TEST OF 260-INCH DIAMETER MOTOR SL-3

William Cohen
NASA
Office of Advanced Research and Technology

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Motor SL-3 is one in a series of very large solid rocket motors in a program to show feasibility of the class of powerful, low-cost propulsion. The meaning of the word feasibility is, of course, open to interpretation in many ways. From our view-point, it means that all of the materials, processes, technologies, and operations, requiredto make this class of motor will be demonstrated. Since low-cost is the primary justifications for considering the large motors, the design concepts and operating principles which are sought and established are those which lead to cost-effectiveness, rather than to optimization in strength, or weight, or specific impulse.

Description of Motor The test to be described was the third in the program. The first two motors were identical, half-length designs, and the primary goal of motor SL-3 was demonstration of key components of a full 260" diameter motor. This prototype full motor has been defined by mission analysis made primarily for earth orbital payloads in the neighborhood of 100,000 pounds. The vehicle for such payloads was a combination of a 260" solid motor first stage and the existing SIVB stage of Saturn V, which also has diameter of 260". The full solid motor defined this way is illustrated in FIGURE 1. It has propellant load of 3.4 million pounds, length 1,650 inches, throat diameter of 89 inches, and a thrust-time curve shaped to optimize the flight dynamics.

The SL-3 test was to demonstrate as many of the elements of FL-1 as possible within the usual limitations of available funding. The 89" diameter ablative nozzle was considered to be most important, because of the size and also because it was of the re-entrant or submerged design, which appears to be desirable for some vector control systems. It was necessary to make use of the motor case and some of the nozzle components from a previous motor. This required that the burning rate of the propellant be increased to produce mass flow necessary for the 89" diameter throat nozzle, and prevented any investigation of the special propellant charge design called for by the full length motor.

Two new secondary elements of the motor were tested in concept; a set of inert slivers for tail-off control, and the key elements of a burn-through failure warning system. Slivers have been widely used in solid rockets, hence the objective of the inclusion in the test was primarily to prove materials and manufacturing methodology. The elements of the failure warn system are a conductive rubber liner material which is to be used interchangeably with standard liners, and a tungsten probe in the combustion zone. An electric circuit external to the motor is established, with the final leg between the probe-electrode and the conductive liner completed when the combustion gases reach the liner FIGURE 2. By proper location of the conductive liner and through use in redundant circuits, a clear signal can be obtained if combustion gases have reached undesirable locations.

The limitation on motor length required that propellant with an higher burning rate be established so that the 89" diameter throat could be tested. This also resulted in burning time of 80 seconds rather than the 130 seconds of the full motor. The formulation established was similar to that used in the previous motors, but contained more burning rate additives and a modified, anhydride-free binder. It reached the design burning rate of .71 inches per second rate at 600 psi. The modification to the propellant resulted in changed processing characteristics, especially in pouring and flow properties under low head. This apparently resulted in regions of imperfect fusion among the 320 batches of propellant, and anomalies such as voids within the charge. As a consequence of these imperfections, the pressure history of SL-3 shows a number of pulses and peaks, and pieces of propellant were ejected during at least one pulse. The shock waves accompanying the solid discharge overstressed parts of the nozzle exit cone causing it to break off.

The motor was fired in a combined cast-cure-test pit on June 17, 1967. The pit concept has been described elsewhere in detail. Briefly, the motor is made and fired in a pit 120 feet deep by 55 feet in diameter. The motor is vertical in the pit exhausting upward. Propellant is made in 5,000 pound batches, brought into a movable casting building placed over the motor, and poured through three casting legs. Curing at 135°F is effected through circulation of warm air. On completion of cure, the building used for processing is rolled back, exposing the motor for firing upward. The motor is ignited by an aft-end seperable igniter which is supported on a tower placed above the nozzle. After ignition, the igniter motor rides up the tower and flys away restrained by cables. Shortly thereafter the igniter tower is retracted. The thrust and weight of the motor is taken by three five million pound load cells at the bottom of the pit. FIGURES 3 and 4 illustrate the pit concept and show a motor in the pit with igniter above it.

<u>Description of Test</u> The aft ignition motor operated as designed. It was released .284 seconds after zero time, and was free of the igniter tower shortly thereafter. The main motor achieved stable chamber pressure of 466 psi at .44 seconds, and built up to peak design pressure of 643 psi at 25 seconds, where the thrust was 5.88 M pounds. Combustion then proceded approximately as designed, except for pressure peaks resulting from the propellant anomalies mentioned above. The largest pressure pulse occurred at 66.2 seconds, accompanied by ejection of pieces of propellant through the nozzle. This produced first a negative transient in the thrust level, followed by positive pressure and thrust transients. The motor burned for an action time of 80.3 seconds, with average thrust of 5.115 M pounds and the peak thrust of 5.88 M pounds. FIGURE 5

The passage of chunks of propellant at 65 seconds resulted in shock waves and unbalanced forces in the nozzle, causing structural failure of the nozzle exit cone, ejection of the aft portion, and somewhat later, loss of the remander of the cone. FIGURE 6 shows the propellant passage event.

Results The pressure pulses near the end of burning, together with the changes produced by loss of the exit cone, masked the affectiveness of the inert slivers, so that no clear slope change could be detected in the pressure-time or thrust-time curve. The slivers themselves, made of rubber of the same composition as the liner, were essentially undamaged.

The ablation rates of the nozzle materials were close to predicted values, in a completely satisfactory range. The measured change of the throat section was equivalent to average material lost rate of 5.4 mils per second. Although the loss of the exit cone prevented quantitative measure of erosion rate on the materials in that region, the major new element of the nozzle, the submerged 89" diameter throat, was adequately tested. In fact, exposure to over-design conditions produced by the rigors of the pressure peaks, and the passage of solids can be viewed as an additional verification of design and material. FIGURE 7 shows the throat condition after firing.

The motor case, parts of the nozzle shell, and most of the internal insulation, reused from a previous firing, all performed within specification.

The recorded data from the electrical circuits of the burn-through sensor showed the predicted sharp decrease in circuit resistance as each conductive layer was exposed to the combustion gas, verifying the design principle.

The following sections will discuss in detail the design and performance of the various elements summarized above.

Case The motor case for SL-3 was previously used for motor SL-1. It is made of 18% nickel grade of maraging steel which had been vacuum arc remelted. The elements of the case are illustrated in FIGURE 8. To re-qualify it for the test, the longitudinal welds were reinspected by magnetic particle, ultrasonic and radiographic equipment. There was no indication of change in the previously documented defects, but one small porosity pocket not observed before was found. Structural and stress analysis indicated this pocket need not be repaired. The chamber was then hydrotested to pressure of 706 pounds per square inch, in the cast-test pit, using leased hydraulic pumping equipment. After hydro test, the case was removed to the motor preparation building of the Aerojet-General facility for lining and insulation rework.

Post-test inspection of the chamber showed that it had withstood the loads adequately. The strain level measured from strain gages at various locations reached a maximum in hoop of 144,500 pounds per square inch during the firing.

Chamber Insulation Most of the insulation of motor SL-1 was reused for SL-3. The principle additions were a sector of the aft insulation and the cylinder insulation FIGURE 9. Repairs were made to forward and aft components, and new forward and aft boots were installed.

The insulation thickness in the motor varied from 4.10 inches at the aft joint to .20 inches in the forward parts of the cylinder.

Conclusions about the ablation rate of the forward head insulation, (the lowest point, since the motor is fired up) are clouded by a delay in actuation of the motor quench system after the firing, during which time loose char and hot debris covered much of the forward insulation. This caused higher then normal heat degradation of the rubber. The ablation of .93 inches was greater than observed in the previous motors, probably from a combination of heat soak, pressure variation, and premature exposure of areas of insulation associated with the propellant anomalies causing the pressure surges.

In spite of these effects the forward head insulation provided adequate protection and there were no hot spots or suspect areas in the forward dome.

The char and erosion of the aft insulation was similar to that in previous motors, reaching a maximum of 2.05 inches at a joint region, out of total of 4.10 inches.

The insulation of the cylinder of the case showed the effect of propellant anomalies mentioned earlier. In numerous regions the insulation was eroded to bare metal, and in a few places high temperature was detected on the outside of the motor case. The thickness of the original insulation on the cylinder was .14 inches, and in the regions where burning was normal, ablation averaged .007 inches.

Nozzle The nozzle fabrication and assembly procedures for nozzle and exit cone components were identical to those of the previous nozzles of this class of motor. The basic materials were carbon cloth, silica cloth and rubber laminates. As stated earlier, the main advancement in SL-3 was the 89" diameter throat (versus 72" diameter previously) and the submerged design. The need for the submerged nozzle grew from the possible future use of a TVC system of the moving nozzle type, illustrated in FIGURE 10. Other TVC concepts are of course possible, but do not require the submerged portion of the movable vector systems. Note that the SL-3 nozzle, while of submerged movable design, did not in fact move.

The various sub-components of the nozzle were made by tape wrapping and curing under pressure, either in hydroclave or autoclave. After machining to final dimension, assembly of the components was made by bonding with epoxy and silicone resins. The exit cone assembly was a bonded structure consisting of the ablative liner, two end rings, and a glass-epoxy structural shell. The glass structure was built up with layers of cloth interspersed with filament windings, to thickness tapering from .62 inches at the forward end to .12 inches at the aft end.

The nose insert of the submerged nozzle gave the most problems in manufacture. Significant wrinkling of the 6" thick tape billet occurred during debulk operation at pressures of 1,000 pounds per square inch. Although there is little quantitative knowledge about the effect of such a wrinkle on the performance of the billet, the billet was reworked by removal of 3 inches of the thickness. Subsequent layers of carbon tape were formed to build up the thickness to the required dimensions.

The other components of the nozzle were made by similar wrapping technology established in the prior 260" and other large motor programs. FIGURES 11, 12, 13 illustrate some steps in the manufacture. All parts were inspected by x-ray; the bond zones were inspected ultrasonically.

In general the erosion of the nozzle components agreed well with predictions and with the results obtained in previous firings. Measurement of exit cone ablation was vitiated by loss of the exit cone. The cavity behind the submerged nozzle nose had been filled with 5,000 pounds of trowelable rubber which was cured by a 96 hour cycle at 135 degrees. The results showed that the trowelable material is an effective insulator, and in fact is more resistant to erosion then cured rubber laminates. The peak ablation rate was .048 inches a second, compared to 0.055 inches a second for the latter.

<u>Propellant Processing and Motor Casting</u> The motor case was insulated and lined in a seperate building after the hydro test, as mentioned earlier. It was then returned to the cast-cure-test pit and the casting core inserted. It is interesting to note that the feared problem in removing the core from large propellant charges has never materialized, and hence the need for a collapsible core has not arisen. In fact, the extraction of the core from this motor required net force of only 53,000 pounds above the weight of the core itself. There was no indication of propellant sticking on the core. FIGURES 14 and 15 give some illustration of core manufacture and extraction.

The propellant load of 1,656,000 pounds was cast during the period February 13 to March 2. Three hundred and thirty four batches were made in vertical batch mixure of 5,000 pounds capacity, and 320 were qualified for casting. Curing by 135°F air was carried on for 21 days, and cool-down required another 2 weeks with the air temperature reduced to 60 to 65°F.

The propellant in the motor was a modification of that used in the previous two motors, with the burning rate raised to .71 inches per second through change of oxidizer blend and modification of the burning rate catalyst. The major problem was achieving the burning rate with satisfactory viscosity and propellant flow characteristics. The propellant flow and physical properties were determined by laboratory measurements and tests, but the subsequent results show that conditions in processing the large motor are appreciably different from those of the laboratory.

The first indication of discrepency in this respect was from visual inspection of the grain bore. Although there were no grain cracks in the usual sense of the word, there were numerous surface defects which appeared to result from propellant folds or from imperfect fusion of propellant batches. An example of such a flaw is seen at the upper left of FIGURE 16.

Circumstantial evidence and observation leads to the hypothesis that the viscosity of the modified propellant under the low shear stress of casting is sensitive to the efficiency of deairation during mixing. This is based on observation that change in the deairation or vacuum mix cycle from 20 minutes for early batches of propellant to 30 minutes for later batches coincides with significant reduction in the number and severity of the grain bore defects. Prior to the change in the vacuum mix cycle, the average number of defects per foot of bore was 4.1, and the average defect void volume exposed to examination was 11.7 cubic inches. After the change in the vacuum cycle, these factors dropped to 1.9 per foot of length and 4.3 cubic inches respectively. It appears then that certain combinations of batch viscosity (resulting from variability in efficiency of deairation), location of the batch within the chamber, and other casting variables resulted in the grain defects causing the observed performance anomalies.

Laboratory testing had indicated that viscosity difference between the original propellant and the high burn-rate propellant was about 1000 poises, hardly enough to explain the major difference in casting and amalgamation properties. Subsequently a subscale motor containing 20,000 pounds of modified propellant was made and fired successfully, apparently serving to verify the laboratory conclusions.

Insulation Burn-Through Sensor Demonstration Good signals from the insulation burn-through sensor were obtained. With a potential of 12 volts between the probe and the conductive liner, the resistance of the circuit changed from the nominal 1M ohms to 200 ohms when the flame reached the liner. In addition, the slope of resistance versus time gave prior warning to burn-through as the char layer approached the conductive layer, changing the characteristics of the circuit.

Conclusion The manufacture and test of motor SL-3 has resulted in the following accomplishments: 1) a nozzle of ablative composite design for thrust near 6M pounds has been demonstrated for duration of 80 seconds, with enough data generated on ablation and erosion to support the conclusion that durations of more than 2 minutes will be possible; 2) the submerged structure and the surrounding insulation for a moving nozzle type of vector control system has been evaluated, with similar conclusions about burn time; 3) the key elements of a burn-through detection and warning system have been tested, verifying the concept under the limitation of short circuit path; 4) the manufacture method for inert slivers for large motors has been established; 5) the reuse of insulation has been demonstrated; 6) the requalification and reuse of large motor cases made of marage steel has been shown. On the negative side, the SL-3 test has shown that deeper understanding of the processing methodology of large multi-batch motors must be obtained, in relation to the flow and viscosity properties measured in the laboratory.