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Final Report

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THE STUDY OF COST ESTIMATIONS AND ECONOMIC ANALYSES OF ROCKET MOTORS AND ROCKET MOTOR SYSTEMS (COST ESTIMATION FOR SOUNDING ROCKET DESIGNS)

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ABSTRACT

NASA/Langley has demonstrated the feasibility of compression-molded plastic motor cases and nozzles for solid rockets. This demonstration consisted of hydrostatic tests, design calculations, and static tests of short-length motors.

The concept of a compression-molded motor case and nozzle for sounding rockets is a radical departure from conventional design. The concept offers unique advantages of cost (Stanford Research Institute was given a contract to obtain the details on this advantage), insulation, bending moment, outgassing after burnout, nonmagnetic characteristics, and frangibility of burned out inerts.

Because the compression-molded rocket motor case and nozzle for sounding rockets represents a radical departure from conventional design, it suffers disadvantages of user acceptance, manufacturer acceptance, and degree of concept development.

SRI examined ten alternative sounding rocket motor designs of comparable ballistic performance and prepared engineering cost estimates of each. The designs based on the Langley comparison-molded inert parts will cost less to manufacture than the present Meteorological RDT&E rocket motor and its metal-case conceptual alternatives. Recommendations are made to more fully develop the advantages of the plastic case rocket and to overcome the disadvantages.

INTRODUCTION

NASA/Langley has demonstrated the feasibility of compression-molded plastic motor cases and nozzles for solid rockets. This demonstration consisted of:

- Hydrostatic tests of rocket motor cases with integral nozzles. These tests showed that the selected asbestos-phenolic molding compound yielded uniquely-high tensile strength and density when molded under the NASA-developed conditions.

- Design calculations of the weight and strength of a motor case for a selected sounding rocket application. These calculations showed that the molded plastic case could give the same mass fraction as the conventional steel case.

- Static tests of short-length motors. These static tests showed that the selected grain perforation gave an acceptable regressive thrust-time curve, that the sandblasting of the interior of the motor case was an adequate technique for achieving case-bonding of the propellant grain, and that the integrally molded nozzle incurred acceptable erosion.

The concept of a compression-molded motor case and nozzle for sounding rockets is a radical departure from conventional design. The concept offers unique advantages, which are discussed below in the order of their occurrence.

Cost - The manufacturing and assembly labor for the rocket and, perhaps, some of the materials costs are less. Stanford Research Institute was given a contract to obtain the details on this advantage, and those details are given subsequently in this report.

Insulation - The molding compound used in the motor case and nozzle was developed as an insulating material, and the molded parts do not require any additional liner or elastomeric protection from the rocket motor combustion products. This leaves the designer free to use a long duration, end-burning grain, if required because of payload "g" loading.

The NASA concept uses this abundance of insulation to incorporate a simple slot perforation in the propellant grain, without concern for additional insulation of the motor walls on those surfaces that are exposed to the flame very early in the firing of the rocket. The favorable mass fraction and increased ability of the grain to withstand thermal cycling result from this slot perforation. The regressive thrust-time curve will reduce dispersion of the rocket at launch.

Bending moment - Sounding rocket motor wall thickness is dependent more on the bending moments incurred during flight than on motor operating pressure. The molded motor case is expected to offer better resistance to these bending moments when compared on a weight basis with steel.

Outgassing - In some instances, payload separation of sounding rockets is required because of the anticipated outgassing of propellant slivers and elastomeric liner and insulation. The selected grain perforation and molding compound do not present this problem.

Nonmagnetic - In some instances, payload separation is required because the magnetic properties of the spent rocket interfere with the measurements being made by the payload. The molded rocket motor case and nozzle eliminate this problem.

Frangibility - Although it has been demonstrated that a pyrotechnic sandwich or an explosive sheet can be used to reduce a sounding rocket motor case to fragments that present no FMH (falling mass hazard), these FMH concepts have not been carried to fruition because of a variety of factors, including cost. The molded motor case is compatible with either concept when the decision is made to continue FMH neutralization work.

Because the compression-molded rocket motor case and nozzle for sounding rockets represents a radical departure from conventional design, it suffers certain disadvantages, which are discussed below.

User acceptance - The users of sounding rockets often have a personal and vested interest in the payload and tracking and telemetry equipment being used for a launch. In most instances, the payload cost is three to ten times the cost of the conventional sounding rockets now in the inventory. These factors discourage such users from consideration of lower cost, less proven rockets.

Manufacturer acceptance - The manufacture and assembly of the NASA-conceived rocket substitutes tighter process control and more tolerant design for several inspection procedures that have become almost traditional because of their regular use by rocket motor manufacturers.

Degree of concept development - The preliminary design of the sounding rocket using compression-molded rocket motor case and nozzle is based on extrapolation from a limited amount of feasibility and characterization study. The selected molding compound is a grade of asbestos-phenolic and its properties may not be reproducibly attainable in the large quantities required for production of the estimated 12,000 motors. The tensile properties achieved in the short length, thick-wall motor with integral nozzle may not be reproducible in the full-length, flightweight motor tube. The case-bonding achieved by sandblasting alone may not maintain its integrity in full-length, flightweight motors subjected to the extremes of temperature cycling and aging demanded of rocket motors. Nozzle throat erosion may not be sufficiently uniform and reproducible. Molded fins with an integral sleeve may not have adequate resistance to aerodynamic and thermal flight loads. Thread or pin fasteners for assembling the molded parts may contribute unacceptable stress or weakening in critical areas.

One approach to user acceptance is to incorporate some advantage other than cost-savings into the design of the sounding rocket at an early stage. Since payload separation reliability is relatively low compared with the rocket motor reliability, the NASA-conceived design could include some feature to improve that reliability. An integral igniter-motor bulkhead-pyrotechnic timer-gas generator as the energy source for payload separation is within the state of the art and offers cost and reliability advantage.

Approaches to manufacturer acceptance include NASA acceptance of the manufactured rockets on a "best-efforts" basis, without the almost traditional volumes of manufacturing records and assuring signatures. The early divulgement of the NASA-developed molding techniques to molding compound and rocket parts manufacturers will allow their accommodation, acceptance, and, perhaps, refinement of these methods for obtaining improved tensile properties and densities. The molding of a weighed charge to net dimensions justifies elimination of hydrotest when it is explained adequately. The simple slot perforation and casting a known-weight propellant grain to known dimensions can eliminate concern for grain-cracking and porosity, when explained. Such departures from convention are logical and could be the subject of a paper at an ICRPG meeting to provide discussion and promote acceptance.

The concept development status disadvantage currently may be insurmountable because of the lack of funds. The funds that are available should be used on those parts of the development that will progressively reduce the chances of arriving at a technological barrier and reduce the remaining development costs. A propellant formulation or development program is to be avoided. Possible substitutes for the selected molding compound should be characterized and their suitability determined. A back-up program to assess the benefits obtainable from filament-wound reinforcement of the motor tube should receive priority consideration.

STUDY FINDINGS

The preliminary sounding rocket design concept used as a baseline for the cost estimation evolved from the NASA/Langley experimental data and first design, the MET RDT&E rocket design as prepared by BAL, and a discussion between NASA/Langley and SRI personnel. Some details were not available at the time the study was initiated, but these were recognized as of no significance in the cost estimate preparation. The alternatives, as developed by SRI, represented additions and substitutions, without gross changes of the baseline design. The costs of the alternatives are summarized in Table 1 and discussed subsequently.

Alternative A - Reinforced Asbestos-Phenolic Motor Tube

At the initial discussion of the motor design, there was some question of motor tube strength at the thickness dictated by inert parts weight and ballistic performance. One method of obtaining some reduction of thickness was lowering of the motor operating pressure. The cost ramifications of this change would be minor.

An approach with significant cost effect was reinforcement of the motor tube. Some consideration was given to reinforcing bands, orientation of the molding compound fibers, or use of reinforcing laminates in the molded tube. All of these were rejected in the initial discussions because of incompatibility with the molding techniques and because of the additional labor required during mold loading. External reinforcement with paper or cloth was rejected because a Thiokol effort had demonstrated the difficulty in maintaining thickness reproducibility with commercial materials and processes.

Filament winding did not initially appear promising because of the high cost associated with filament-wound rocket motors. A detailed analysis of these costs identified mandrel preparation and removal, manual reinforcement patch and boss installation during the winding process, and winding of irregular shapes as the major contributors to the high cost. The motor tube presents ideal conditions for low cost application of filament winding as reinforcement. The uniform diameter and the elimination of any need for a mandrel allow low set-up time, high wrapping speeds, and automated curing cycles. These advantages showed up in the estimate for labor and materials of $23.00 per motor for winding a 0.1 inch (0.25 cm) thick reinforcement.

Table 1

SUMMARY OF COST ESTIMATES

Inert Parts / Alternative →	Molded Asbestos-Phenolic	Molded and Wrapped Asbestos-Phenolic A	Molded and Wrapped Glass-Phenolic #1 B	Molded and Wrapped Glass-Phenolic #2 C	Initial Met RDT&E Design D	Deep-Drawn Steel #1 E	Deep-Drawn Steel #2 F	Deep-Drawn Aluminum #1 G	Thick Wall Aluminum #2 H	Deep-Drawn Aluminum #2 I
Motor Tube										
Rolled, welded and drawn	$ --	$ --	$ --	$ --	$ 60.00	$ --	$ --	$ --	$ --	$ --
Molded	66.00	--	--	--	--	--	--	--	--	--
Molded and Filament-wrapped	--	69.00	49.00	58.50	--	--	--	--	--	--
Deep-Drawn	--	--	--	--	--	50.00	43.00	43.50	32.00	40.00
Head Closure and Piston Support										
Stamped	--	--	--	--	6.00	--	--	--	--	--
Integral with Motor Tube	X	X	X	--	--	X	X	X	X	X
Nozzle Retention Threads										
Machined Ring	--	--	--	--	7.00	--	--	--	--	--
Integral with Motor Tube	X	X	X	--	--	X	X	X	X	X
Parachute Tube										
Threaded Tube	--	--	--	--	--	--	9.50	--	9.50	10.50
Integral with Motor Tube	X	X	X	X	X	X	--	X	--	--
Nozzle										
Molded with throat insert	42.00	42.00	19.50	--	15.00	15.00	19.50	19.50	19.50	19.50
Integral with Motor Tube	--	--	--	X	--	--	--	--	--	--
Fins										
Stamped	--	--	--	--	10.00	10.00	--	--	--	--
Molded	--	--	--	10.00	--	--	--	--	--	--
Integral with Nozzle	X	X	X	--	--	--	X	X	X	X
Resistance-weld Assembly	--	--	--	--	35.00	10.00	--	--	--	--
Hydrotest (100%)	--	--	--	--	10.00	--	--	--	--	--
Tooling Amortization	25.00	35.00	35.00	35.00	10.00	--	--	--	--	--
Internal Insulation										
Elastomeric, Bag-cured in place	--	--	--	--	100.00	100.00	100.00	100.00	100.00	100.00
Integral with Motor Tube	X	X	X	X	--	--	--	--	--	--
Propellant Loading	68.25	68.25	68.25	68.25	68.25	68.25	68.25	68.25	68.25	68.25
Igniter and Payload Separator										
Mortar/Mech. Timer/Aft igniter	38.15	38.15	38.15	--	38.15	38.15	--	38.15	--	--
Mortar/Pyro Timer/Fore igniter	--	--	--	25.00	--	--	--	--	--	--
Heat-released Spring/Fore igniter	--	--	--	--	--	--	17.50	--	17.50	17.50
	$239.40	$252.40	$209.90	$196.75	$359.40	$291.40	$257.75	$269.40	$246.75	$255.75

With a conservative estimate of $120,000 for facilities and tooling, this alternative showed no cost advantages over the baseline design. Its utility may be in its indication of a low cost approach to be taken to obtain weight reduction or strength improvement, or both, that might be found necessary as the design work progresses.

Alternative B - Reinforced Glass Roving-Phenolic Motor Tube

The relative contribution of the asbestos-phenolic olding compound cost to the total rocket cost directed immediate attention to material substitution as a means of reducing the rocket cost. The tensile properties of the short-length, heavywall motors molded at Langley, using a selected grade of asbestos-phenolic, were uniquely favorable and lend some weight to continued use of the premium-price material. However, if these properties are not reproducible in full-length, flightweight, motor tubes, the entire low cost sounding rocket concept might falter.

A prudent back-up for the molding efforts was a survey of reinforcement techniques to supplement the motor tube tensile properties achieved by the Langley molding conditions. Filament-winding was found economical because the motor tube offered a uniform diameter and did not require interruption of the winding cycle for manual placement of reinforcement patches and bosses.

Asbestos-phenolic molding compounds as a class, offer excellent tensile and insulation properties. They suffer somewhat from reproducibility because of their dependence on a natural fiber, and the half-million pounds (220,000 kg) required for 12,000 motor tubes will amplify this problem. The dependence on natural fibers also keeps these molding compounds in an ultimate price range near $2.00/lb ($4.40/kg).

Glass-roving-phenolic is the least costly of the molding compounds that has good physical strength and acceptable insulation capability. Since the NASA-conceived design is not demanding of the insulation capability, consideration should be given to a reasonably thorough effort to substitute the $0.50/lb ($1.10/kg) glass-roving-phenolic molding compound for the asbestos-phenolic. Characterization of selected samples of this type of molding compound subjected to the NASA-developed molding conditions should be given priority in the technology development program.

Another consideration necessary at this time is the FMH program. The pyrotechnic sandwich and sheet explosive wrap concepts are completely compatible with a filament reinforcement wrap, but the former concept could disperse a total of about 180 tons (163,400 kg) of asbestos into the atmosphere, depending on the combustion efficiency of the pyrotechnic composition. Since asbestos is currently of concern as an atmospheric pollutant, this dispersion would likely be objectionable to the municipalities near rocket launch sites.

The characterization of glass-roving-phenolic molding compounds for the molded motor tube and the design analyses necessary to establish optimum motor operating pressure, molded tube thickness, and reinforcement wrap thickness are worthy of consideration for the potential cost savings and compatibility with the FMH program.

Alternative C - Integrated Pyrotechnic/Ordnance Wafer

In the initial discussions of the conceptual design, it was decided that the ballistic mortar, mechanical timer, and other parts of the payload separation system would be as designed and estimated for the MET RDT&E rocket. This decision allowed better comparison of the unique concepts of the Langley design with the more conventional components of the MET RDT&E rocket motor. Aft-end ignition was retained in deference to current launch crew practices of "arming" the motor by inserting the igniter.

The introduction of the MET RDT&E rocket, or its lower cost variation as envisioned by NASA/Langley, will meet considerable opposition from present users of sounding rockets because of the lack of demonstrated reliability of either rocket. In anticipation of such opposition, the technology development and reliability demonstration efforts must be very carefully balanced and coordinated.

The payload separation system flight failures exceed rocket motor failures. Launch crew procedural errors cause more flight failures than those resulting from rocket motor failures. There have been no accidents with sounding rockets attributable to premature ignition of rocket motors or to use of fore-igniters. The ordnance technology is in hand for the immediate design of a wafer that can contain the fore rocket motor igniter, a gasless pyrotechnic delay, and a solid propellant gas generator to supply the ejection energy for the payload. This wafer can serve also as the forward bulkhead for the rocket motor. "Safe-arm" of the igniter and pyrotechnic delay can be incorporated by the conventional electromechanical devices or by side insertion of a squib or through-bulkhead-initiator without destroying the ability to maintain good hermetic and pressure seal of the rocket motor. Use of a nozzle seal is thereby permitted, with reduction of the possibility of grain damage by probes of curiosity.

Alternative C requires some design and test effort to obtain the integrated pyrotechnic-ordnance wafer. The estimate of $25.00 for the package allows $10.00 for the wafer and $15.00 for the other components of the pedestal package. The combined cost reduction and reliability improvement effects warrant serious consideration of this alternative as a target for NASA.

In addition to these molded motor alternatives, comparable cost estimates were prepared on a sounding rocket motor (MET RDT&E) now in development and qualification, along with alternative conceptual designs using selected metal components and manufacturing techniques that could reduce the cost of this motor now being qualified.

The MET RDT&E sounding rocket motor in development has a payload/height performance comparable to the Arcas. It has a 10-second regressive thrust-time history, so its ballistic performance does not directly compare with that of the Arcas. The regressive thrust is obtained from a case-bonded grain with a single slot perforation. This configuration presents high volumetric loading and advantage in stress relief during temperature cycling, but it is accompanied by case insulation requirements because of the early arrival of the propellant flame front at the motor case immediately below the ends of the slot.

The present design uses ARMCO 21-6-9 stainless steel for the motor tube because this relatively expensive alloy can be rolled, welded, and drawn to finished dimensions, accepts resistance-welded attachments readily, and maintains adequate tensile properties after such welding, thereby eliminating post-assembly heat-treatment of the rocket motor.

Stamped fins, motor head cap, and pedestal support tabs of a compatible stainless steel are resistance-welded to the tube. A nozzle retention ring machined from stainless steel is resistance-welded within the tube. The assembled rocket motor case is pressure tested to a proof pressure of 2500 psig. The interior is lightly sandblasted before a precut elastomeric side wall insulation sheet, rear end collar, and end cap are installed and bag-cured in place. The propellant is vacuum cast into the motor and cured.

At the production rate of 3000 motors/year over a 4-year production program, experience in metal fabrication does not support the selection of the relatively expensive stainless steel on the basis of its economy of assembly into rocket motors. The elimination of machining of the tube diameters and elimination of heat-treatment of the completed assembly are significant savings but other tube-forming processes with less expensive alloys result in acceptable diametric tolerances, and develop the modest tensile properties required in the sounding rocket motor. Forming a motor tube with an integral head cap and nozzle retention threads eliminates the alignment difficulties during resistance-welding and eliminates the need for 100% pressure testing after assembly. The task required exploration of such alternative lower-cost metals and fabrication processes.

The other questionable design choice in the MET RDT&E development program was the motor tube internal insulation. The installation of molded pieces and layup of 0.1" thick precut elastomeric sheet is labor-intensive. Bag-curing in place required relatively large equipment investment. The plastic motor cases are totally self-insulating, so it was concluded that the development of directly comparable MET RDT&E cost estimates should include a search for lower-cost alternatives to the insulation of metal cases.

The substitution of metals evolved to 4130 steel and 7075 aluminum alloys for their comparability in weight performance to the ARMCO stainless alloy. Their raw material prices of $0.18 and $0.60/lb show potential savings when compared with $1.00+/lb for the stainless alloys. The development of alternatives to the ARMCO stainless then centered on choices of fabrication methods for the motor from the 4130 and 7075 alloys.

Extruded 4130 steel tube of the required diameter and thickness would cost about $20/ft, or $135 per motor tube. This is not competitive with the ARMCO rolled, welded and drawn tube. Extruded 7075 aluminum tube of 5" diameter has a minimum wall thickness of 0.28", which is unacceptable for weight performance. Extruded tubing was therefore eliminated from further consideration.

Rolled and welded or seamless drawn tubing was next considered. For the anticipated production quantities, the logical progression was to deep-drawn motor cases with integral heads and nozzle retainer rings. Drawn tubing with welded head caps and retainer rings was bypassed because it offered no advantage of any kind. Five deep-drawn alternatives were identified for detailed review.

In the search for alternatives to the current insulation materials and installation technique, the design features of solid rocket motors with diameters from 4.5 to 6 inches were reviewed. None have internal insulation requirements identical with the MET RDT&E design, and production experience with internal insulation of 5" motor tubes with an L/D of 12 was not found. The use of a hard insulation tube or spin-curing of insulation in place showed no economy over the current insulation sheet layup and bag-cure. Because of the 10-second exposure of the motor walls to the flame front, the insulation could not be eliminated. The cost estimates of all of the metal-case rocket motors therefore include the current insulation materials and techniques.

Alterantive D - Current Design. The cost estimates for the MET-RDT&E motor case confirmed the BAL estimates. SRI estimates of the motor case insulation and propellant loading operation are \$30-\$35 lower than BAL. Possible explanations are the labor rates, learning curves, or materials costs, but further investigation is not justified since the difference is favorable to the existing design. The estimate of \$359.40 supports all of the molded motor cases as cost-lowering alternatives.

Alternative E - Deep-Drawn 4130 Steel. In the search for alternative fabrication methods capable of the diametrical tolerances and wall thickness requirements, drawn tubing showed most promise. The selected steel alloy, 4130, presents 150K psi tensile strength after the drawing operation. This equals the performance of the ARMCO stainless used in the design. The 4130 cost of \$0.18/lb is very favorable. Refined tradeoffs might lead to some other steel selection that would give improved motor performance but the cost estimate for this steel is very representative of what can be achieved in good deep-drawing facilities. The total advantages of the integral head cap and nozzle retainer threads must combine fabrication costs, elimination of 100% pressure test after assembly, and assurance of nozzle alignment.

This alternative presents no technological risk and requires no new U.S. plant investment, considering the availability of ovens, presses and machining facilities such as those of Norris Industries in the Los Angeles area. In either event, the cost estimate of \$291.40 presents a significant savings when compared with current design, but it is higher than the cost estimates of the molded case alternatives.

Alternative F - Deep-Drawn 4130 Steel with Separable Parachute Tube. Before an appreciation of current deep-drawing capability was developed an alternative that allowed threaded attachment of the parachute tube was considered and cost estimates were prepared. On a directly comparable basis, the costs are not significantly different from those developed for the integral design. This alternative includes a nozzle, fin, and igniter and payload separator substitution that brings the cost estimate down to \$257.75. The estimate is retained because payload changes might profitably utilize the threaded tube concept and the estimate allows comparison of the 4130 steel with the 7075 aluminum alternative that is subsequently discussed.

Alternative G - Deep-Drawn 7075 Aluminum. Aluminum alloys can be readily deep-drawn and 7075 alloy is comparable on a weight-strength basis to 4130 steel and the ARMCO stainless used in current design. The 4130 steel requires paint to achieve corrosion resistance comparable to the aluminum or stainless. The 7075 aluminum deep-drawn integral motor case cost estimate is only slightly lower than that of the 4130 steel on a directly comparable basis. A nozzle and fin substitution brings the cost down to $269.40, but this alternative is retained for comparisons rather than for any really unique advantages.

Alternative H - Deep-Drawn 7075 Aluminum with Separable Parachute Tube. The decision on 7075 aluminum was aided by the review of the CPIA Rocket Motor Manual. The Zuni motor uses a 5" diameter, deep-drawn, 7075 aluminum motor tube with integral head cap, nozzle retainer threads and warhead retainer threads. Weight calculations of an added parachute tube showed that this design weighed 18.7 pounds, compared with about 20.8 pounds for the equivalent ARMCO stainless parts in the current design. The wall thickness of 0.138" is designed to allow a Pmax of 2300 psi at 165°F. Since the Zuni motor is 5 feet long, it, too, can hold the 55 pound propellant grain with a single slot perforation. The standard design Zuni case has been purchased in large volume at a unit price of about $32, including the manufacturing punches and dies.

The cost estimate of $246.75 is not significantly different from that of the integral deep-drawn aluminum alternative, if the igniter and payload separator substitution is taken into consideration. It is retained to support the recommendation for exploratory development work on the use of existing hardware.

Alternative I - Thickwall 7075 Aluminum with Separable Tube. The cost estimating of 7075 aluminum motor tubes proceeded on the assumption that the 0.138" wall thickness will be adequate for withstanding flight loads other than motor operating pressure. If calculations or tests demonstrate the error of this assumption, the wall thickness can be increased to 0.150" without degrading the aluminum alternatives' weight performance to a level below that of the ARMCO stainless. The cost estimate of a thick-wall, deep-drawn, 7075 aluminum motor case and separable parachute tube is only $255.75 and slightly higher than the 0.138" wall thickness counterpart.

The cost estimates of all alternatives are summarized in Table 1. It was concluded that deep-drawn motor cases of 4130 steel or 7075 aluminum are at least equal in weight performance to the current design and offer significant cost reduction capability, but that the lowest-cost metal-case sounding rocket design is still significantly more expensive than the lowest-cost design utilizing compression-molded inert parts. Recommendations are made on exploratory development toward improved and lower-cost sounding rockets.

STUDY DATA BASE AND ASSUMPTIONS

The data base for this study consisted of cost data extracted from the SRI data bank and from 17 reports on sounding rockets, their materials of construction, and fabrication techniques. The data were adjusted to 1970 dollars and confirmed in discussions with two rocket motor manufacturers and three materials suppliers. Profits of the prime contractor are negotiable by the government and will range from 0% to 15% depending upon the economic climate. It is not included in the estimates.

The sounding rocket concept required three molded parts weighing a total of 40 lbs (18 kg). The propellant grain, cast directly into the sandblasted case, weighs 55 lbs (25 kg). All alternatives are comparable in performance to the MET RDT&E Sounding Rocket Motor. The production rate is to be 3,000 motors per year for four years--a total of 12,000 rockets. Weekly production rate is 60 motors.

Learning Curves

On the basis of current practice in the rocket community, and with supporting information from the literature, a learning curve of 92 percent was selected for labor estimates used in this study. The ratio of average unit to first unit for a production of 12,000 units is 0.32, and this ratio was applied to:

- Inert parts molding labor
- Inert parts finishing labor
- Propellant loading labor
- Motor finishing labor .

The ratio was not applied to material prices because the quantity price quotes and data reflect the materials suppliers' application of learning curves to his processing. It was not applied to the reinforcement wrap cost because these costs depend on machine speed and materials costs, with little or no opportunity for improvement based on the machine operators' experience.

Labor Rates

Early in the study, it was assumed that labor rates of the solid rocket industry would be most applicable for the estimates. During the course of the study, U.S. Department of Commerce data made apparent the premium being paid for the skill level, hazards, and job insecurity associated with the ordnance industry, when compared with rubber and plastic goods manufacturing.

The burdened rates, adjusted to 1970 dollars, are $13.85 and $9.00 per hour, respectively. The difference in labor rates indicates the desirability of separate contracts with plastics and ordnance manufacturers when the NASA rocket is to go into production.

The following specific assumptions were made to arrive at the estimates of Table 1:

Reinforcement wrap cost

Nominal diameter - 5 in. (12.7 cm)
Nominal wrap thickness - 0.1 in. (0.25 cm)
Burdened labor rate - $13.85/hr
Nominal material cost - $2.00/motor
Baseline design estimate length - 6 ft (183 cm)

Inert parts finishing labor

3 molded parts - tube, nozzle, fin assembly
0.1 man-hour per part set-up time
Net-molded to finished dimensions, visually inspected, drilled for retention pins.
Burdened labor rate - $9.00/hr
Baseline design estimate - 1.0 man-hours per set, including set-up time

Inert parts molding labor

3 molded parts - tube, nozzle, fin assembly
1/8 man-hour per part set-up time
Net-molded to finished dimensions
Burdened labor rate - $9.00/hr
Baseline design estimate - 40 lbs (18 kg) total for 3 parts.

Molding compound cost

Molded to dimension and weight tolerances - negligible waste
Baseline design estimate - asbestos - phenolic - $2.00/lb ($4.40/kg)

Ignition and payload separation ordnance cost

Motor forward bulkhead is integral with timer and mortar wafer
Igniter per BAL estimate for 3000/year - $16.90
Pedestal parts and assembly per BAL estimate - $17.78
Baseline design estimate (BAL + 10% fee) - $38.15

Motor finishing labor

Uniform cross-section, simple slot perforation
Propellant trim at one end of grain only
Visual inspection
Burdened labor rate - $13.85/hr
Baseline design estimate - 0.5 man-hours/motor

Propellant loading labor

60 motors (1 week's production) loaded from one propellant mixer loaded with 3500-4000 pounds (1600-1825 kg) propellant

Includes: Sandblast and assembly of motor case into casting fixtures
Propellant mixing, casting, and curing
Removal of motor from casting fixtures
Attachment of nozzle and fin assembly
Loading into GFE shipping container

Burdened labor rate - $13.85/hr
Baseline design estimate - 55 lb (25 kg) propellant grain

Propellant ingredients cost

CTPB or "optimistic" HTPB binder - AP/Binder/AL-70/16/14
10% waste and process control samples
Baseline design estimate - $0.50/lb ($1.10/kg) - input materials

Cost Estimation Graphs

Figures 1-5 supply flexibility in cost estimation as the NASA design weights change or assumptions are modified.

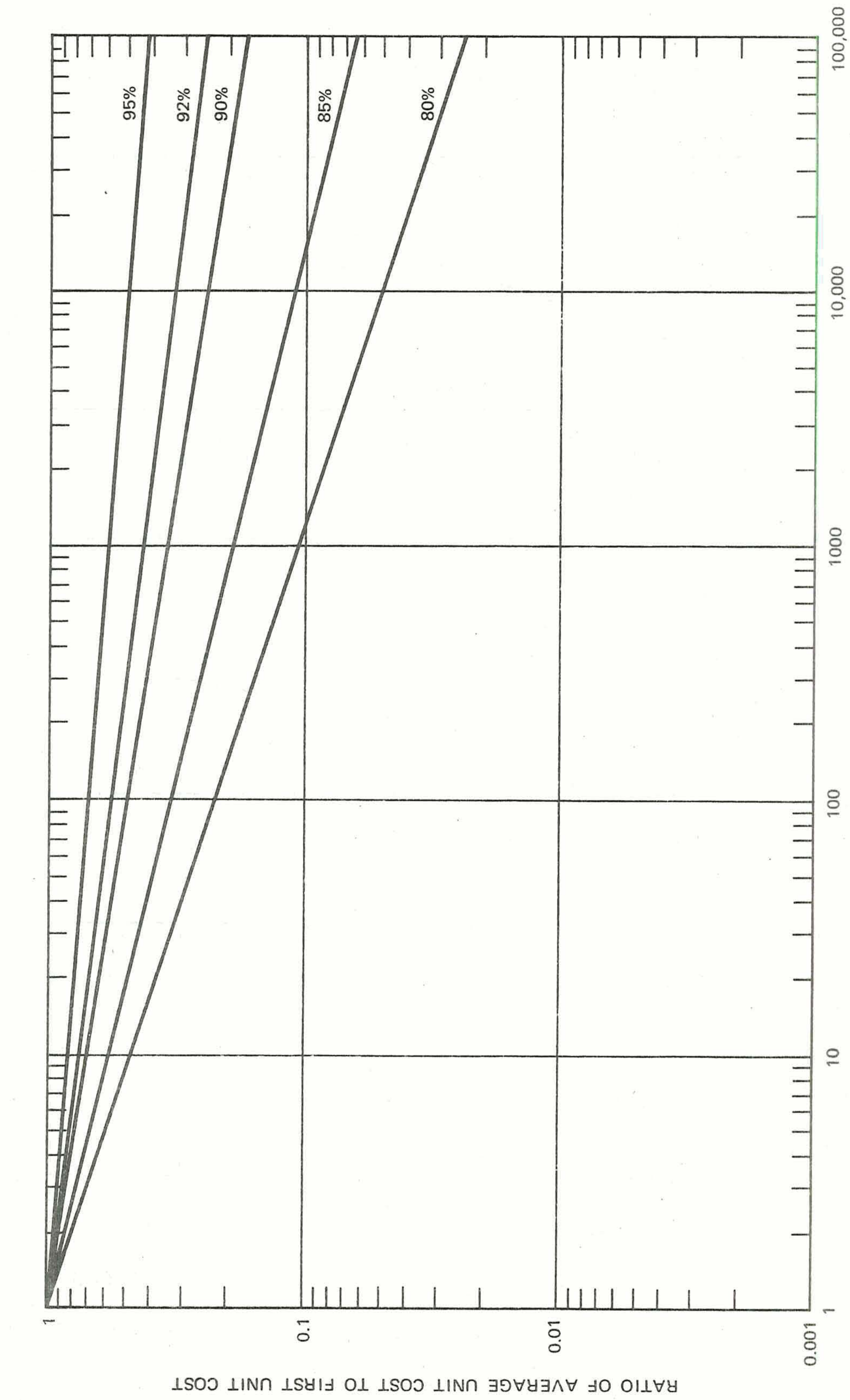

FIGURE 1 LEARNING CURVES

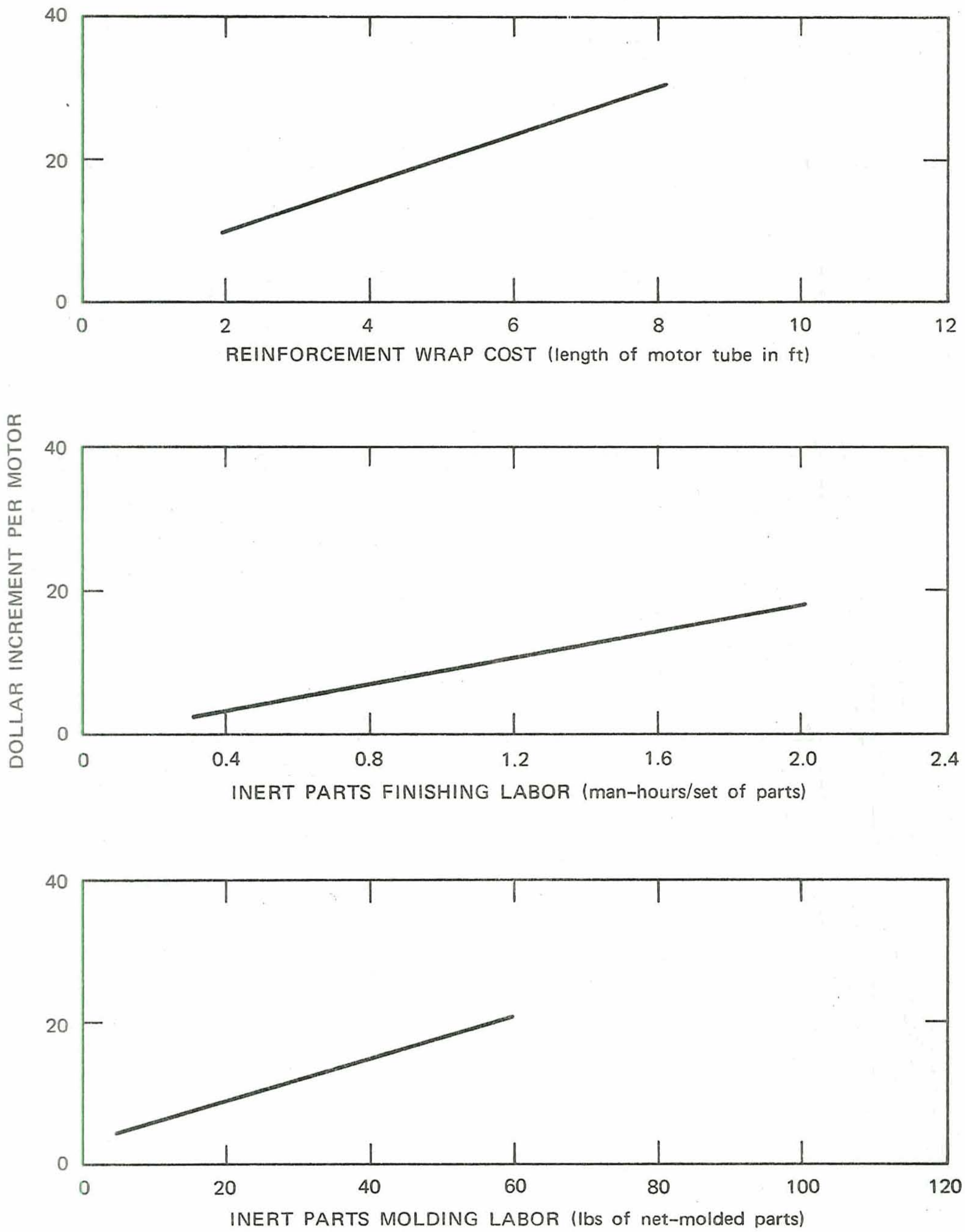

FIGURE 2 MOTOR PARTS MANUFACTURING EFFECTS ON MOTOR COST

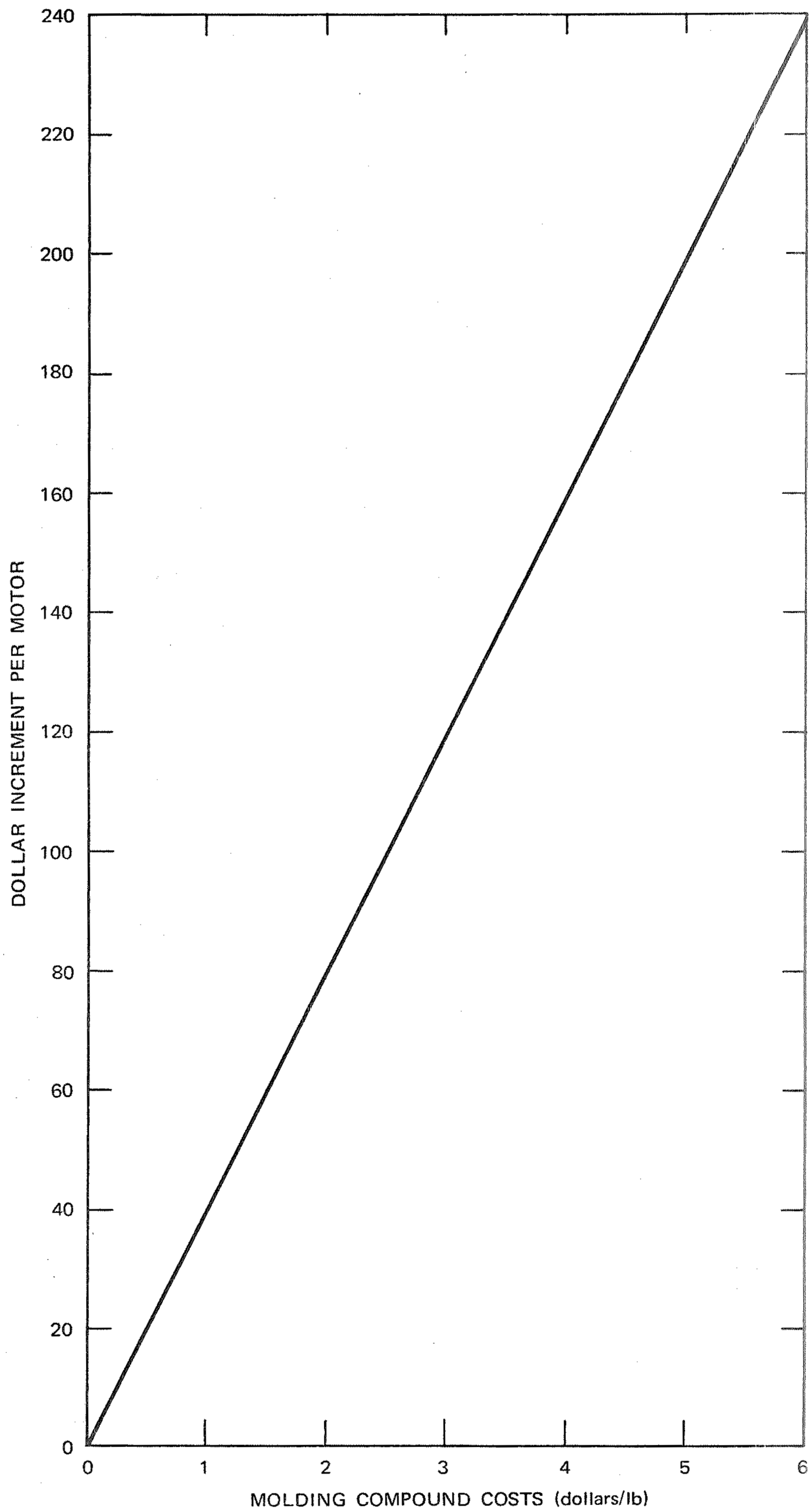

FIGURE 3 MOLDING COMPOUND EFFECTS ON MOTOR COST

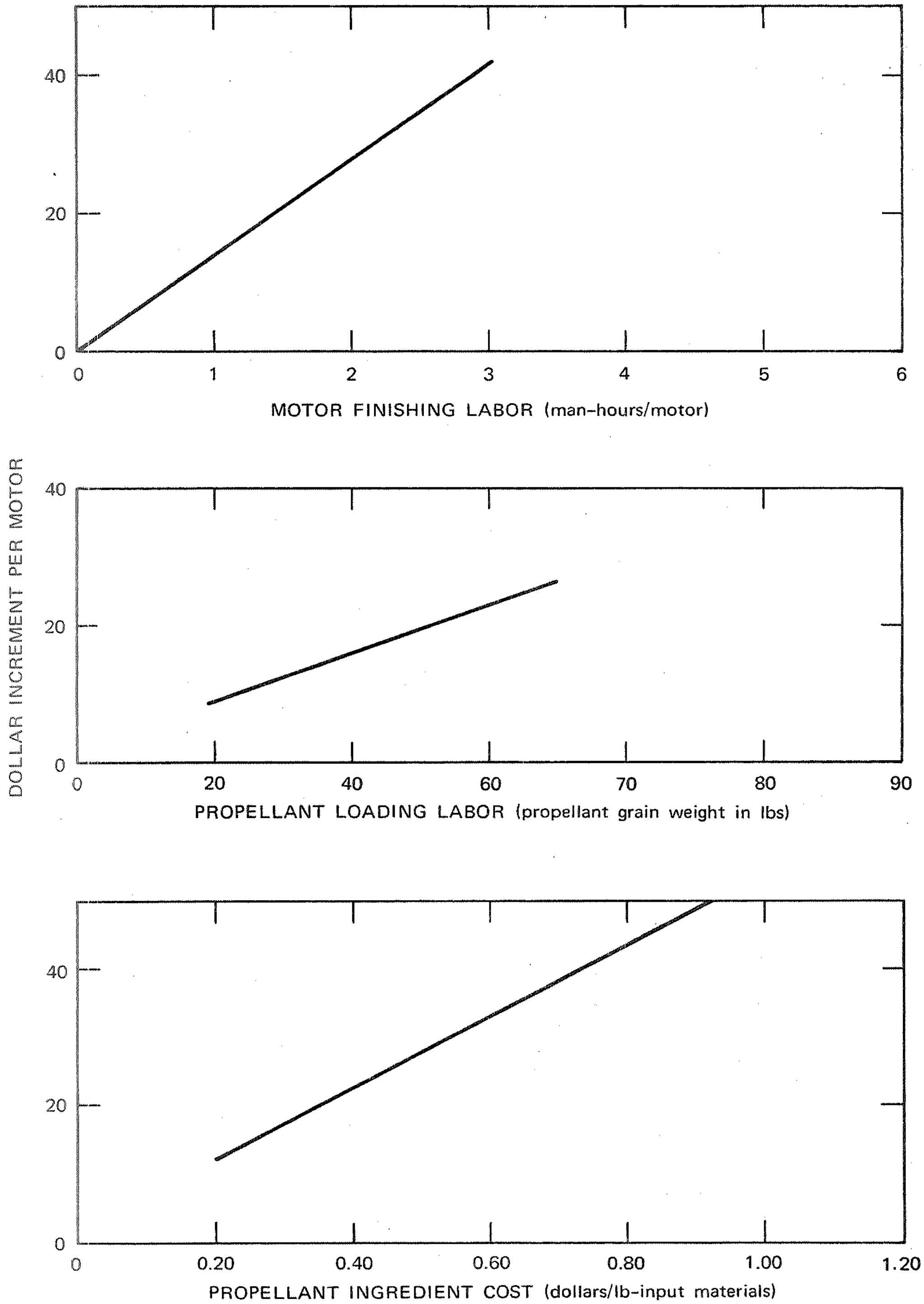

FIGURE 4 PROPELLANT LOADING EFFECTS ON MOTOR COST

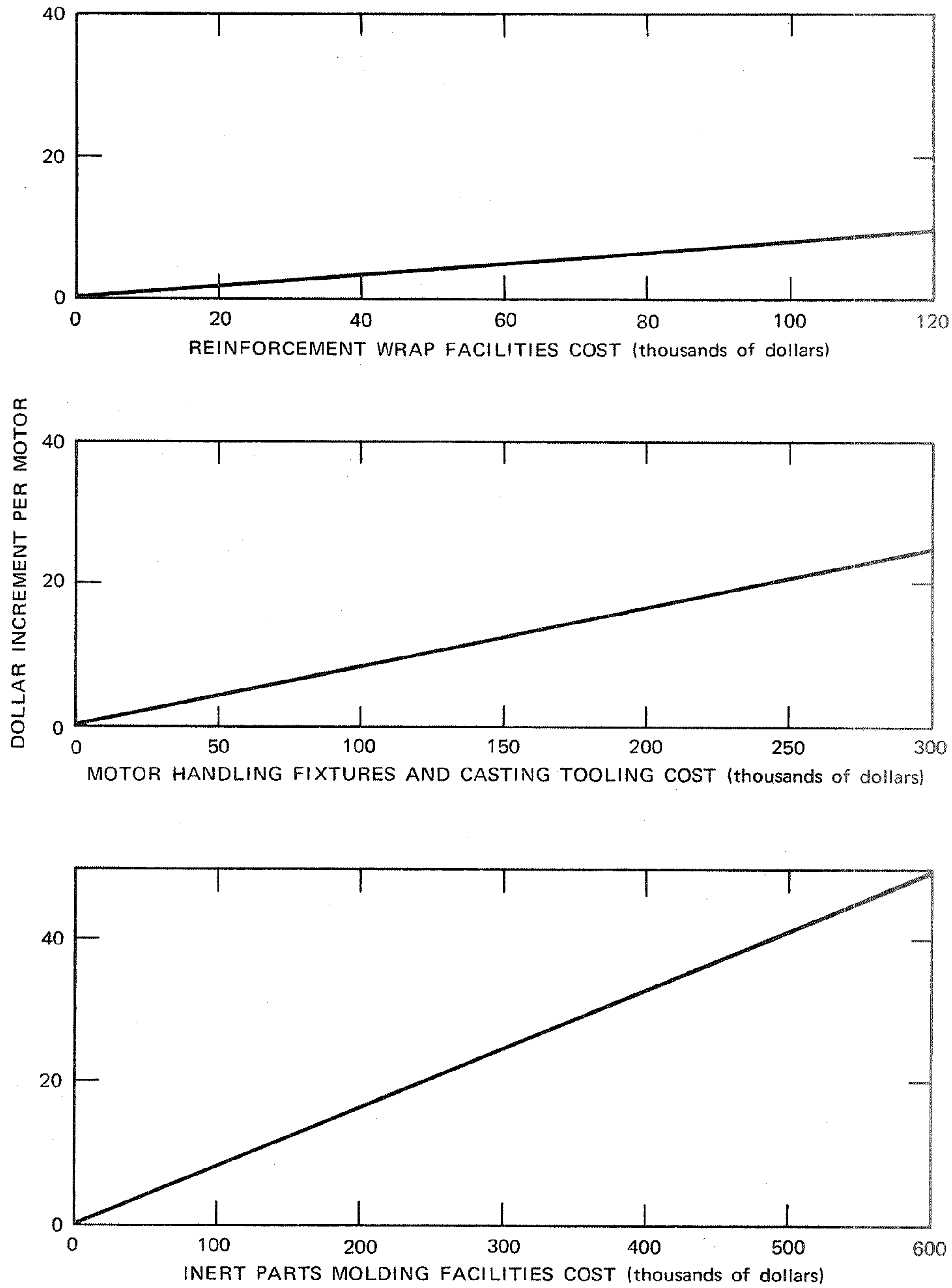

FIGURE 5 FACILITIES WRITE-OFF EFFECTS ON MOTOR COST

A family of learning curves are presented in Figure 1. The 92 percent curve has already been applied to the graphs of:

- Inert parts molding labor
- Inert parts finishing labor
- Propellant loading labor
- Motor finishing labor

If the learning curve assumption is to be changed, or the production quantity is not 12,000 units, the point estimates made from these four labor curves should be multiplied by 3.125 to obtain first unit costs, and then multiplied by the selected ratio from the learning curves graph in Figure 1.

The cost effect of changes in inert parts weight, propellant grain weight, molding compound cost, propellant ingredients cost, and motor length can be read directly from the graphs in Figures 2-5.

Deep-Drawing Facilities. For the molded parts, it was necessary to include amortization of a molding facility for the motor inert parts. To obtain the uniquely-high densities and favorable tensile properties in the compression-molded items, NASA has developed new temperature-vacuum-pressure cycles that assure proper flow and consolidation of the bulk resin. The $25 amortized on each set of rocket motor parts allows the construction of an efficiently-instrumented and automated plant to reproduce these cycles.

Serious consideration was given to assignment of a like cost to the deep-drawn motor cases to keep the cost estimates of both tasks directly comparable. The Shillelagh, Zuni, Sidewinder, and perhaps other deep-drawn solid rocket motor cases, have led to the installation and existence of extensive modern facilities with very adequate capacity for the projected 12,000 motors. It would not be realistic to ignore these facilities and assign costs of a hypothetical installation to the deep-drawn case cost estimates if production occurs in the United States. The deep-drawing facilities in existence in Canada are not known. Finally, the demonstrated cost advantage of the molded motor concepts, as summarized in Table 1 does not call for the imposition of hypothetical facility costs upon the metal-cased alternatives.

Deep-Drawn Motor Tubes and Separable Parachute Tubes. The cost estimates for these components are based on production contract award data, calculations using cost estimating relations in the SRI data base, and a confirming quotation from Norris Industries, the leading producer of such items. The steel estimates allow $4 for painting or otherwise applying a weather-protective coating to obtain corrosion resistance comparable to the ARMCO stainless. The integral tubes will not present any new aerodynamic load problem, but the threaded joint of the separable tubes is a potential failure point that requires careful consideration that was beyond the scope of this cost study. Because the parachute tube is not subjected to the motor operating pressures, it may be possible to gain in overall performance by reducing this wall thickness. The aluminum alternatives weigh somewhat less than the ARMCO stainless and can be made thicker in the vicinity of the threaded joint with only a slight loss of this weight advantage. With these two weight reserves to work out of, the design of an adequate threaded joint presents no risk.

Nozzles and Fins. Several nozzle and fin groupings can be substituted within the cost estimates, depending upon the desired comparisons. The least change and technology risk is involved in use of the current design--an integrally molded nozzle with throat insert and retainer ring and stamped fins resistance-welded to the motor tube. The cost of this combination is estimated at $35.00. Careful alignment is required during welding and it is not possible to resistance-weld the fins to the plastic or aluminum tube alternatives.

A second nozzle and fin combination is an integrally molded component using the costly asbestos-phenolic resin to obtain the highest physical properties and minimum fin thickness and accompanying drag. This is estimated to cost $42.00.

If some drag penalty from thicker fins can be accepted, the third combination nozzle and fin will use low-cost glass-phenolic resin to bring the estimated cost down to $19.50.

An unpriced alternative to be kept in mind should the drag penalty of plastic fins be found unacceptable is the use of stamped metal fins with suitable attach points to allow integral molding with the nozzle. This approach will also allow pre-attachment of a metal strap to take up the load at the forward tips of the fins.

Igniter and Payload Separator. The current RDT&E sounding rocket design uses a conventional aft igniter and a mechanical timer and solid propellant mortar to effect payload separation. This combination is estimated to cost $38.15 and it is retained in some of the alternatives to make direct comparisons.

A substitution that can be made with no element of technology risk and that can improve reliability is a combined fore igniter with a pyrotechnic delay train to initiate a solid propellant ejection gas generator. The progress in the use of precision pyrotechnic delays and ejection gas generators that has occurred in penetration aids and decoys makes this substitution worthy of consideration from the reliability improvement point alone. The cost estimate of $25.00 is conservative and favorable.

The metal-case alternatives (and the plastic alternatives provided a metal dome or head cap is planned) can use a third combination of igniter and payload separator that offers potential reliability improvement and cost reduction. A spring under tension and potted in a high melting point wax, or a spring of NITINOL, the "memory metal" now being studied at Naval Ordnance Laboratory, could be expected to release their energy to the payload ejector when the heat transfer from the rocket motor brought their mass to the appropriate temperature. The MET RDT&E sounding rocket releases its payload some 100 seconds after burnout. This roughly corresponds to the time for rocket motor metal parts to reach their maximum skin termperature after burnout. This application requires detailed calculation of payload ejection energy requirements, and heat transfer, but the potential elimination of the mechanical timer and ordnance items seems worth the effort. A first cost estimate of $17.50 for this combination is based on a $10 fore igniter and a spring potted in a high melting point, microcrystalline, wax.

CONCLUSIONS AND RECOMMENDATIONS

It was concluded that deep-drawn motor cases of 4130 steel or 7075 aluminum are at least equal in weight performance to the current MET RDT&E design which uses ARMCO 21-6-9 SS and offer significant cost reduction capability, but that the lowest-cost metal-case sounding rocket design is still significantly more expensive than the lowest-cost design utilizing compression-molded inert parts.

To further the development of plastic case sounding rockets, recommendations were made.

1. The early divulgement of the NASA-developed molding techniques to molding compound and rocket parts manufacturers will allow their accomodation, acceptance, and perhaps, refinement of these methods for obtaining improved tensile properties and densities.

2. Possible substitutes for the selected molding compound should be characterized and their suitability determined. A back-up program to assess the benefits obtainable from filament-wound reinforcement of the motor tube should receive priority consideration.

3. More detailed exploration of integrally-molded metal and plastic combinations for the fins is appropriate to advance this design area.

4. A review of current rocket motors compared with existing and planned NASA sounding rockets could identify systems where use of existing hardware could lower the cost.

5. An integral igniter-motor bulkhead-pyrotechnic timer-gas generator as the energy source for payload separation is within the state of the art and offers cost and reliability advantage. Exploration of the technology risk and costs of heat-released springs would take advantage of the residual heat of the rocket motor to time the release of the payload ejection energy.

6. A low-cost hybrid sounding rocket design based on a combination of a compression-molded case for the fuel grain and ZUNI rocket hardware for the oxidizer tankage could be developed and tested at Langley, and would further the plastic motor case work.