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TECHNOLOGY FOR LOW COST SOLID ROCKET BOOSTERS

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ABSTRACT

For a number of years NASA, through the Lewis Research Center, has been engaged in developing technology for reducing the cost, and improving the reliability of large solid rocket motors. A brief review of some of the more significant developments in technology for low cost motors is presented and an estimate of the total cost reduction obtainable by incorporating this new technology package into the design of large solid rocket motors is made. The technology review includes the propellant, case material, insulation, nozzle ablatives and thrust vector control areas. The effect that the new technology would have on motor cost was determined for a typical, expendable 260-inch booster application. Included in this cost analysis was the influence of motor performance variation due to both specific impulse and weight change. For the application considered, it was found that motor costs could be reduced by as much as 30 percent when the new technology was introduced into the design. Although this cost advantage will vary depending on the vehicle application, it is clear that significant cost reductions can be made in most applications. It is concluded that new technology can significantly improve the economic attractiveness of future large solid rocket motors.

INTRODUCTION

The 260-inch Solid Rocket Motor Demonstration Program, which was completed in 1967, established the feasibility of large solid rocket motors. In addition this program also demonstrated its inherent simplicity, low cost potential and reliability. The results of the three 260 inch motor tests that formed the heart of the program can be found in references 1 and 2. Since the end of this 260 inch Solid Rocket Motor Demonstration Program, NASA has supported, through the Lewis Research Center, additional advanced technology for large solid rocket motors. The objective was to further improve cost effectiveness, investigate critical technical problem areas and improve motor reliability.

This advanced technology activity was broad in scope and included work in all major component areas. The results are reported in references 3 to 24. One of the significant developments was the qualification of a number of new technologies that could produce collectively a significant reduction in the potential motor cost that had been demonstrated in the earlier 260 inch motor tests.

The objectives of this paper are first to review briefly those new technologies that will have a major impact on reducing motor costs, and secondly to assess the combined effect that the introduction of these new technology elements would have on motor cost for a typical, expendable 260 inch booster application. Included in this cost analysis is the effect of motor performance variation resulting from either specific impulse or weight changes due to the introduction of the new technology.

DISCUSSION

TECHNOLOGY FOR LOW COST BOOSTERS

Propellant An interesting development in the propellant area has been the results obtained with the relatively new hydroxyl terminated polybutadiene (HTPB) binder. The attractiveness of this prepolymer is its low cost; less than 1/2 the cost of the polybutadiene acrylic acid acrylonitrile terpolymer (PBAN) which was used in the past 260 inch motor tests. In addition improvements in specific impulse and mechanical properties were potential benefits of the HTPB propellant. A program was therefore initiated to investigate the suitability of the HTPB binder for use in large solid rocket motors. The results of this program are presented in reference 3. A summary of the program results are shown in table I, and for comparison the characteristics of the PBAN propellant used in the third 260-inch test motor are included. In addition to the low cost of the polymer, the HTPB propellant exhibited excellent processing characteristics. For non-vacuum, bayonet casting of large solid rocket motors the propellant viscosity at low applied shear stress levels is an important factor in assuring homogeneous, void free propellant grains. In reference 4 it was shown that, if the propellant viscosity was less than 40 kilo poise at 5,000 dynes per cm^2 applied shear stress 3 hours after curing agent addition, a low and acceptable rate of propellant void incidence is obtained. The HTPB propellant viscosity is seen to meet this requirement quite handily (table I). From a mechanical properties standpoint, the HTPB propellant also provides about a 50 percent increase in propellant strain capability, which will substantially improve the propellant structural safety margins. And finally, because of the low viscosity and good mechanical characteristics of the HTPB propellant, the concentration of ammonium perchlorate can be increased (higher solids loading) and thereby improve its specific impulse. In table I, it can be seen that the improvement is about 2 seconds. The specific impulse numbers shown were obtained with 100 pound ballistic test motors, and at least a 1 to 2 second increase above these values can be expected when scaled to 260 inch size motors. In summary, the HTPB propellant has been found to be adaptable to the processing requirements of large solid rocket motors and its use will reduce motor costs and increase the propellant structural capability. The impact on motor cost will be assessed later.

Case Materials Technology programs in the case material area have been focused on reducing cost and improving the structural reliability of the case by improving its fracture toughness. Fracture toughness is a characteristic that indicates how susceptible a material is to failure under load due to the presence of crack-like defects or flaws. The higher the fracture toughness, the greater the tolerance to material flaws. The lower the fracture toughness, the greater the probability of inadvertent case failure due to the accidental or undetectable presence of flaws. An example of the catastrophic nature of this type of case failure can be found in reference 5.

Two new case material candidates have been studied; one is a 12 percent nickel maraging steel (ref. 6) and the other is HY 150 (ref. 7). The material and fabrication characteristics of these two high fracture toughness steels are shown in table II. Included in the table for comparison purposes are the characteristics of the 18 percent nickel, 200 grade maraging steel used in the 260-inch test motor cases. Both of the new steels possess lower yield strength than the 18 percent nickel steel. The 12 percent nickel steel is only 10,000 psi lower, however, the HY 150 steel is 50,000 psi lower. The lower strength capabilities of the new material will result in a motor performance penalty due to the added case wall thickness (weight) necessary to withstand hoop stresses developed during pressurization. However, the new materials both have higher fracture toughness. Accordingly, their allowable critical flaw depths are estimated to be 3 times greater for the 12 percent steel and about 4 times greater for the HY 150 steel (table II). For 260-inch motor cases, both of the new materials have critical flaw depths greater than the required wall thicknesses. Therefore, critical sized flaws cannot be obtained and at worst the vessel will leak rather than fail catastrophically. This desirable characteristic of "leak-before-failure" has been demonstrated in both the 12 percent nickel and HY 150 materials when operating at design conditions required for 260-inch motor cases (refs. 6 and 7).

Fabrication of cases from the two new steels rather than 18 percent nickel steel should be easier and less costly for several reasons. One factor is the higher fracture toughness of these materials. Because the allowable critical flaws are so large, the effort required for weld inspection and repairs can be substantially reduced. In addition, the HY 150 material is much easier and cheaper to weld. This is a result of the fact that weld edge preparation can be done by flame cutting and a much faster welding process can be used. As can be seen in table II, there is a moderate fabrication cost reduction for the 12 percent nickel steel and a large cost reduction for the HY 150 steel. Although the HY 150 steel case would be by far the most economical to fabricate, we have not yet considered the performance and consequent cost penalty associated with the extra case weight for HY 150 steel. The impact of these performance changes on cost will be discussed later.

Case Insulation A comprehensive program (ref. 8) was initiated to develop a low cost case insulation system for large solid rocket motors. In this program, a wide range of materials was evaluated. These included trowelable, castable, and sprayable materials, as well as some which were pressure-cured with secondary bonding. Included in this evaluation were the determination of the materials thermal performance and the cost of raw materials, installation and tooling. Based on the above factors a trowelable insulation system was chosen for use in the case cylindrical section, the fore and aft domes, and the propellant boots. The trowelable insulation consisted of a PBAN-epoxy binder with Sb_2O_3 and asbestos fillers. A photograph of the troweling process made during trial installation tests is shown in figure 1. In figure 2 the completed cylindrical section test installation is shown. In the picture an insulation buildup between adjacent layers has been trimmed off. An estimate of production costs for this new insulation system indicated a 50 percent cost reduction below that for the insulation system used on the 260-inch test motors.

Nozzle Ablatives The nozzle ablative material technology programs (refs. 9 to 11) have identified some interesting materials. The ablative materials that are required for solid rocket nozzles can be divided into two groups. One group is comprised of nozzle throat region materials which are usually expensive because of the high erosion resistance required in that area. The second group contains materials that can be used in the nozzle entrance and exit-cone regions where the erosion environment is much less severe and where lower cost materials can be used effectively. Some of the more attractive new materials are shown in figure 3. The first material listed for each region was used in the 260-inch test motors and it is included for reference purposes. In the nozzle throat region, only carbon-phenolic tape materials were found to be economical because of the high erosive resistance required there. However, several different grades of the carbon-phenolic tape were found to be adequate from both a structural and a fabrication standpoint. These materials are lower cost than carbon-phenolic used in the 260-inch test motors, but they also have slightly increased erosion rates. For carbon-phenolic "B", the net affect of the lower material cost and higher erosion rate is a 15 percent reduction in material costs.

In the entrance and exit cone regions there are two materials that offer large potential cost reductions. They are the canvas-phenolic and the paper-phenolic tapes. The canvas-phenolic material cost is about 80 percent less than that of the silicon-phenolic reference material. In addition, its lower density will improve motor performance by increasing mass fraction. In summary, it appears that a substantial ablative material cost reduction, somewhat over 50 percent, can be made available by using these new low cost materials in the nozzle.

Thrust Vector Control In the thrust vector control (TVC) area, the objective was the design and selection of a reliable and economical system for use on the large solid rocket motor. The previous 260-inch test motors did not have provisions for thrust vector control. From an assessment of the wide variety of TVC systems in use and those which have experienced some development work, the flexible-seal gimballed nozzle and liquid injection thrust vector control (LITVC) systems were selected for detailed analysis and technology development work. In order to compare these two TVC systems, it was necessary to determine typical thrust vector control requirements. This was accomplished in-house at Lewis and the results of this study are reported in reference 12. A vehicle consisting of a 260-inch booster (3.4 million pounds of propellant) and an S-IVB second stage was chosen to analyze TVC requirements. A careful analysis was made of control requirements in order to keep them to a minimum and thereby simplify and reduce the costs of the TVC systems. It was found that a relatively low thrust vector deflection angle of 1.8° and deflection rate of 3 degrees/second was more than sufficient to control the vehicle.

The flexible-seal system designed to meet the previously established TVC requirements is shown in figure 4. The advantages of the flexible seal for gimballing the nozzle are simplicity, low weight and cost. The seal consists of rubber and metal rings that are secondarily-bonded together, as can be seen in the cross-section in figure 4. This construction technique is different from the molding methods typically used on smaller flexible seals. The flexible seal is designed to perform four important functions.

They are: to support the nozzle weight and axial pressure forces, to provide for pivoting the nozzle for thrust vector control, to resist gas pressure buckling loads and to prevent gas leakage. Due to the relatively low thrust vector deflection requirement, a simple conical metal ring cross-section was chosen instead of the more ideal spherical one. In addition, a cylindrical seal envelope was used because it also simplifies construction by keeping the size of all rings identical. Although a flexible seal of large size with these unique features appeared practical, it was as yet untried. A program was therefore undertaken to demonstrate that seals of this size and design can be fabricated and operated satisfactorily. A photograph of one of the two fabricated seals is shown in figure 5. A summary of the results obtained during testing of the seals is shown in table III. Both seals were successfully deflected to the design vector angle of 1.95° and both seals successfully withstood the 850 psig proof pressure. In addition, the actuation torque was adequately predicted. During overtests of one seal, it successfully withstood 3.3° vectoring and 1140 psig pressurization without failure. These results established the feasibility of designing, fabricating and operating very large flexible seals. Details of the flexible-seal design and test results can be found in reference 13.

The LITVC system was selected for consideration of use in the large solid rocket motor because of its history of successful use on a number of other solid rocket motors. The most notable example is the 120-inch solid rocket motors used on the Titan IIIC vehicle, the largest solid rocket motor in use today. One of the disadvantages of the LITVC system is its relative complexity and corresponding high cost. The LITVC system design for the 260-inch motor (ref. 14) was therefore made as simple as possible. Various tank geometries, pressurizing techniques, liquid injectants and injectant valve arrangements were studied. The best system from simplicity and cost standpoints had the features shown in figure 6. Nitrogen tetroxide was the selected injectant. Sixteen injectant valves were needed to provide the required thrust vector deflection. The injectant valves were uprated versions of those used in the 120-inch Titan solid rocket motor in order to reduce development costs.

Detail design and cost information for the two TVC systems previously described can be found in reference 14. A summary of this information is shown in table IV. It can be seen that the inert weight of the LITVC system is about 3 times that of the flexible-seal system. The additional weight of the LITVC will result in a cost penalty due to the reduced vehicle performance. Considering the total cost for design, development and production of 30 units, the liquid injection system cost was found to be 81 percent greater than that for the flexible-seal system. The cost penalty associated with the additonal inert weight of the LITVC system was estimated to be 153 percent of the flexible-seal system costs. To estimate this cost penalty, the increase in motor size required to compensate for the higher liquid-injection system weight was determined, so that payload capability would be equal to that for a motor with a flexible-seal system. Credit was given to the LITVC system for the added impulse derived from the liquid injection. The additional motor size was then converted to a dollar value by using an average cost per pound of motor. The total cost of the liquid-injection system including direct costs and those due to performance penalties (table IV) is over 3 times that of the flexible-seal system.

In summary, the flexible-seal TVC system appears to be the best choice for large solid rocket motors because of its significantly lower cost and simplicity. Supporting this conclusion is the recent successful demonstration of the capability to fabricate and operate full scale seals.

DESIGN AND COST OF ADVANCED SOLID ROCKET BOOSTER

In the previous discussion several new technologies with the potential for reducing the cost of large solid rocket motors were reviewed. The purpose of this part of the discussion is to present representative motor designs that incorporate these new technology elements, and to estimate the resulting total cost advantage.

In figure 7, the features of a low cost 260-inch solid rocket motor design are presented. This particular solid rocket design was made for a propellant weight of 3.4 million pounds. Using an SIVB second stage, the combination will deliver a 99,500 pound payload into a 100 nautical mile orbit. The design includes the new technology in all of the component areas previously discussed. In addition, it features a grain design with the highly configurated section, which increases the initial propellant burning surface, at the aft end of the motor for easier processing. The grain was designed with a regressive motor thrust after approximately 40 seconds in order to prevent the vehicle dynamic pressure from exceeding a 950 lb/ft^2 limit. A second regressive portion of the motor thrust was provided to limit vehicle acceleration. A bell nozzle geometry was employed because it provides some improvement in thrust coefficient and weighs less than a comparable conical nozzle. The aft skirt design shown is similar to the one developed in reference 25. A tabulation of the motor weights for the design shown is presented in table V.

The reduction in motor cost that can be expected for advanced motor designs, one using a HY 150 and the other a 12 percent nickel case material, is shown in table VI. The costs are expressed as a percentage of the cost of a reference motor designed using the 260-inch test motor technology base. The design and cost of the reference motor were obtained in reference 25. The motor which contains the HY 150 steel is seen to have the lowest cost; about 65 percent of the cost of the reference motor cost. The largest cost reduction, about 17 percent, results from the use of the HY 150 material in the case. A large reduction is also obtained in the nozzle shell and thrust vector control area. The nozzle shell in both advanced motors also was designed to use HY 150 steel and it accounts for about 1/3 of the reduction shown for the nozzle shell and TVC combination. Additional cost reductions are noted in the nozzle ablative, case insulation and propellant material areas. Due to the higher fabrication cost of the 12 percent nickel case material, the cost reduction for this design is only 2/3 of that for the HY 150 case material.

The cost figures shown in table VI were derived for equal size motors containing 3.4M pounds of propellant. However, because of changes in component weights and propellant specific impulse the advanced motor designs have different performance and consequently different payload capabilities than the reference motor design. A more equitable comparison would be made on an equal performance or payload basis, however, this requires mating the solid booster to a specific launch vehicle. To make this comparison, the previously mentioned vehicle consisting of a 260-inch booster and an SIVB second stage was utilized. Payload performance was computed for the three motor designs over a range of booster propellant weight as shown in figure 8. Then, a payload of 103,500 pounds was selected for the cost comparison. This results in propellant weights of 3.72 and 3.25 million pounds for the motors with the HY 150 and 12 percent nickel cases, respectively and 3.4 million pounds for the reference motor design. The motor costs for the HY 150 and the 12 percent nickel case designs were then corrected to the new sizes by using an average cost per pound of motor. The result of the equal performance comparison is shown in table VII It can be seen that the difference between the motors designed with HY 150 and 12 percent nickel steel cases has been decreased, but there is still a slight advantage for the HY 150 steel. It is therefore apparent that the increase in motor size and cost associated with the extra case weight required when the case is made of HY 150 steel is more than offset by its lower fabrication cost. The cost reduction in an equal-performance comparison to the reference motor is 30 percent for the advanced technology motor with the HY 150 case. In absolute terms this amounts to a savings of $2.3 million per motor.

It should be noted that the cost advantage associated with the HY 150 steel is a function of the vehicle under consideration and more specifically the ΔV delivered by the solid rocket booster. In the case of the 260-SIVB vehicle used in the previous example the booster ideal ΔV of 14,000 ft/sec is relatively high. However, in applications where the ΔV may be even higher the cost advantage of the HY 150 would diminish as a result of the increased sensitivity to booster performance. Eventually, if the ΔV were high enough it may be more cost effective to use the 12 percent nickel steel or even the 18 percent nickel steel, however, the probability of this occurring is slight. Conversely, as the booster ΔV decreases below the 14,000 ft/sec the cost advantage of the HY 150 steel improves due to a reduction in vehicle sensitivity to booster performance.

CONCLUSIONS

A systematic investigation of solid rocket motor components has been conducted with the objective of reducing costs and maintaining or improving reliability. The results of this program indicate that new technology can reduce motor costs on a common performance basis by as much as 30 percent. This is a significant achievement; large solid rocket motors that were previously estimated to cost about $1.73 per pound can now cost $1.21 per pound. Although further cost reductions can be made, for example in the nozzle ablatives area, additional returns would be nominal. The technology required to develop and use these low-cost components in solid motors appears to be well in hand. Thus, the economy and reliability of such motors makes them attractive candidates for future expendable booster applications.

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Table I. HTPB Binder and Propellant Characteristics

	PBAN propellant for third 260 motor	HTPB propellant
Binder cost, \$/lb	1.20	0.45
Propellant viscosity K poise at 5000 d/cm^2	42	15-20
Mechanical properties		
Max stress, psi	100	102
Max strain, percent	25	37
Specific impulse at standard conditions, lb sec/lb	244	246

Table II. Comparison of 260-inch Motor Case Materials

	18 percent Ni* 200 grade maraging	12 percent Ni 180 grade maraging	HY 150
Properties			
Yield strength, psi	190 000	180 000	140 000
Fracture toughness, ksi$\sqrt{\text{in.}}$	100-130	180-250	200-300
Critical flaw depth, in.	0.279	0.736	1.22
Fabrication			
Weld edge prep	Machined	Machined	Flame cut
Welding	Slow	Slow	Fast
Inspection	Thorough	Moderate	Moderate
Weld repairs	Substantial	Minor	Minor
Fabrication cost			
Total/lb	\$10	\$8-9	\$2-4

*Used in 260 inch test motors.

Table III. Large Flexible Seal Test Program Results

	Requirement	Attained	Overtest
Vector angle, degrees	1.95	1.95 (both seals)	3.3 (seal #2) (no failure)
Proof pressure psig	850	850 (both seals)	1140 (seal #2) (no failure)
Actuation torque, at 1.95°, 10^6 in.×lb	5.0 w/o boot (predicted)	4.98 w/o boot 5.6 w boot	

Table IV. Comparison of TVC Systems For a 260-inch Solid Motor Booster

	Flexible seal	Liquid injection
System inert weight, lb	5198	16 333
	Cost, percent	
Design, development, and production of 30 units	100	181
Additional motor cost due to performance penalty	0	153
Total	100	334

Table V. Weight of Advanced 260-inch Motor Design

Motor	
Case (HY 150)	258,380
Insulation and liner	40,628
Nozzle	
Steel structure	14,877
Insulation	2,474
Ablatives	8,225
Overwrap	702
Nozzle exit cone	
Attach ring	634
Fiberglass structure	8,471
Ablatives	14,472
Propellant	3,447,743
TVC	
Flexible seal	4,366
Actuation system	891
Ignitor	
Structure	1,725
Propellant	275
Structure	
Aft skirt	6,901
Base heat shield	2,933
Other	761
Roll control system	3,318
Separation system	3,662
Instrumenation and electrical systems	2,104
	Total 3,823,542 pounds

Table VI. Effect of Advanced Technology on 260-inch Motor Cost

	Cost, percent		
	260-in. test motor tech (reference)	Advanced tech	
		HY 150 case	12-Ni case
Case	30.3	13.4	26.2
Nozzle shell and TVC	18.1	7.7	7.7
Nozzle ablatives and exit cone	15.0	10.0	10.0
Insulation	3.5	3.3	3.3
Propellant materials and processing	25.6	22.2	22.2
Igniter	.4	.4	.4
Miscellaneous	7.1	7.7	7.7
Total	100.0	64.7	77.5

Table VII. Effect of Advanced Technology on 260-inch Motor Cost

	Cost, percent		
	260-in. test motor tech (reference)	Advanced tech	
		HY 150 case	12-Ni case
Cost for equal size motors	100.0	64.7	77.5
Cost for equal payload capability	100.0	69.4	72.5

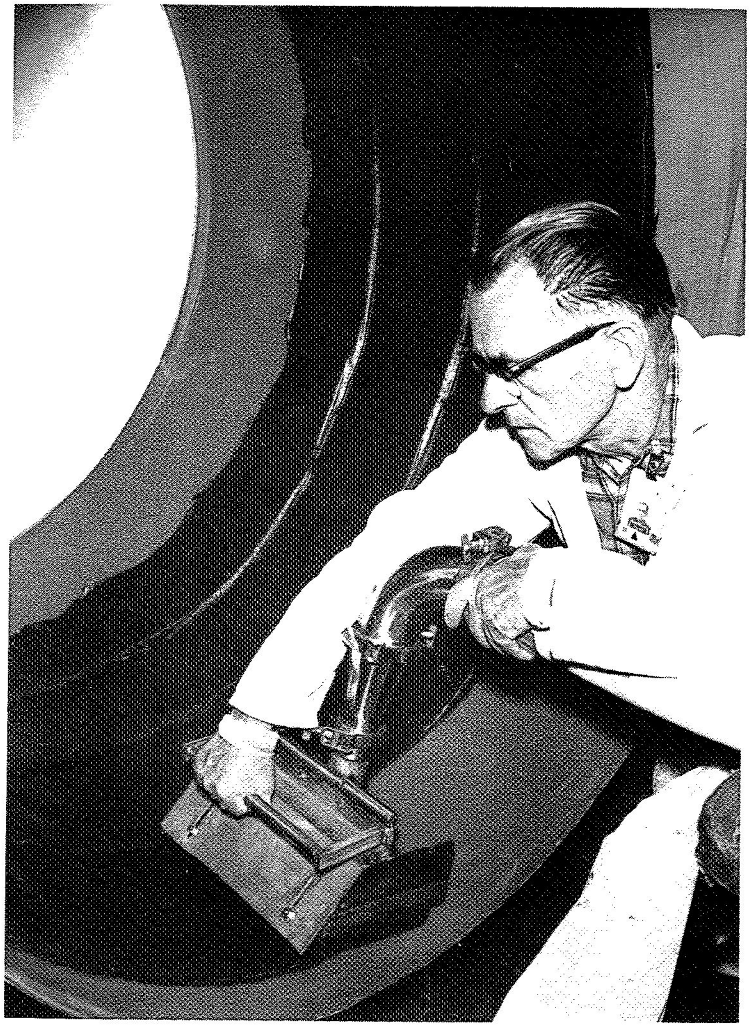
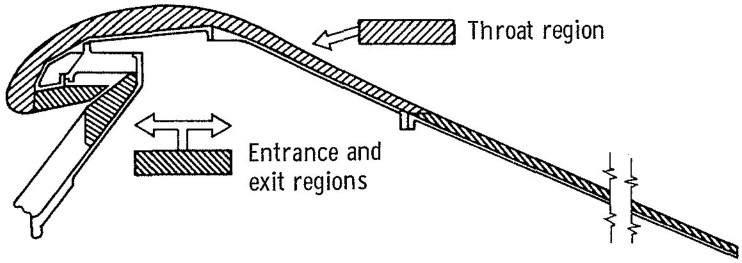


Figure 1. - Installation of IBT-106 sidewall insulation.

Figure 2. - Completed IBT-106 sidewall insulation demonstration.



LOCATION	MATERIAL	MATERIAL COST, $/LB
THROAT REGION	CARBON-PHENOLIC*	24
	CARBON-PHENOLIC "A"	20
	CARBON-PHENOLIC "B"	17
ENTRANCE AND EXIT REGIONS	SILICA-PHENOLIC*	7
	SILICA-EPOXY NOVALAC	6.3
	PAPER-PHENOLIC	2.3
	CANVAS-PHENOLIC	1.5

*260-IN. TEST MOTOR TECHNOLOGY.

Figure 3. - Nozzle ablative technology.

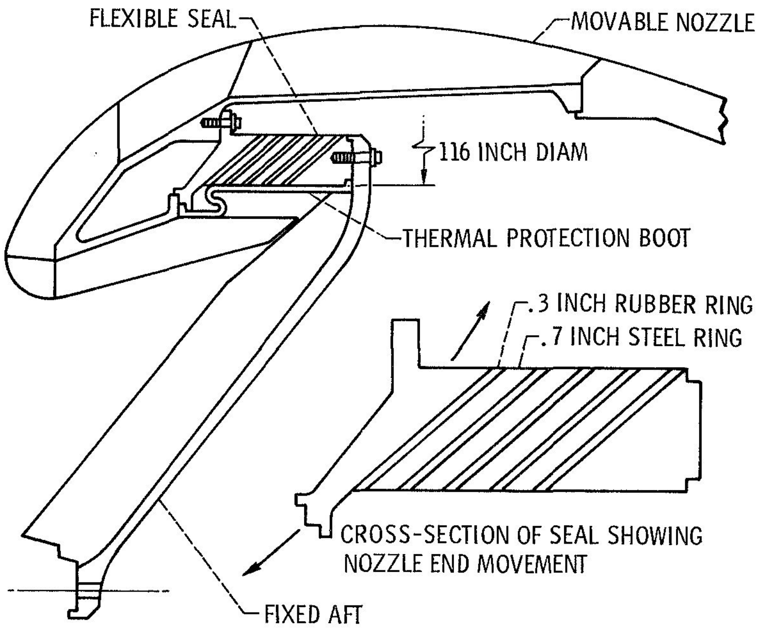


Figure 4. - Flexible seal details for 260-inch motor design.

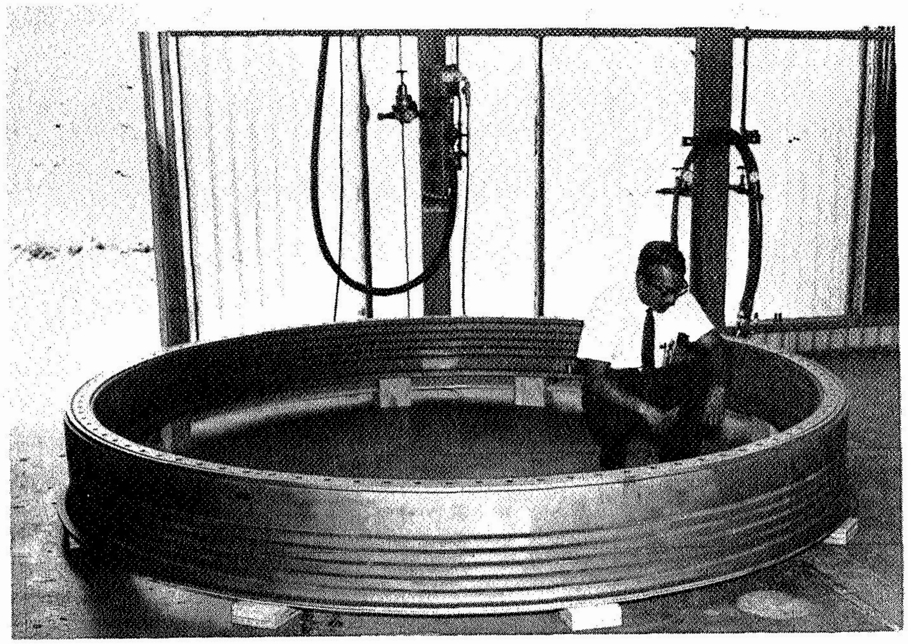


Figure 5. - First large solid motor flexible seal assembly. CS-55864

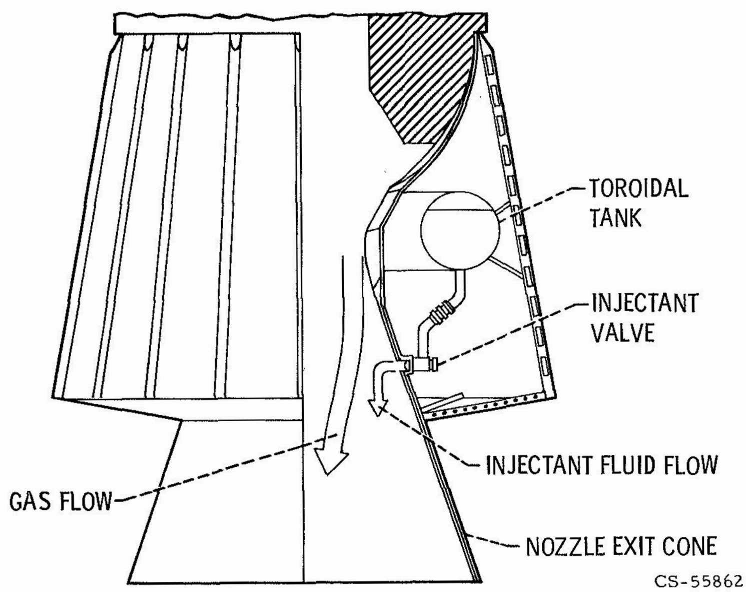


Figure 6. - Typical liquid injection thrust vector control system.

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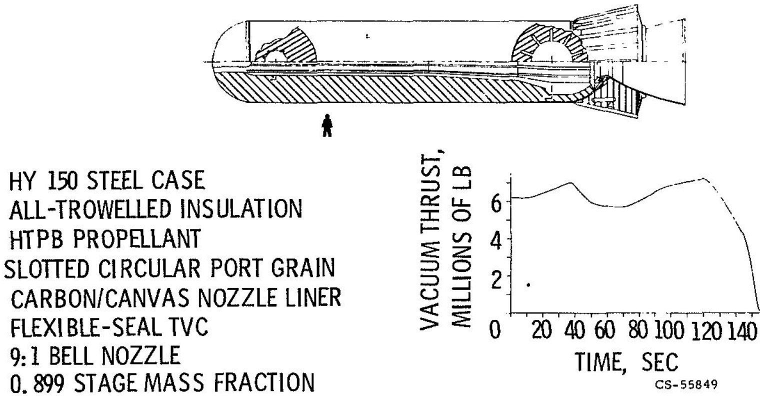

Figure 7. - Low cost 260-inch solid motor design.

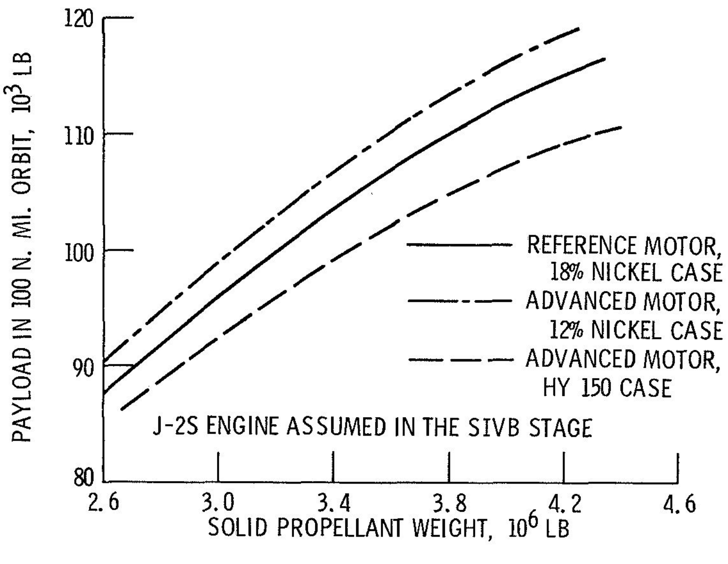

Figure 8. - Performance of vehicle with 260 inch booster-SIVB second stage.