Cost and Performance Considerations in the Selection of Structural Materials for Ultra-Large-Size Booster Motors

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Preliminary design requirements were established for the fabrication of a unitized, 260-in.-diam solid-rocket motor to propel a payload of 1 × 10⁶ lb to a terminal velocity of 6500 fps. Performance and relative costs were determined for motors constructed of a variety of structural steels. Two primary fabrication methods were considered: one approach is based on no requirement for heat treatment other than simple aging, whereas the other is based on the assembly of previously heat-treated subassemblies. Structural materials and chamber pressures were evaluated to arrive at minimum-cost and minimum-weight vehicles for the required mission. It was found from the analysis that large differences in motor costs result from the use of different structural materials for chamber fabrication. On the other hand, there is a relatively small difference in cost regardless of whether the motor was designed for minimum cost or minimum weight. This is because, for a given structural material, there is only a small difference in the chamber pressure producing minimum cost and minimum weight, and cost is relatively insensitive to chamber pressure near the optimum value. Significant increases in cost can result from the use of chamber pressure far from that producing minimum cost.

Introduction

PROPULSION cost considerations are becoming more important as the number and size of payloads increase. Previous efforts at weight optimization for launching systems have often resulted in the choice of liquid rockets, whereas cost optimization could well lead to increased use of solid rockets. Missile launch weights for Saturn- and Nova-class vehicles may be as high as 15×10^6 lb, with a very large portion of this launch weight allocated to the first-stage booster. The objective of this paper is to present an analytic procedure for selecting solid-rocket-booster structural materials to produce a minimum-cost, first-stage motor.

Basic missile requirements have already been established for many future space missions, and some engines and many components are being developed now. Because of these constraints, the approximate energy requirements (velocity gain) of the first stage are established; cost optimization based on vehicle staging is thus precluded and is relegated to a study of material selection. Answers are needed to many questions such as "Is it better to use a low-cost, low-strength, structural material or a high-cost, high-strength, structural material for the pressure vessel?" Another problem results because the strengths of some materials vary significantly with thickness. For instance, heat-treated AISI 4130 steel has a yield strength of about 160 ksi‡ when used in a 0.2-in.-thick section; yet this same material has a yield strength of only about 60 ksi when used in a pressure vessel that is 1.44 in. thick, as a result of nonuniform heat-treat response. Plate thickness required for pressure vessels varies directly with design pressure and inversely with design strength. Chamber pressure, then, directly influences the vehicle trajectory and ballistic performance as well as the thickness of the pressure-vessel material. Table 1 is a tabulation of over-all "ground rules" for cost analysis on the basis of chamber pressures selected to be consistent with space-system requirements.

In the following analyses, a single unitized booster with a booster payload§ of 1×10^6 lb and a launch weight of almost 4×10^6 lb was studied. For more ambitious space missions, clustered boosters would be required; for instance, four 260-in.-diam motors would be used in a cluster to carry a booster payload of 4×10^6 lb. Because the thrust-to-weight ratios and velocity gains remain unchanged, the analysis of a single-motor system is applicable to clustered systems. Aerodynamic drag for very large, earth-escape missions is on the order of 0.25% of the total propulsion energy, and so aerodynamic drag does not enter significantly into the cost-optimization analyses.

The major items that must be established for consideration of cost and performance in the selection of structural materials for ultra-large-size booster motors are 1) mechanical properties for materials fabricated in various thicknesses, 2) accurate material and fabrication costs for completed pressure vessels, and 3) a mathematical model that can be used to evaluate relative merits of alternative structural materials.

Pressure-Vessel Fabrication Costs

The intent of this paper is not to derive actual costs but to develop a uniform method of comparing costs by the same yardstick for aspects considered. To accomplish this, planning sheets for essential steps in fabrication were developed for all materials and pressures investigated. These planning sheets do not completely define the fabrication effort required and do not take into account such possibilities as repairs, time in transit, and dead time.

Material thicknesses and quantities were determined by design studies for the various very large, solid-rocket boosters considered, and possible materials and approach for fabrication were selected. Fabrication cost data used in this analysis covered the manufacture of inert metal parts for chamber assemblies, including forward and aft heads, barrel sections, skirts, and attachment bosses, but excluding nozzle assemblies. Tooling and facility costs were not amortized into the fabrication costs, but these costs would be similar among all homogeneous structural materials considered. Because of the

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‡ Throughout this paper, yield strengths are stated at 0.2% offset.

§ "Booster payload" is defined as all mass forward of the booster stage and includes useful payload as well as additional propulsion.

Table 1 Basic requirements for space-vehicle booster motor

Booster payload, lb[a]	1×10^6
Booster velocity gain, fps	6500
Booster burnout angle with vertical, deg	60
Thrust-vector control method	Fluid injection
Booster diameter, in.	260
Web burning time, sec[b]	120
Structural-materials yield strength, ksi[c]	75 to 300
Chamber pressure, psia	250 to 700

[a] Payload is defined as all mass forward of the booster stage and includes useful payload as well as additional propulsion.
[b] The long burning time is required from aerodynamic considerations.
[c] 0.2% offset.

limiting nature of the cost assumptions, all values are presented as relative costs, using 1×10^6 dollars as the base.

Design Analysis

Because a study of this type requires detailed design data for 50 to 75 solid-rocket boosters, a method of designing by use of a computer was used in the analyses. One layout drawing was made of a typical motor design near the expected size, and this motor was given detailed stress and heat-transfer analyses. Weight-scaling equations[1] were used in conjunction with the layout drawing to obtain weight coefficients. Motor requirements were computed (by machine) for various structural materials and operating pressures. Iterations on booster size were performed until each design was capable of imparting a burnout velocity of 6500 fps to the assumed 1×10^6-lb payload. Trajectory evaluations were made in which drag and gravity losses were considered. Thus, the dimensions and weight of structural materials for pressure vessels and the weights for the nozzle, insulation, propellant, and miscellaneous items were determined.

Materials and Heat Treatment

Three basic classes of structural material were considered in this analysis: 1) maraging steels, 2) direct-quench-and-temper steels, and 3) mill-hardened plate.

With the maraging steels (18% Ni, 7% Co), maximum strength and toughness can be obtained with simple low-temperature aging cycles for which ample heat-treat facilities exist. An advantage of using this material is the elimination or minimization of warpage during heat treatment, thus removing the need for complicated preparation of fixtures to ensure dimensional stability. Of equal importance is the ease of making repair welds. The primary objection to maraging steels is their relative newness as prospective materials for rockets.

Heat-treat costs per chamber for the maraging steels would approximate a fixed cost of $75,000 for the first chamber and $5000 for each chamber thereafter (cost assumed for this study).

M-255 (AMS 6434/AGC M-255) or D6aC steels have been successfully used for some time in the production of high-strength, light-weight motor cases. With these steels, a controlled-atmosphere furnace and extensive quench facilities must be used, which would cost approximately 3×10^6 dollars (ROM) and would have to be amortized against 40 typical five-unit motor assemblies to achieve the cost of $15,000 per heat-treated component, as used in this analysis.

For the mill-hardened material, no heat-treat facilities are required. If desired, welds can be reinforced by skin-milling or chemical milling at a cost of about 2 dollars/lb of metal removed. For instance, if a final wall thickness of 0.60 in. and a 20% weld reinforcement factor are required, the starting thickness of the material would be 0.75 in. Removing this material would cost approximately $18,000 per chamber unit, or $90,000 for a typical five-unit chamber.

Fabrication Approach

Two primary fabrication plans were considered (Fig. 1). Approach A was based on no requirement for heat treatment other than simple aging treatments, and approach B was based on the assembly of previously heat-treated subassemblies.

For Approach A rolled-and-welded construction was considered for the center barrel sections. Domes were fabricated by "orange-peel" construction, in which gores formed from plate stock were joined to a conventionally spun cap. The spun cap and aft-dome nozzle-attachment ring were of the same size in order to make the gore sections interchangeable and thus minimize tooling and fabrication costs. Skirts were scalloped and were welded directly to the head. The maraging steels and M-255 (at 150-ksi yield strength), HY 80, HY 150, and AISI 4130 steels were considered.

Approach B was identical to approach A except that all heat-treated subassemblies included rolled-and-welded reinforcement rings to permit joining after heat treatment. M-255 steel at 180-ksi yield strength was considered for this approach. In motors for the specific chamber pressures considered in this paper, center cylindrical sections were added, and the length of the short cylinder was varied in connection with the forward and aft heads as shown in Table 2.

Cost Analysis

Price quotations (FOB the mill) were obtained from the various steel companies that melt and process the selected materials. The main requirement placed on these companies was ability to roll plate to a trimmed width and length of 120×420 in. Based on an analysis of these quotations, a schedule of plate prices as shown in Table 2 was established for use in calculations involving chamber costs. A cylinder-assembly multiple of 240 in. (which included a reinforcement ring in approach B) was selected. The total cylinder length was divided by this unit length to determine the number of center barrel assemblies. The excess length was divided equally between the forward-head and aft-head assemblies. Motor configurations were analyzed for the most economical

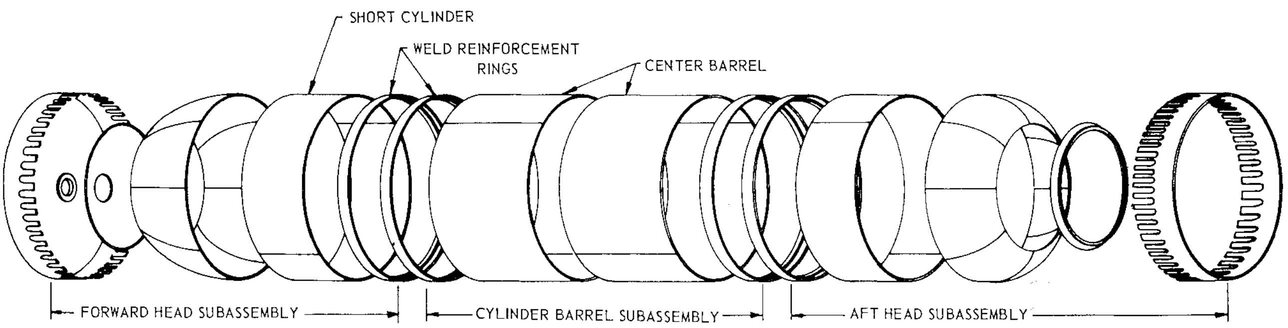

Fig. 1. Fabrication approaches. For Approach A, when no heat treatment is required, the weld reinforcement rings are omitted; for Approach B, subassemblies are heat treated as units, and the weld reinforcement rings are used.

Table 2 Summarized design data, weights, and cost for chamber fabrication

Alloy	Price used in cost analysis, \$/lb	Relative total chamber cost, \$ millions	Relative chamber cost/lb, \$/lb	Yield strength, ksi[a]	Design pressure, psia	Cylinder length, in. (equator to equator)	Short-cylinder length, in.	Number of center segments	Total pressure vessel wt., thousands lb
18% nickel	1.54	2.65	4.12	300	375	1375	87	5	57
18% nickel	1.54	2.96	3.36	300	750	863	71	3	81
18% nickel	1.54	3.50	3.11	300	1050	770	25	3	105
18% nickel	1.54	3.59	3.58	200	375	1451	125	5	89
18% nickel	1.54	4.10	2.97	200	750	917	98	3	127
18% nickel	1.54	5.04	2.85	200	1050	831	55	3	166
M-255	0.45	4.21	3.73	180	375	1478	19	6	101
M-255	0.45	3.71	2.39	180	750	937	108	3	143
M-255	0.45	4.28	2.14	180	1050	853	66	3	188
M-255	0.45	2.92	2.09	150	375	1538	49	6	125
M-255	0.45	3.28	1.71	150	750	978	9	4	177
M-255	0.45	3.73	1.49	150	1050	900	90	3	234
HY 150	0.32	3.01	1.90	135	375	1581	70	6	142
HY 150	0.32	3.44	1.58	135	750	1007	23	4	201
HY 150	0.32	3.94	1.38	135	1050	933	106	3	267
HY 80	0.30	4.94	1.39	75	375	2103	91	8	325
HY 80	0.30	5.72	1.20	75	750	1322	61	5	446
HY 80	0.30	7.11	0.94	75	1050	1319	59	5	627
AISI 4130	0.13	3.28	2.22	143	375	1557	58	6	132
AISI 4130	0.13	3.23	2.00	137	450	1320	178	5	145
AISI 4130	0.13	3.38	1.94	133	500	1231	15	5	157
AISI 4130	0.13	4.96	1.45	82	563	1379	89	5	315
AISI 4130	0.13	7.65	1.21	60	675	1639	99	6	597
AISI 4130	0.13	8.34	1.20	60	750	1619	89	6	657
AISI 4130	0.13	9.53	1.13	60	900	1649	104	6	803

[a] 0.2% offset.

method of building subassemblies with the plate size quoted from the mill. Flow charts of the assembly sequence and manufacturing operation sheets for the operation sequence, set-up time, run time, and total hours per part were developed. Manufacturing hours were assumed to be charged at \$30/hr, and material costs were increased by 5% to cover costs of scrap. Comparisons of relative chamber costs are summarized in Table 2.

Relative fabrication production costs for the pressure vessels of the various motor configurations considered are plotted in Fig. 2. Curves were drawn showing variance in fabrication costs as a function of yield strength and pressure for fabrication approach A. Fabrication approach B is represented in Fig. 2 by discrete points. The break in the curves at 200 ksi represents the difference in the material cost of high-nickel-content steel, as compared with the cost of mill-hardened plate.

Calculation of relative production costs without considering material costs produces curves of the shape shown in Fig. 3. These curves represent the variance of fabrication costs as a function of material thickness for 260-in.-diam motors of constant mission. The plotted curves represent manufacturing costs for approach A, which is fabrication with mill-hardened plate or with maraged steels. The discrete points represent costs for approach B, which is accomplished with the direct-quench-and-temper steels. None of the plotted costs include heat treatment.

The significance of the fabrication-cost data presented in this paper is that, for the mission considered in this paper, it should be possible to calculate quickly relative chamber-fabrication costs for the first stage, for any combination of chamber pressure and material yield strength. Relative manufacturing costs are obtained from plotted data in Fig. 3; chamber weight is obtained from Table 2; the appropriate material is selected; and manufacturing costs, raw-material costs, and heat-treat costs are added to arrive at the required cost figure.

The analysis presented in this paper represents approximate first-article cost and contains allowances only for shop engineering and project support.

Mathematical Model

Once the structural materials of interest have been selected and their cost in a fabricated chamber determined, it remains to establish a mathematical model for evaluating the minimum-cost and minimum-weight motors. In establishing a mathematical model to evaluate the relative merits of using alternative structural materials for large solid-rocket boosters, it is necessary that 1) each booster considered be capable of achieving the desired velocity gain, 2) each structural material be considered in terms of its most favorable environment, and 3) a method be available for combining cost, performance, design, and mechanical properties into an evaluation analysis.

The requirement of item 1 was satisfied when trajectory evaluations were made on the computer for each design of a solid-rocket booster. The requirement of item 2 was satisfied by considering values of chamber pressure of interest for each structural material investigated. The approach used to satisfy item 3 is described in the following text.

When an attempt is made to select the "best" structural material for a fixed booster application, the question arises as to what motor-operating conditions to use for the evaluations. For instance, the best chamber pressure for use with one structural material is not the best to use with another material. To represent each structural material in its most favorable design environment, chamber pressures were studied in relation to each structural material considered.

In general, as chamber pressure is increased, greater nozzle performance is obtained because of a more favorable pressure ratio (ratio of chamber pressure to atmospheric pressure). Nozzle throat size is smaller, and, consequently, nozzle weight is reduced. Insulation thickness increases, and the weight of the pressure vessel increases. The increase in pressure-vessel

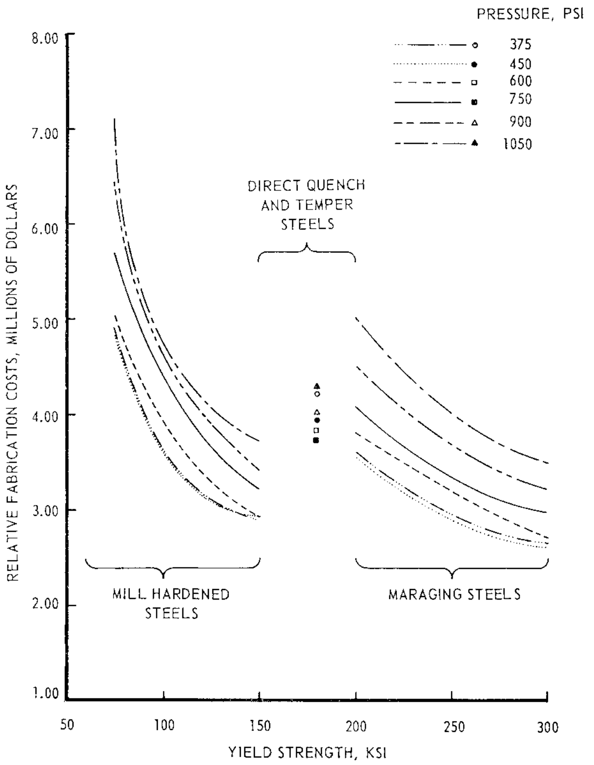

Fig. 2 Relative fabrication costs vs yield strength.

weight is a result of increased wall thickness, which is due to a higher design pressure and possibly to a strength reduction for some heat-treated steels. If the net result is an increase in total inert weight (decrease in propellant mass fraction), additional propellant may be necessary to allow for the increase in inert weight in maintaining the velocity required for the mission. The increase in nozzle efficiency will reduce the amount of added propellant necessary to achieve the desired burnout velocity.

Cost and Performance Analysis

The first step in the cost and performance analysis is to obtain motor designs at various chamber pressures for each structural material under consideration. The design assumptions are listed in Tables 1 and 3. Material strength for each thickness (chamber pressure) is obtained by using Table 2. Typical weights of motor components for the design analysis are shown in Fig. 4 for high-nickel steel at a strength level of 200 ksi; this figure shows how total motor weight and the weight of each component (such as nozzles and pressure vessel)

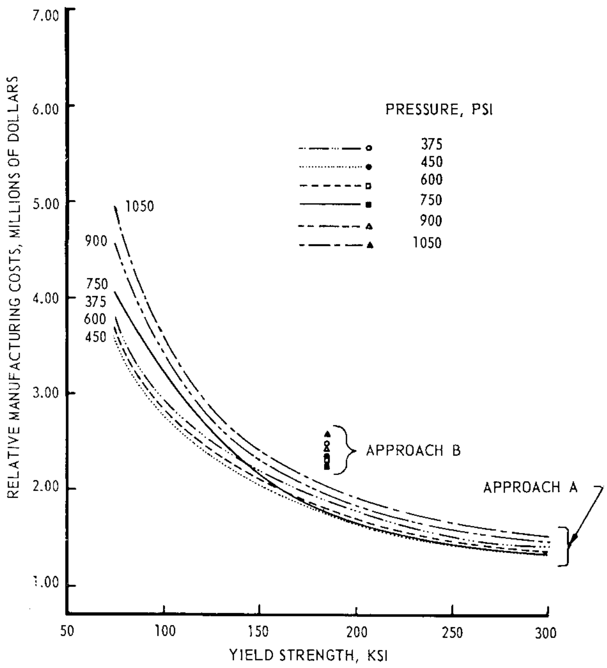

Fig. 3 Relative manufacturing costs vs yield strength.

Table 3 Design assumptions

Propellant specific impulse, lbf-sec/lbm[a]	246.5
Propellant density, lbm/in.^{3}	0.063
Propellant mass-flow coefficient, lbm/lbf-sec	0.00635
Average propellant port-to-throat area ratio	1.3
Specific-heat ratio, γ	1.2
Pressure-time curve: neutral burning; 6-sec tailoff	
Nozzle half angle, deg	17.5
Design pressure/operating pressure[b]	1.5
Interstage-structure weight, lbm	15,000
Fluid-injection TVC system weight, lbm	36,000
Fluid injectant used, lbm	25,000

Nozzle expansion-ratios[c]		Estimated component costs	
Nozzle expansion ratio	Chamber pressure, psia	Item	Cost, $/lb
5.0	250	Propellant	0.95
5.5	300	Nozzle	20.0
6.5	400	Insulation	10.0
7.5	500	Miscellaneous	20.0
8.5	600		
9.5	700		
10.5	800		

[a] Based on a chamber pressure of 1000 psia at sea level; optimum expansion of a conical nozzle with a 15° half angle.
[b] This factor includes the factor of safety as well as an adjustment to account for peak pressure due to burning rate and temperature variations.
[c] Based on near-optimum values from similar studies.

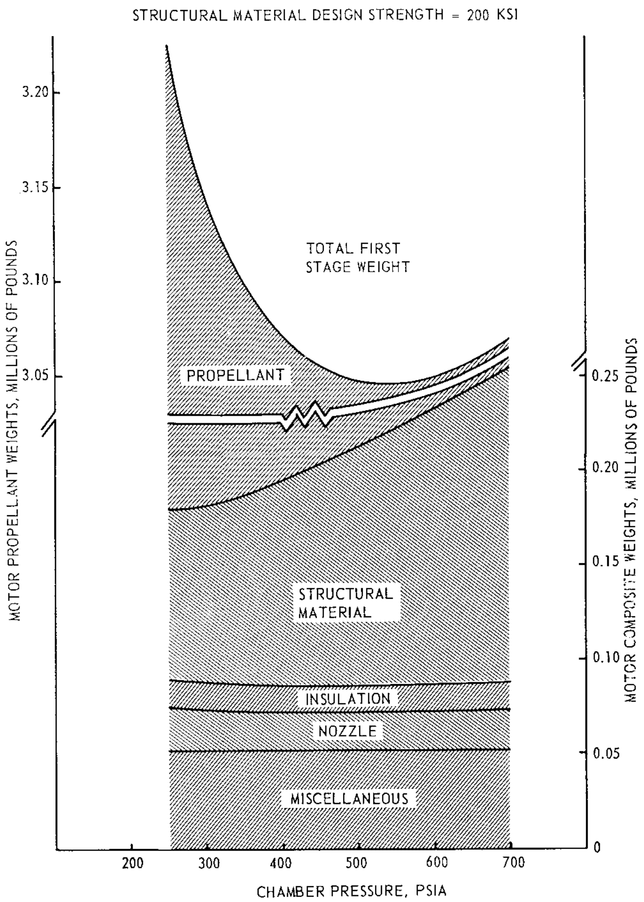

Fig. 4 Motor composite weights vs chamber pressure.

vary with operating chamber pressure for booster designs in which a 6500-fps burnout velocity is given to a 1×10^6-lb payload.

The next step in the procedure is to cost these motor designs individually for 200-ksi, high-nickel-steel structural material and to establish a curve for total relative cost vs chamber pressure. The results, showing relative component cost as well as total cost, are presented in Fig. 5. The pressure-vessel structural costs were obtained with the use of Table 2, whereas the other component costs are shown in Table 3. The costs shown in Table 3 are based on a previous paper presented at an ARS meeting and do not necessarily represent the current cost of these items.[2]

For comparison, the curve for total launch weight and the curve for total relative cost vs chamber pressure were plotted on the same graph (Fig. 6). It is interesting to note that chamber pressure for the minimum-cost motor is lower than it is for the minimum-weight motor; use of chamber pressures slightly below those associated with minimum weight results in only a slight increase in total motor weight, but the distribution between propellant mass and inert mass has shifted, resulting in a higher proportion of propellant mass than in the minimum-weight motor. As there is now an increase in propellant weight, which is low-cost, and a decrease in relatively high-cost inert weight at a near-constant total weight, total cost is decreased.

The emphasis in these analyses for minimum weight and minimum cost was primarily on unitized construction rather than segmented construction of boosters. One of the primary advantages of segmented construction is mobility; the individual segments of the 260-in.-diam motor, however, would be so large that the benefit of mobility would be lost. For academic interest, however, a motor having four central segments (five joints) was designed to be fabricated of 200-ksi, high-nickel material and was evaluated through the trajectory with the computer results presented in Fig. 6; optimum chamber pressure for minimum-weight boosters occurred at a value approximately 100 psia lower for a segmented motor than it did for a unitized motor.

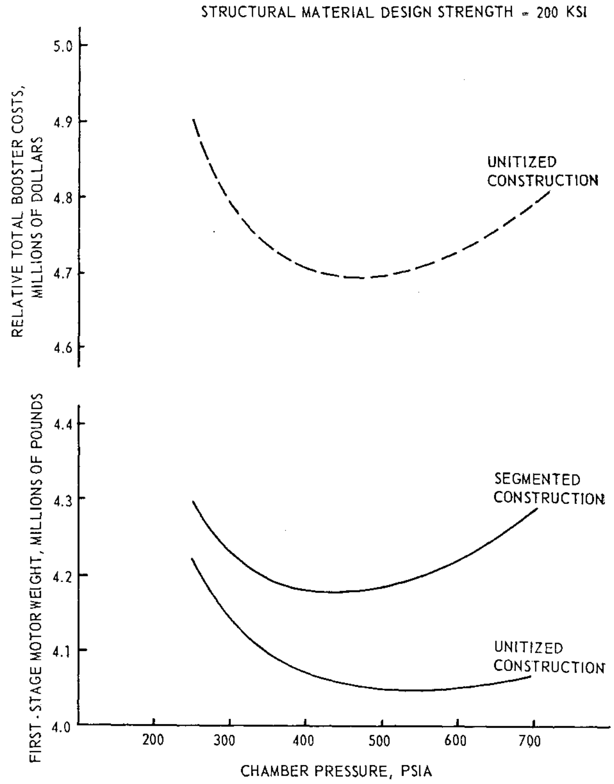

Fig. 6 First-stage motor weight and relative booster cost vs chamber pressure.

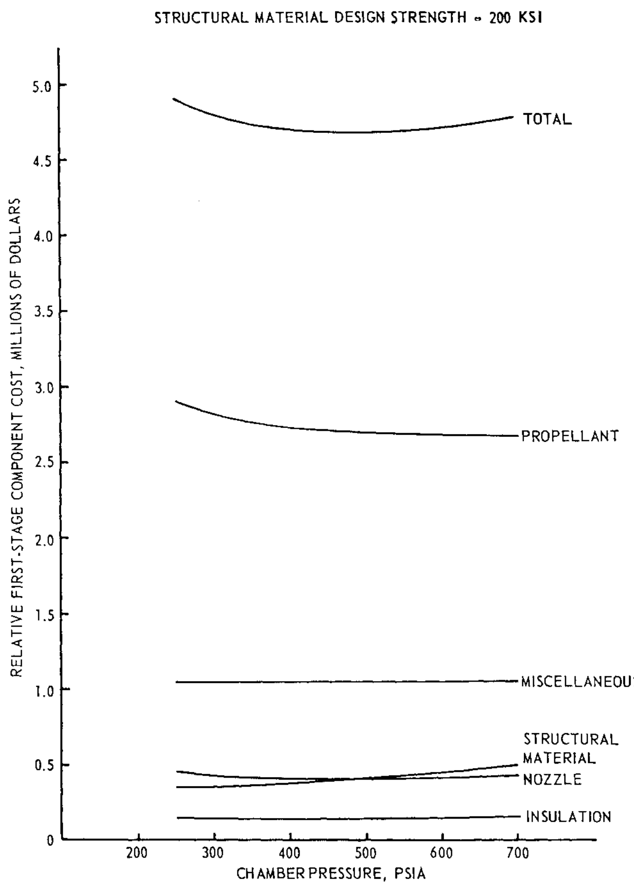

Fig. 5 Relative first-stage component cost vs chamber pressure.

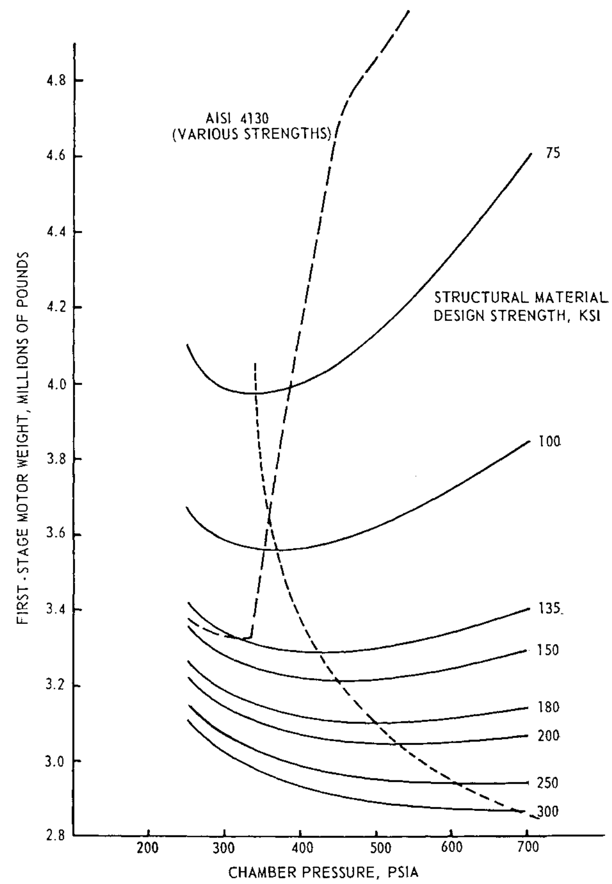

Fig. 7 First-stage motor weight vs chamber pressure for various structural-material design strengths.

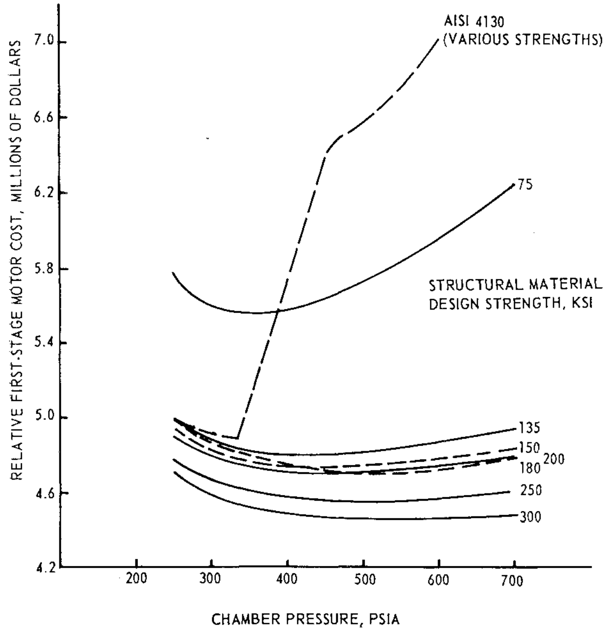

Fig. 8 Relative first-stage motor cost vs chamber pressure; first production unit.

Table 4 Optimum chamber pressure for prospective structural materials: minimum weight and cost

Material	Yield strength, ksi[a]	Booster weight, 10^6 lbm	Chamber pressure, psia[b]	Relative total cost[b]
18% nickel	300	2.88	530	4.46
		(2.87)	(690)	(4.48)
	200	3.05	470	4.70
		(3.05)	(530)	(4.71)
M-255	180	3.10	500	4.70
		(3.10)	(500)	(4.70)
	150	3.22	410	4.73
		(3.21)	(450)	(4.74)
HY 150	135	3.29	400	4.81
		(3.29)	(425)	(4.82)
AISI 4130	(variable)	3.33	330	4.89
		(3.33)	(330)	(4.89)
HY 80	75	3.97	350	5.56
		(3.97)	(340)	(5.56)

[a] 0.2% offset.
[b] Numbers in parentheses are the corresponding values for the minimum-weight systems.

Calculations were made on the bases of minimum weight and minimum relative cost for each prospective structural material. The results shown in Fig. 7 indicate the total booster weight vs operating pressure for motor designs to satisfy the mission requirements. It can be seen from the curves in Fig. 7 that the optimum chamber pressure for minimum-weight motors increased as design strength increased. Approximate costs were individually determined for each of the motors studied; these costs are shown in Fig. 8, where total relative booster cost was plotted as a function of chamber pressure for each of the various structural materials. Each motor "designed" with the digital-computer program was capable of imparting a burnout velocity of 6500 fps to a 1×10^6-lb payload. Pertinent data from Figs. 7 and 8 for the minimum-weight and minimum-cost motors are presented in Table 4. The final column of Table 4 indicates the total relative motor costs for using the various structural materials. The lowest-total-cost motors would result from using alloys with higher strength and high costs for structural materials. Use of low-strength, low-structural-cost materials results in increased total motor cost, because a much larger booster would be required to perform the desired mission. Chamber pressure required for minimum-cost boosters would be lower than the pressure required for minimum-weight boosters, when high-strength structural materials are used. When the low-strength steels are used, the chamber pressure that produces minimum cost would be very close to the pressure required for minimum-weight boosters. The cost per pound of fabricated structural material for low-strength alloys is near the cost per pound of propellant; this is a condition for which minimum-weight motors are also minimum-cost motors, but the condition is slightly modified because the nozzle cost and size affect the analysis.

Summary and Conclusion

A procedure has been presented by which structural materials can be selected for ultra-large-size booster motors. The procedure, based on a fixed mission requirement, includes consideration of structural-material strength, cost, and performance for designs and trajectory evaluations prepared on a digital computer. Chamber pressure was a major variable in the study to determine materials and operating conditions for minimum-weight or minimum-cost solid-rocket boosters.

Results of the analysis indicated that the chamber pressure producing minimum motor cost generally occurs at a lower value than the pressure producing minimum motor weight. Lower total motor costs result from the use of the high-strength, high-cost (dollars per pound of structural material) alloys than from the use of the low-strength, low-cost alloys. Optimum chamber pressures for either minimum-cost or minimum-weight motors tend to increase as the structural-material strength increases. These values of chamber pressure range from about 330 psia for low-strength alloys to about 690 psia for high-strength alloys. Motor weight and cost are relatively insensitive to chamber-pressure variations near the optimum values.

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