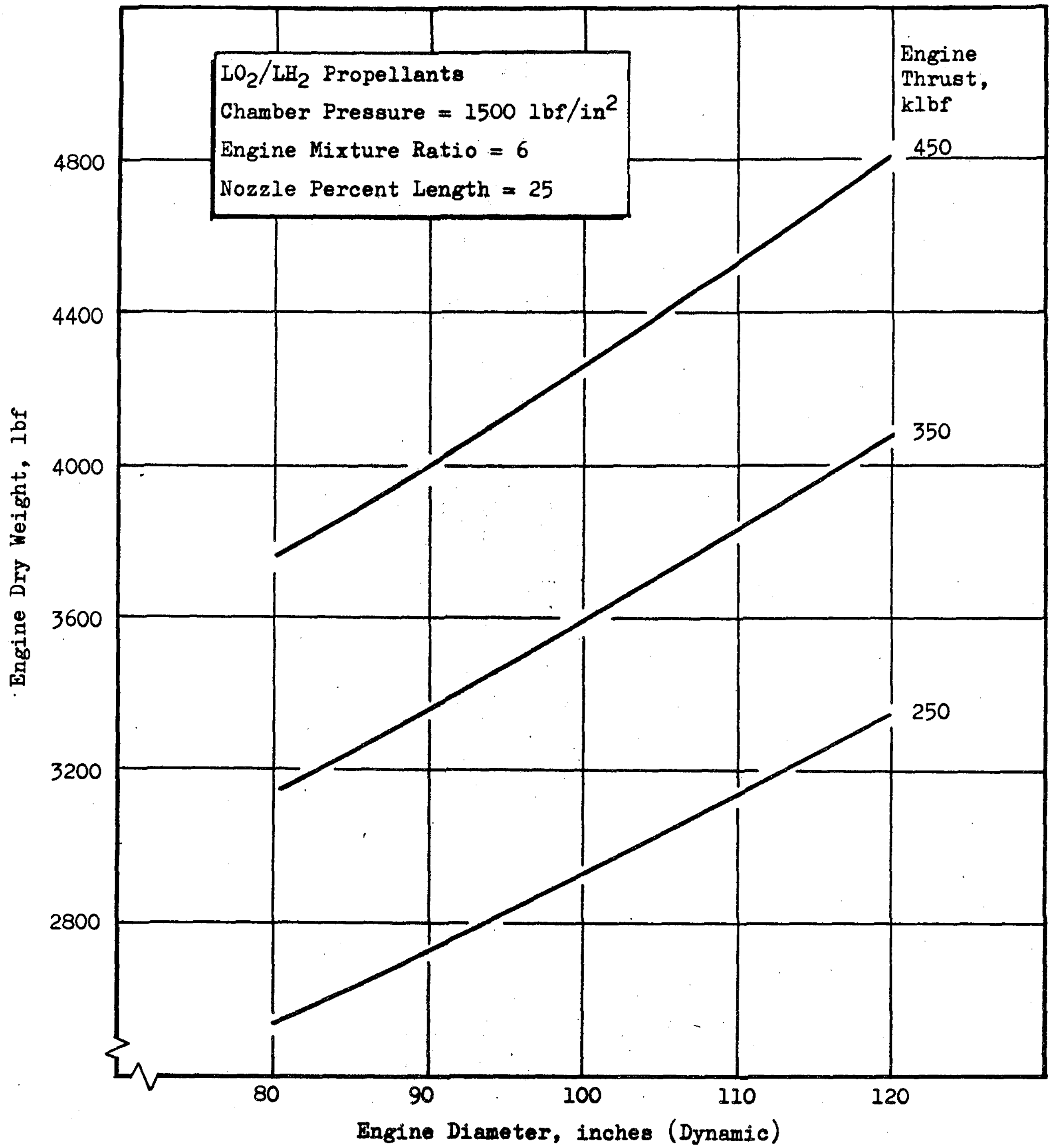


Figure 32. Aerospike Engine Dry Weight vs Engine Diameter

TABLE 2

AEROSPIKE INCREMENTAL ENGINE WEIGHT DATA*

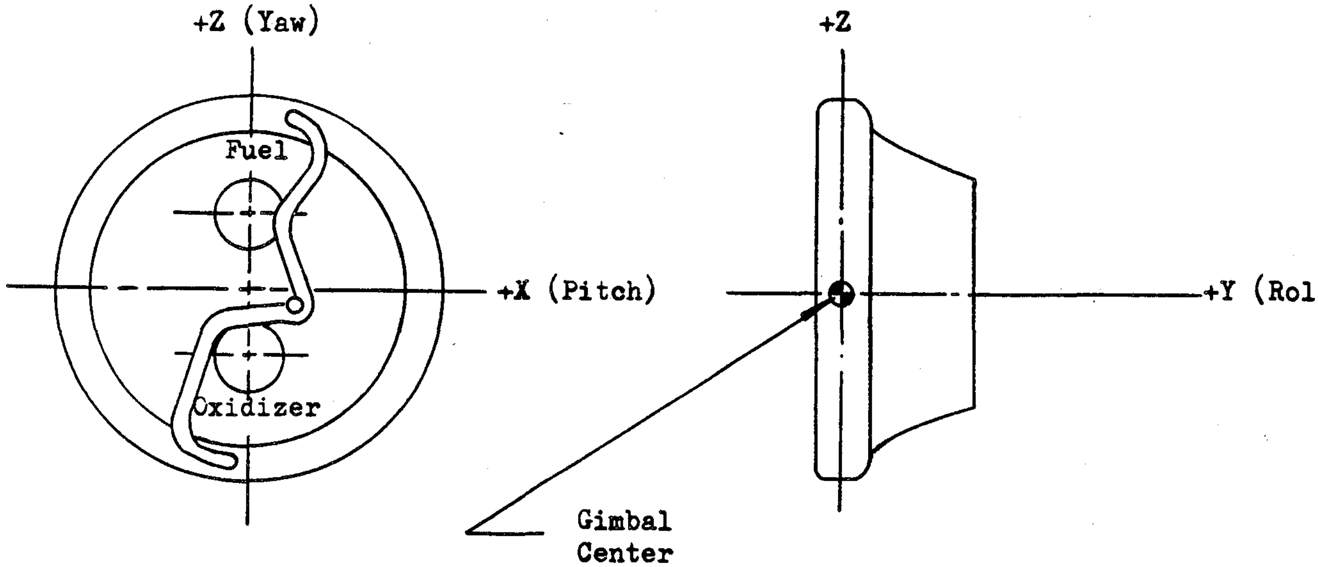
Engine Thrust (vacuum), klbf	Accessory Weight, lbf **	Wet Weight, lbf	Burnout Weight, lbf
250	311	69	24
350	377	86	34
450	420	101	43

* To obtain total engine wet weight add incremental wet weight plus incremental accessory weight to the dry engine weight presented in Figure 32.

To obtain total engine weight at burnout add incremental burnout weight plus incremental accessory weight to the dry engine weight presented in Figure 32.

** Includes heat exchanger, inlet flex lines, and power takeoff.

[redacted]



Module Thrust, klbf	Module Diameter, Inches	Moment of Inertia slug-ft^2			Center of Gravity Location, inches*		
		X	Y	Z	$\bar{X}$	$\bar{Y}$	$\bar{Z}$
250	80	363	427	342	0.5	10.1	0.3
	100	624	735	588	0.5	10.7	0.3
	120	839	989	791	0.5	11.7	0.3
350	80	450	529	424	0.5	9.9	0.3
	100	764	900	720	0.5	10.9	0.3
	120	1022	1205	963	0.5	12.1	0.3
450	80	537	632	506	0.5	9.8	0.3
	100	904	1065	852	0.5	11.0	0.3
	120	1202	1417	1133	0.5	12.5	0.3

* Measured from gimbal center.

Table 3. Estimated Aerospike Engine Moment of Inertia and Center of Gravity Location Data

[redacted]

350- and 450-klbf vacuum thrust Aerospike engines. As noted, the variation in cg location with the different thrust levels is small and is primarily affected by module diameter. These design data are for Aerospike engines having 25-percent length nozzles, with the turbopumps and other components packaged within the nozzle cavity. The cg location can be moved forward by relocating the turbopumps forward of the module. However, this relocation results in increasing engine length, and if a gimbaled engine is employed, the inlet flex lines will no longer be in the gimbal plane. A more complex flex-line system must then be used.

AEROSPIKE ENGINE INSTALLATION AND INTERFACE REQUIREMENTS

ENGINE THRUST VECTOR CONTROL SYSTEM

The thrust vector control system most suitable for the majority of currently anticipated engine installations in the thrust class presented herein is that of mechanical gimbaling of the engine. Mechanical gimbaling is accomplished by two double-acting hydraulic actuators oriented at 90 degrees, with their axes (nearly) parallel with the module axis. The hydraulic actuators are attached at one end to the vehicle thrust structure and at the other end to a toroidal thrust transmission ring within the module as shown in Fig. 33. The system is powered by a hydraulic motor, an accumulator, a reservoir and the associated components. The hydraulic motor is driven by the oxidizer pump turbine. This motor will be a variable-displacement type to provide the required gimbaling power during periods of mixture ratio variations or engine throttling.

Typical Aerospike engines (i.e., the AF ADP demonstrator module) have been designed for a $\pm$7-degree equivalent (circular pattern) gimbal-angle capability. Larger or smaller gimbal-angle capabilities can be provided in the flight engine design. The related gimbal/structural design capabilities are projected for the following gimbal rates and accelerations:

1. Gimbal rate of 30 degrees per second and
2. Gimbal acceleration of 30 radians/sec^2.

PROPELLANT NPSH

Turbopumps for Aerospike engines have been designed to operate at low inlet NPSH values. Typical of the NPSH requirements are those for the AF ADP turbopumps which were designed for a minimum NPSH of 16 feet for the oxidizer and 60 feet for fuel. To provide this capability, hydraulic turbine-driven

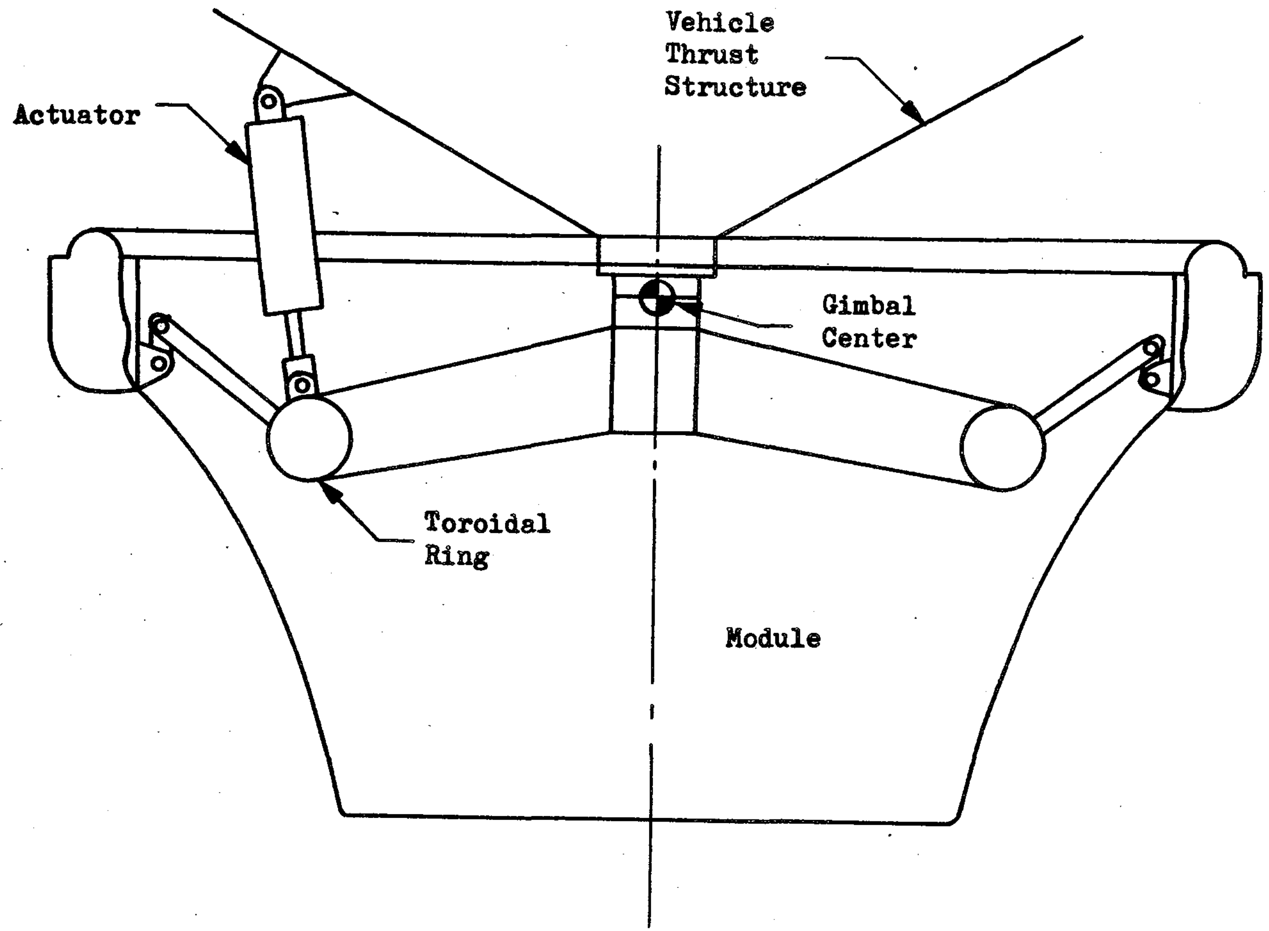


Figure 33.

Aerospike Engine - Thrust Vector Control Assembly Schematic

pre-inducers were used; they perform the same function as a boost pump, but are an integral part of each main pump. The pre-inducer allows the main pump impellers to operate at high speeds without cavitation, thus minimizing turbomachinery size and weight. These pump-mounted pre-inducers allow power to be extracted from the main turbines (either directly or indirectly), thus providing a lightweight, highly efficient, boost pump system which permits the low NPSH engine operation.

Typical NPSH requirements in terms of pressure units (NPSP) as a function of propellant temperature are presented in Fig. 34 for Aerospike engines in the 250- to 500-klbf thrust range. The NPSP values are specified at the pump inlet; inlet duct and flex line pressure drops are not included. The pumps are designed for nominal inlet velocities of 40 ft/sec.

Lower NPSH values can be accommodated if a vehicle requirement exists. Idle stage start, on essentially zero NPSH (i.e., vapor-phase propellant) can be used to settle the propellants, provide liquid propellant to the engine, and provide a small acceleration head to supplement tank pressure in supplying NPSH. Typical propellant supply requirements are shown in Fig. 35 for both idle stage and main stage operation. This operational mode is vehicle-oriented, and can be applied in conjunction with the vehicle system design.

ELECTRICAL AND PNEUMATIC POWER REQUIREMENTS

Electrical interface requirements will be those of supplying electrical power to the electrical control circuits, ignition circuit, component monitoring and functional checkout, and for primary and auxiliary flight instrumentation. Primary instrumentation is related to those parameters critical to all engine static firings and subsequent vehicle launches; auxiliary instrumentation is related to use during the research and development and acceptance

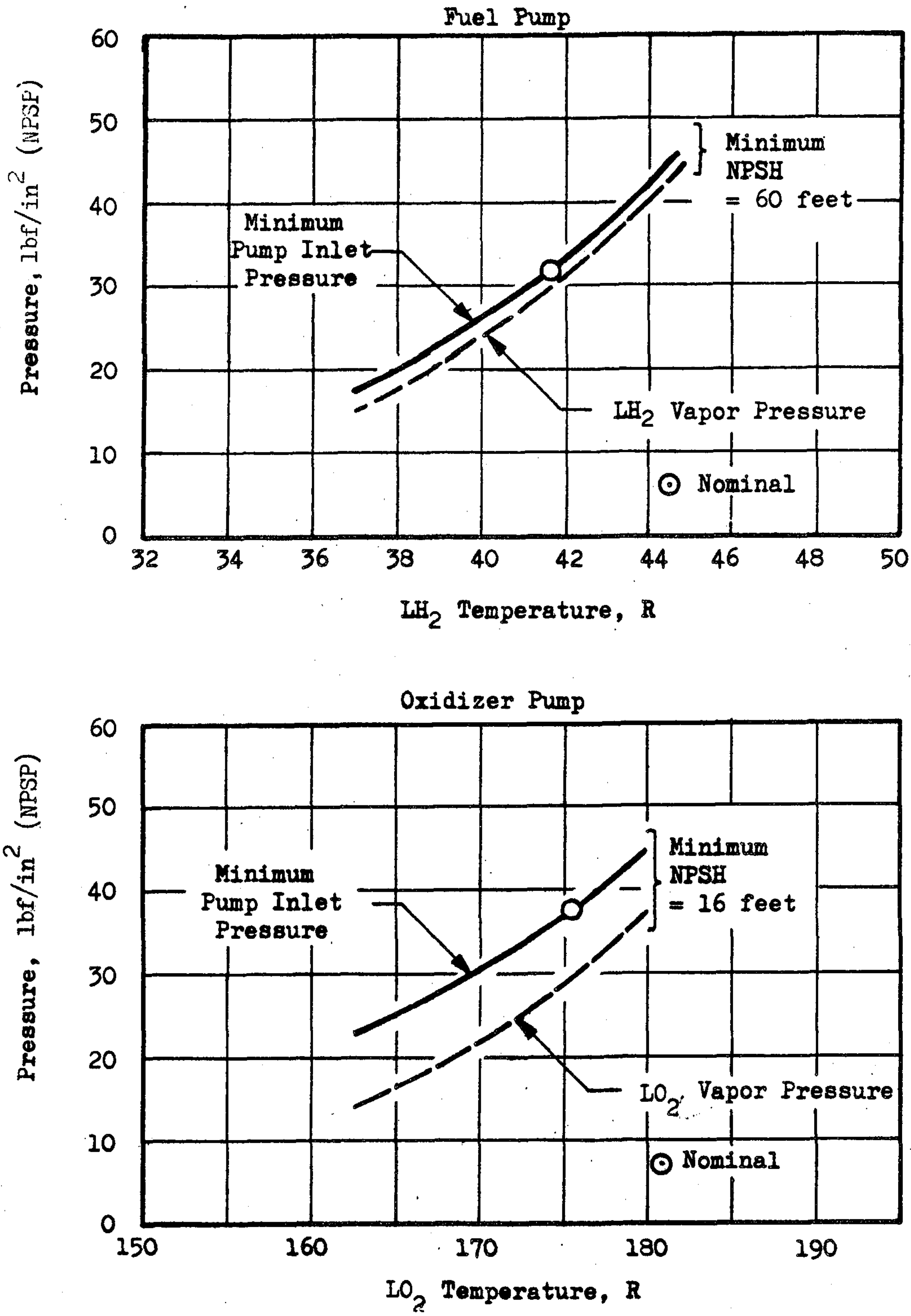


Figure 34. Pump Requirements

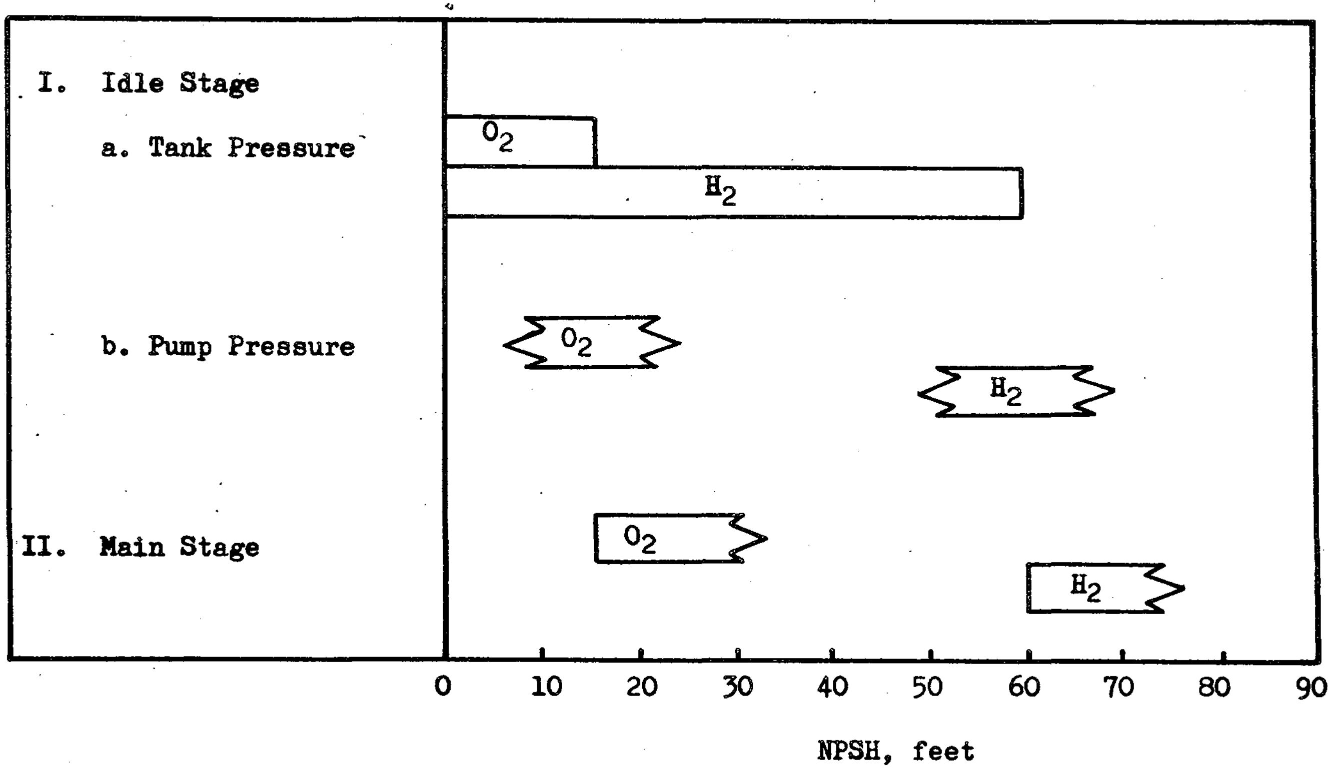


Figure 35 . Propellant Supply Requirements

[redacted]

portion of the engine static test program and initial vehicle flights. In general, electrical requirements for the subject thrust range are estimated to be similar in type and magnitude to those of the Rocketdyne J-2 engine system and are shown below.

Electrical Power Requirements

	Maximum Power Required	Maximum Voltage	Maximum Duration
Ignition System	600 watts	24 - 30 (dc)	up to 12 sec.
Control System (Sequence Control)	360 watts	24 - 30 (dc)	Continuous
Instrumentation	40 watts	24 - 32 (dc)	Continuous
Mixture Ratio and Thrust Control	30 watts (400 cps)	108-121 (ac)	Continuous
	15 watts (400 cps)	40 (ac)	Continuous

Estimated pneumatic requirements, (helium supplied at 750 lbf/in^2 and 310 R) are presented for the various pneumatically controlled engine operations in Table 4. Based upon a flight profile, the total helium requirements and usage rates can be determined. (No vehicle-supplied hydraulic power requirements are projected for the Aerospike engines; the gimbal hydraulic power is supplied by a power take-off on the oxidizer pump turbine).

AUXILIARY POWER

Auxiliary power takeoff can be incorporated in the turbopumps. For example, the oxidizer turbopump designed for the AF ADP engine, which provides for mounting of the 25-hp, 8000-rpm hydraulic pump for gimbal actuator power supply (3000 lbf/in^2), uses an accessory drive pad in the turbine exhaust region at 90 degrees to the turbopump axis. Greater power takeoff capability is available for other power requirements.

[redacted]

[redacted]

TABLE 4

ESTIMATED PNEUMATIC REQUIREMENTS

(Helium)

Actuation	Flowrate (lbm/sec)	Duration (Milliseconds)
Main Fuel Valve, Opening	0.05	200
Main Oxidizer Valve, Opening	0.02	500
Main Fuel Valve Closing	0.10	100
Main **Oxidizer** Valve, Closing	0.10	100
Tapoff Throttle Servo	0.003	5000
Tapoff Throttle Closing	0.14	100
Oxidizer Turbine Throttle Servo	0.003	5000
Oxidizer Turbine Throttle Closing	0.14	100
*HGI Oxidizer Valve, Opening	0.015	200
HGI Fuel Valve, Opening	0.015	200
HGI Oxidizer Valve, Closing	0.03	100
HGI Fuel Valve, Closing	0.06	50
Isolation Valve, Opening	0.07	200
Isolation Valve, Closing	0.14	100

Note: Maximum flowrate occurs at shutdown with simultaneous closure of the Main Oxidizer Valve and the Oxidizer Turbine Valve, and is 0.24 lbm/sec.

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* HGI - Hot Gas Igniter

[redacted]

[redacted]

FLIGHT LOADS

Estimated lateral and axial loads criteria for Aerospike engines in the 250- to 500-klbf range is presented in Fig. 36.

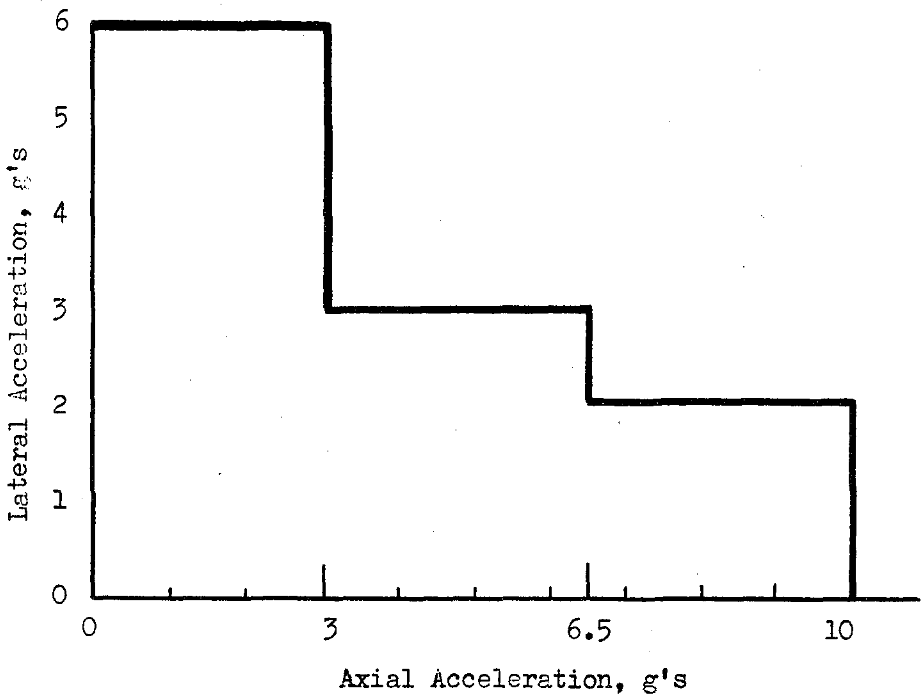

Fig. 36 Flight Load Capability Data

Greater load capabilities can be incorporated in the engine structural design if specific vehicle requirements are established.

INSTALLATION

An orthographic drawing of a 100-inch diameter, 250-klbf vacuum thrust Aerospike engine is presented in Fig. 37. The general layout for Aerospike engines in the 250-to 500-klbf thrust range and 75-to 125-inch diameter range will be similar.

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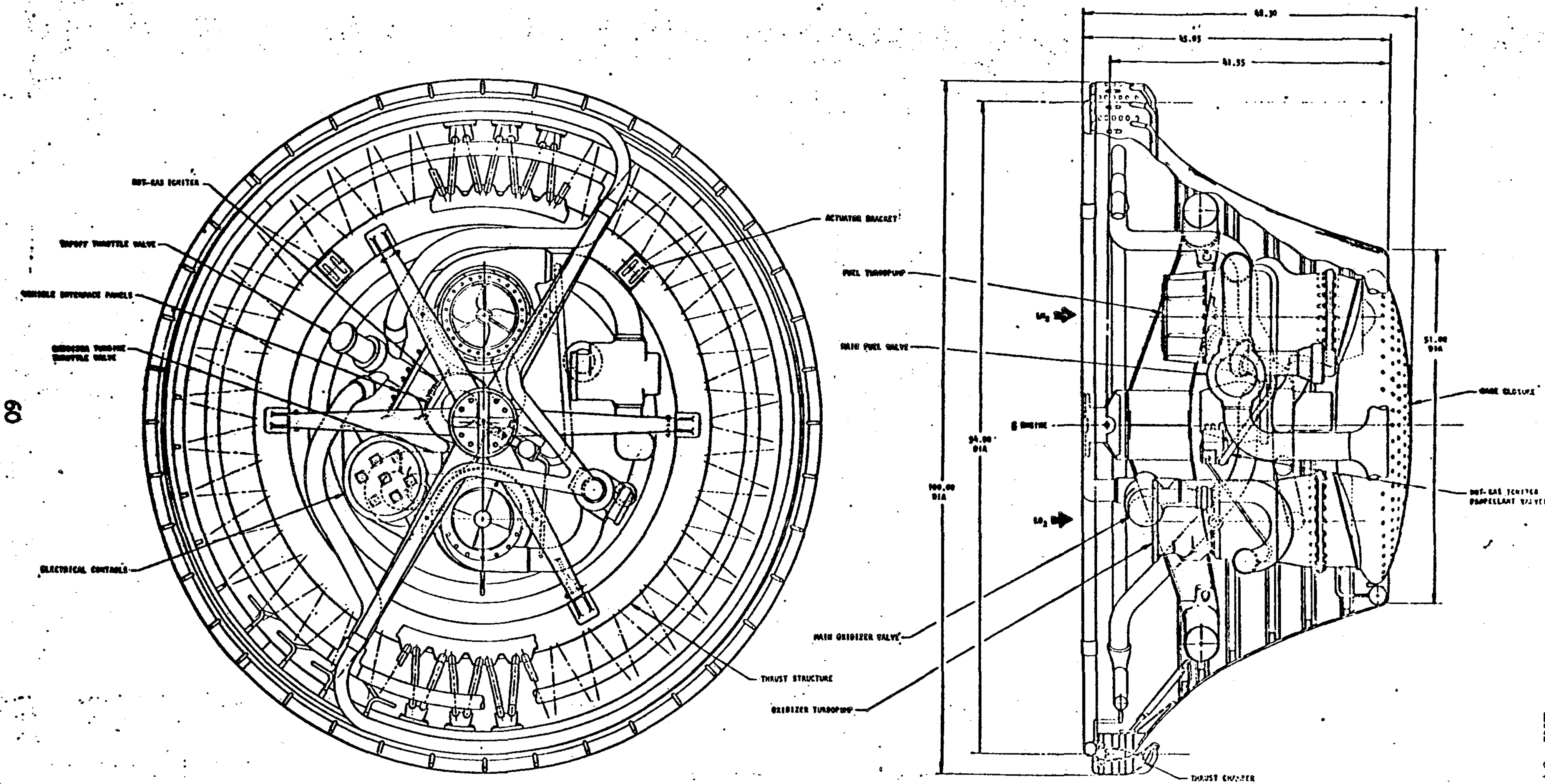

Figure 37. Orthographic Drawing; 250-klbf Aerospike Flight Engine

[redacted]

The typical Aerospike engine described herein is designed to operate (in all modes) in any attitude from horizontal to vertical.

The Aerospike engine can be installed in single- or multiple-engine clustered configurations. The Aerospike engine installations offer several advantages: (1) the static and dynamic (gimbaled) envelopes remain the same diameter. In a cluster installation, this allows the closest possible spacing (from 2 to 5 inches) between modules. In a single-engine installation, the short length permits a minimum boattail or interstage structure; (2) the heat shield may be mounted directly to the vehicle thrust structure thus precluding the additional structure and weight characteristically required to support the shield in a conventional single or clustered, bell-nozzle engine system; (3) the short length of the Aerospike engine (approximately 25 percent of the length of an equivalent thrust bell configuration) results in minimal fairing and closure surface areas for single- or multiple-engine installations.

The interaction of the exhaust plumes and base pressure resulting from a cluster of Aerospike has been experimentally investigated. A cold-flow test model of a five-Aerospike-engine cluster, with minimum spacing between engines, was tested. The model was tested with all engines producing axial thrust and with one outer engine gimbaled 10 degrees inward. Tests revealed little or no effect of the outer four engines on the center engine over the wide ambient pressure (altitude) range tested.

The effect of slipstream on the performance of a single Aerospike engine also has been experimentally investigated with cold-flow model tests and hot firings of model Aerospike engines at the AEDC test facility. Results

[redacted]

showed that the aerospike nozzle performance in a slipstream of varying Mach numbers and in still air is a function of the vehicle base pressure. Thus, still-air performance can be achieved by Aerospike nozzles under flight conditions by designing boattails that maximize vehicle base pressures; i.e., so that base pressure achieves free-stream pressure.

LEAKAGE

Design studies of Aerospike engines indicate that it can be designed for zero leakage (propellants and pressurants) during operation and during a non-operative space coast. (This is defined as less than 10^{-7} standard cm^3/sec helium under operating pressure).

PROPELLANT TANK PRESSURIZATION

The Aerospike engine provides the capability for incorporation of heat exchangers for heating the propellant tank pressurization gases and the option of supplying the tank pressurization gases directly.

Heat exchangers can be designed for the flowrate and temperature requirements, and incorporated in either of several locations:

1. the turbine exhaust duct
2. the base exhaust manifold and closure, or
3. the main chamber tapoff lines (Higher temperature gases can be tapped off to provide the same turbine inlet temperature.)

The Aerospike engine can be designed to provide heated hydrogen directly through a tapoff of the hydrogen flow after the hydrogen has completed the cooling circuit and prior to injection. Also, fuel-rich tapoff gases from the combustion chamber at a mixture ratio of 1.1:1 and a temperature of approximately 1960 R can be provided by using the same tapoff manifold which provides the turbine drive gases.

[redacted]

Using an auxiliary tapoff manifold, combustor gases ranging from 0.5:1 to over 2:1 mixture ratio, and 1460 to 2460 R could be provided.

OPERATIONAL LIFE

Previous large liquid rocket engine operational requirements have been designed for one flight duration. The durability qualification requirements of these systems have been typically established as 12 equivalent flight durations and 20 start-stop cycles. Although long operating life was not a design objective of these systems, the actual life achieved for Rocketdyne engines has been significantly higher than the requirements. Of interest is the durability demonstrated by a J-2 engine (engine J 022-1) (230-klbf, O_2/H_2 system) which achieved approximately 5.6 hours (20,094 sec) of accumulated duration with 103 starts without major component replacement; this system also met system requirements throughout the test program.

Typical flight durability objectives for the advanced, high-performance Aerospike engine include the following:

- 10-hour time between overhauls
- 100 reuses
- 300 starts
- 300 thermal cycles
- 10,000 valve cycles

Testing on the key component, with respect to engine cumulative and cyclic life, has been conducted; the test results have confirmed that engine life objectives indicated above are realistic and will be achieved in a flight-type engine.

[redacted]