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PROJECT APOLLO

A Feasibility Study of an Advanced
Manned Spacecraft and System

FINAL REPORT

VOLUME IV. ON-BOARD PROPULSION

Book 1 — Text and Appendix P-C

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Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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4.3 ALTERNATE SYSTEMS STUDIED

4.3.1 Bell Aerosystems Proposed Propulsion System

4.3.1.1 SUMMARY

Bell selected the propellant combination liquid fluorine/liquid hydrogen for the main propulsion system coupled with a unique propellant feed system utilizing the better advantages of the turbo pump and pressurization feed. The results of their study are summarized in Appendix P-B and represents an excellent analysis and proposed solution to the APOLLO propulsion Their engine emphasizes capacity for multi-purpose missions, multiple firings, reliability, and redundancy.

The main propulsion and mission attitude control systems are mounted in a single propulsion module fitting easily within the envelope of the D-2 APOLLO capsule. The total impulse capability of the main propulsion system is approximately 4 million pound seconds. The upper thrust capability is 24,000 lb for superorbital abort and it has a maximum of fifteen restarts of the main engines in space for course correction and lunar orbit and deorbit. Either one or both pump-fed 12,000-lb thrust chambers may be utilized for lunar orbit and deorbit, expending approximately 93 percent of the total usable weight of propellants in four starts. Midcourse corrections are accomplished from a separate helium pressure-fed system to facilitate achievement of the large number of total firings for the maximum mission. Pressure-fed firings are made using the two main engines with thrust decreased to approximately 4000 lb. Bell concludes that the reliability of the pumped/pressure-fed system is essentially equivalent to a pure pressure-fed system

The proposed system shown in Figure I-4-28 has the further advantage of occupying only a minimum amount of the total available volume, saving perhaps as much as 10 feet of the cylindrical, 10-ft diameter APOLLO mid-section

Detailed technical discussions, schematics, performance, and estimated weight breakdowns, as well as operating sequence and safety and reliability analyses are included in Appendix P-B. In this Appendix, Bell discusses its detailed program plan approach and facilities available for this program implementation.

1. H_2 LOW PRESSURE TANK — 2 RQ'D
2. F_2 LOW PRESSURE TANK — 4 RQ'D
3. H_2 HIGH PRESSURE TANK — 2 RQ'D.
4. F_2 HIGH PRESSURE TANK — 1 RQ'D.
5. ATTITUDE CONTROL & ULLAGE ROCKET PACKAGE — 4 RQ'D.
6. THRUST CHAMBERS
7. TURBINE PUMP
8. GIMBAL ACTUATORS
9. SPACE RESERVED FOR SOLAR ARRAY
10. HEAT SHIELD (DELETED FROM END VIEW)

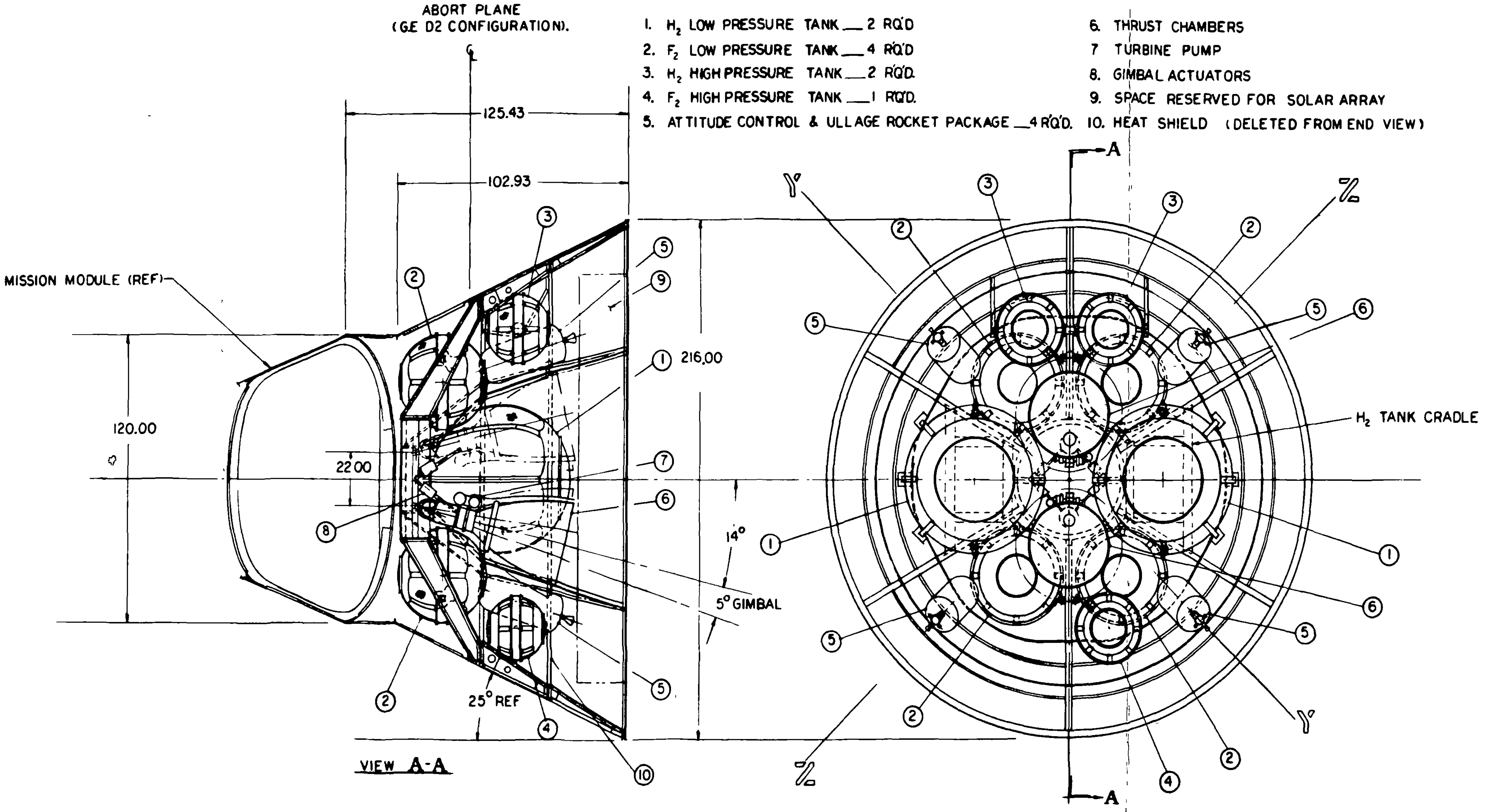

Figure I-4-28. Bell proposed propulsion system

4.3.1.2 DESIGN REVIEW

Bell's proposed use of fluorine hydrogen unquestionably provides an edge in performance and payload over the recommended Aerojet O_2/H_2 system. This edge in performance may be significant for some of the proposed APOLLO missions, but with the resultant payload determined during this study of nearly 8000 lb, both O_2/H_2 and F_2/H_2 exceed the 15,000 lb weight limitation. As described in the parametric study above, there are several alternatives to provide the successful APOLLO mission, but in each case the O_2/H_2 appears adequate. Nevertheless, the Bell system has considerable merit and should be seriously considered for future spacecraft applications, particularly if propulsion volume is limited.

The primary disadvantage of Bell's proposed system is twofold:

(1) System and starting complexity with the proposed combination pumped-fed and pressure-fed system, and

(2) The disadvantages of using liquid fluorine on a manned spacecraft.

Bell Aerosystems and others have been actively working with fluorine for several years and valuable information is now available in storage, handling and testing this propellant. Their report describes some of Bell's detailed experiences and it is their conclusion that fluorine is suitable for manned spacecraft. However, it would appear that there is still substantial work to be done in understanding the storage and handling of liquid fluorine before it reaches the present state of technology of handling oxidizers like liquid oxygen.

A summary of the Bell proposed APOLLO main propulsion system is shown in Table I-4-XVI. These weights were derived for a system capable of providing 7500 feet per second with a 10 percent propellant reserve for a vehicle gross weight of 14,715 lb. These numbers would be adjusted for the particular D-2 vehicle to reflect the increased payload. The tabulated performance is for a single engine which is capable of operating either at 12,000 pounds thrust in the pumped-fed mode or at 4000 pounds thrust as a pressure-fed system.

TABLE I-4-XVI. APOLLO MAIN PROPULSION PERFORMANCE SUMMARY

(1) Requirements	
Vehicle Gross Weight	14,715 Lb
Δ V Total	7,500 Ft/Sec
Δ V Midcourse Corrections	500 Ft/Sec
Δ V Lunar Orbit Exit and Entry	7,000 Ft/Sec
(2) Engine Performance	
a. Pump Fed Engine	
Propellants	Liquid Fluorine/Liquid Hydrogen
Engine Vacuum Thrust, Lbs	12,083
Engine Mixture Ratio, °/F	11.92 ± 1-1/2%
Engine I_{sp}, Nominal, Sec	446.2
Engine I_{sp}, Minimum Observed Guarantee, Sec	443.6
Thrust Chamber Vacuum Thrust, Lbs	12,000
Chamber Pressure, Psia	300
Mixture Ratio, $^{O}/F$, Thrust Chamber	13
Area Ratio, A_e/A_t	45
I_{sp}, Nominal Thrust Chamber, Sec	448.2
I_{sp}, Minimum Observed Guarantee Thrust Chamber, Sec	446.2
Fuel Pump Discharge Pressure, Psia	465
Oxidizer Pump Discharge Pressure, Psia	400
Turbine Fuel Consumption, Lb/Sec	0.33
Turbine Exhaust Thrust, Lb	83
Exhaust Gas I_{sp}, Sec	250
b. Pressure Fed Engine	
Propellants	Liquid Fluorine/Liquid Hydrogen
Vacuum Thrust, Lbs	3,983
Mixture Ratio, $^{O}/F$	10
Chamber Pressure, Psia	100
Area Ratio, A_e/A_t	45
I_{sp}, Nominal, Sec	448
I_{sp}, Minimum Observed Guarantee, Sec	445.8

TABLE I-4-XVI. APOLLO MAIN PROPULSION PERFORMANCE SUMMARY (Cont)

APOLLO MAIN PROPULSION WEIGHT SUMMARY (1963 Version)	
Thrust Chamber Assembly	
Including valves, engine mount, turbine pump assembly, gimbal actuators, etc.	555.1
Propellant System	
Including low pressure and high pressure tanks, insulation lines, valves, module structure, tank supports and interconnecting lines	899.0
Pressurization System	
Including helium tanks, tank supports, lines and valves	126.9
Instrumentation Pick-Ups	25.0
Loadable Propellant and Helium	6,831.5
Mission Ullage/Attitude Control System	507.2
Propulsion Module Skin Weight	563.0
TOTAL	9,507.1

The Bell main propulsion system properly emphasizes reliability and safety for this manned spacecraft. Their analysis is shown in Section XII of Appendix P-B and is an excellent piece of work. Bell's reliability analysis evaluates the reliability in terms of mean time between failure. They find that their proposed system appears capable reaching the reliability of 1828 missions between failure. The reliability decrease of the all-pumped system of 14% eliminates the all-pumped system from further consideration for the APOLLO mission. Their analysis shows that the pumped/ pressure fed system is within one percent of the all-pressure fed system.

The complete engine assembly is shown in Figure I-4-29 showing the overall dimensions. The turbo pump assembly is mounted on the thrust chamber from supports about the

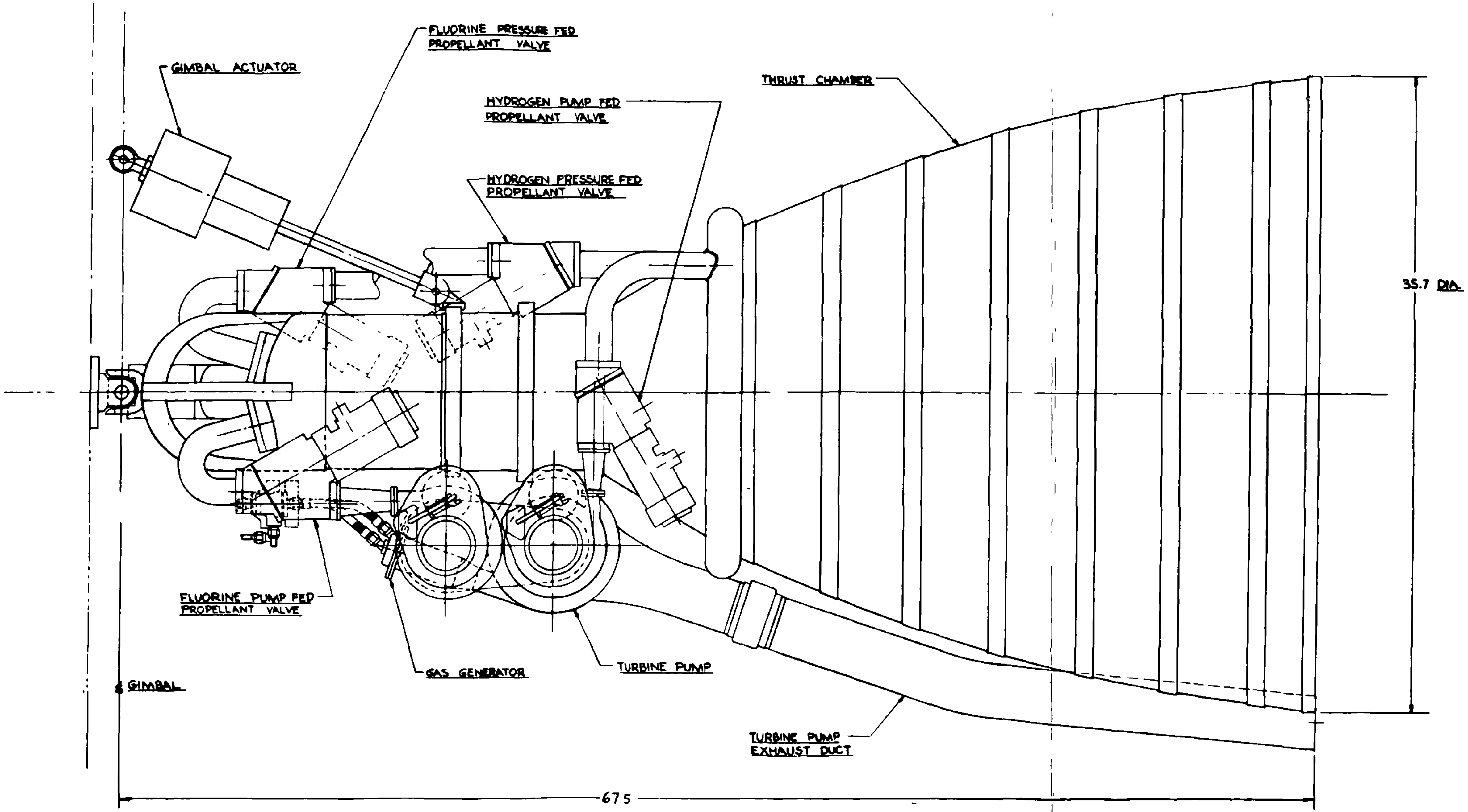

Figure I-4-29. Bell engine assembly drawings throat section. The gas generator, mounted on the turbine inlet manifold, burns fluorine and hydrogen to drive the turbo pump. The complete engine assembly is gimballed to provide thrust vector control of at least 5 degrees in any direction.

The thrust chamber is regeneratively cooled with the hydrogen and operates at pressures of 300 psia during pump fed operation and 100 psia for pressure fed operation. A summary of the thrust chamber characteristics is given in Table I-4-XVII. Additional analysis shows that the thrust chamber could operate at very low chamber pressures (10 to 20 psia) without an injurious temperature rise in the cooling jacket. Such operation at the ultra low chamber pressure would be of particular importance for safety and reliability for lunar deorbit. If there were a multiple failure of both turbo pumped assemblies and the pressurization system, the propellant in the low pressure tanks could be used to accomplish lunar deorbit using the propellant vapor pressures for expulsion and a resultant chamber pressure of 10 to 20 psia. According to Bell's analysis, however, probability of this emergency power requirement is less than one in 2500 missions.

The schematic of the main propulsion system is shown in Figure 1-4-30. The two thrust chambers are turbo-pump fed from low pressure spherical tanks. The chambers can also be operated pressure fed from the high pressure tanks. Thrust levels are 12, 000 and 4, 000 lb respectively. A helium tank, buried in one of the low pressure H_2 tanks, provides positive suction head pressure requirements of the pumps. This helium is also fed through a second system to the high pressure propellant tanks. The turbo pump assemblies are driven by gas generators which burn F_2 and H_2 in a "boot strap" rise of power. Flow control of the gas generator is accomplished by cavitating venturies. The thrust chamber propellant valves provide bleed flow to cool the propellant pumps prior to starting the gas generator. Temperature sensing elements indicate completion of bleed. After thrust shutdown, bleed ports vent the propellants trapped between the pump inlet valves and the propellant valves. The power acquisition for the pumped fed operation is obtained by ullage rockets incorporated with the attitude control system, augmented by the thrust developed by the gas generator exhaust duct.

The high pressure H_2/F_2 tanks may incorporate bladers for positive expulsion, although additional work needs to be done for use with cryogenic propellants.

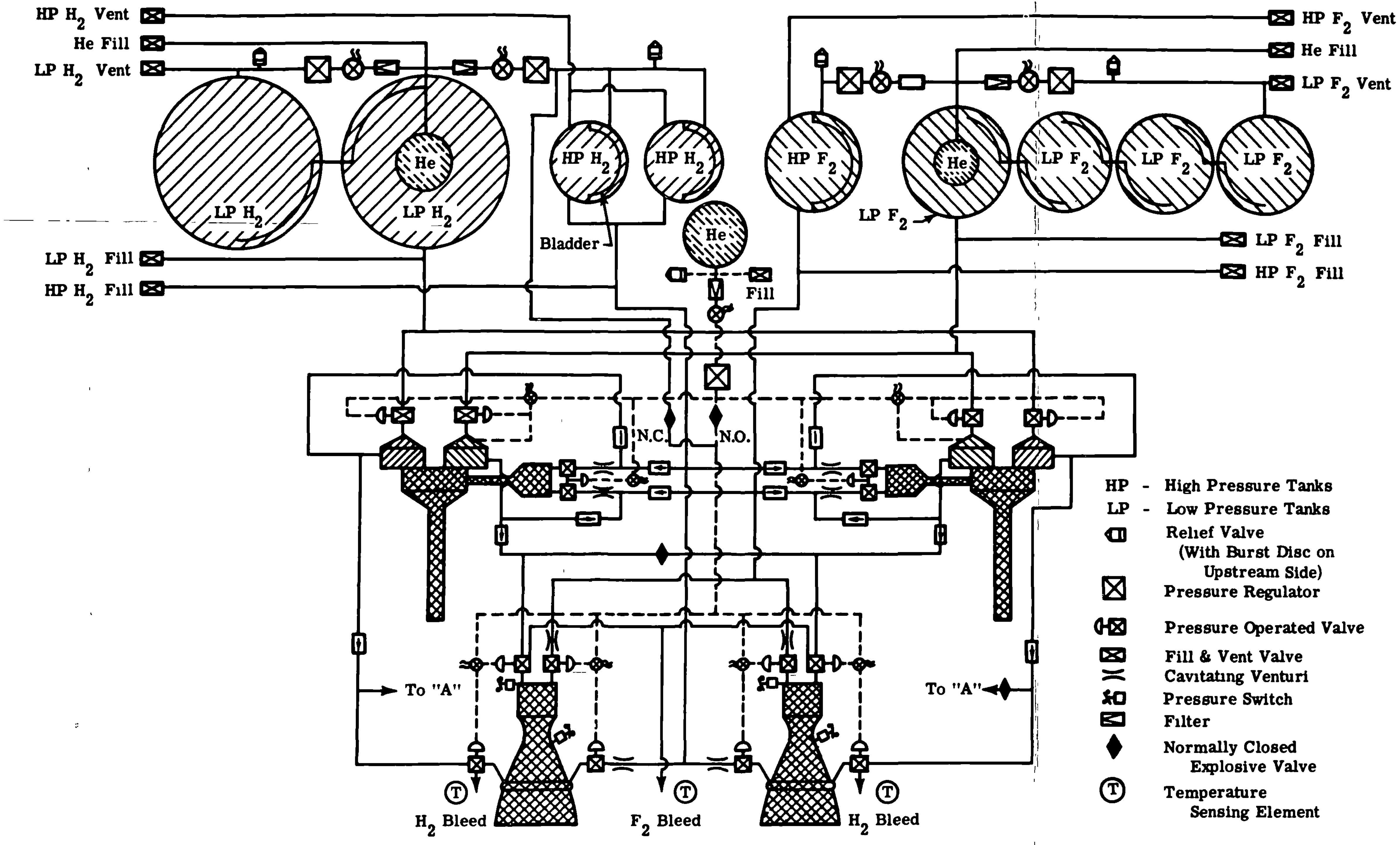

Figure I-4-30. Bell engine schematic

TABLE I-4-XVII. THRUST CHAMBER CHARACTERISTICS

	Rated Conditions	Step Thrust Conditions
Vacuum Thrust, lb	12,000	3,983
Thrust Chamber Pressure, psia	300	100
Mixture Ratio, W_o/W_f	13.0	10.0
Vacuum Specific Impulse, lb sec/lb	446.2*	445.8*
Propellant Flow Rate, lb/sec	26.90	8.92
Regeneratively Cooled Divergent Area Ratio	45	45
Throat Area, sq in	21.545	21.545
Nozzle Exit Diameter, in	35.1	35.1
Oxidizer Feed Pressure, psia	400	111
Fuel Feed Pressure, psia	465	145
Cooling Fluid	Fuel	Fuel

*Minimum observed guarantee vacuum specific impulse, does not allow for 0.7% instrumentation error.

Additional details of the proposed F_2/H_2 system may be found in Appendix P-B.

4.3.2 Reaction Motors Division Proposed APOLLO Powerplant

Reaction Motors has studied the requirements for the NASA APOLLO manned spacecraft in light of their considerable experience with manned rocket engines, including the LR-99 engine currently in use with the X-15 research aircraft. Reaction Motors has studied the APOLLO mission in some detail from the aspects of reliability and quality assurance testing. The report in Appendix P-C includes a particularly interesting basic philosophy for guiding and over-all detail system design.

In summary, Reaction Motors supports the concept that man is the single most important element in the operation of manned spacecraft. Rigorous application of manned qualification and manned safety concepts must constitute a basic philosophy guiding over-all detail system design at every stage of the effort. Further, even with powerplant