ULTRASONIC AND EDDY CURRENT CHARACTERIZATION OF IMPACT DAMAGE IN GRAPHITE/EPOXY ROCKET MOTOR CASES

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INTRODUCTION

Composite materials are widely used in both commercial and defense solid rocket motors (SRM). A typical SRM is shown at Figure 1. Composite parts include, but are not limited to, the case, nozzle, flex seal, igniter, attachments mounting pads, and stiffener rings. They provide an advantage of high strength to weight ratio. In addition these materials are relatively inert chemically and are not subject to corrosion during storage as are metal components. However reduced performance in rocket motors can result from a number of factors. The defects may be introduced during the manufacturing process. This includes bondline contamination, improperly cured materials, porosity and low-density materials. Some of motors have an extended shelf life and thus chemical aging may lead to the degradation of mechanical properties. Impact damage is of big concern for composite SRMs due to the brittle nature of graphite epoxy composite materials. Impact damage could be sustained during manufacturing, transportation and storage of SRMs and can potentially lead to catastrophic failure.

Impact damage causes a combination of fiber breakage, matrix cracks and delaminations. The factors, which potentially influence the damage extent, are porosity, structure support conditions and location of the impact on the structure. An unsupported case, when the motor is not loaded, is more susceptible to delaminations when impacted than a case backed with insulator and propellant as in a loaded motor. Fiber breakage is the primary concern in the cylinder part of the motor case because in-plane tensile loads are predominant there. Delaminations are a concern when there are in-plane shear and compressive loads, which occur in domes, skirts and nozzles. Assessing the effect of damage is accomplished empirically by materials testing, analytically by using fracture analysis, or by combining both analytical and empirical methods. NDE must provide data for the analyst which describes the damage in terms of the number of broken fibers, extent of delaminations and cracks, and the effect on elastic properties.

This paper addresses the nondestructive characterization of impact damage in composite SRM case materials. It is demonstrated that ultrasonic and eddy current inspections provide complimentary information about impact damage.

IMPACT DAMAGE TEST MATRIX

Filament wound graphite/epoxy composite plates $[0,+30,-30,90]_6$ were used in this study. Eight 4 inch x 4 inch coupons were cut from each of five 12 inch x 12 inch plates. These plates were manufactured with different porosity levels resulting from different levels of compression during cure. Plate thicknesses were around 0.25 inch, slightly increasing with the increase in porosity.

Each coupon was impact-damaged at its center using a Dynatup Model 8200 Drop Weight Impact Test Machine. The machine consisted of a drop weight to which an instrumented tup was attached. The tup was used to measure the impulse (force versus time) of the impact event. A ½-inch hemispherical steelhead attached to the end of the tup was used to impact the coupons. Solid and edge support conditions were used to support coupons during the impact (Figure 2a).

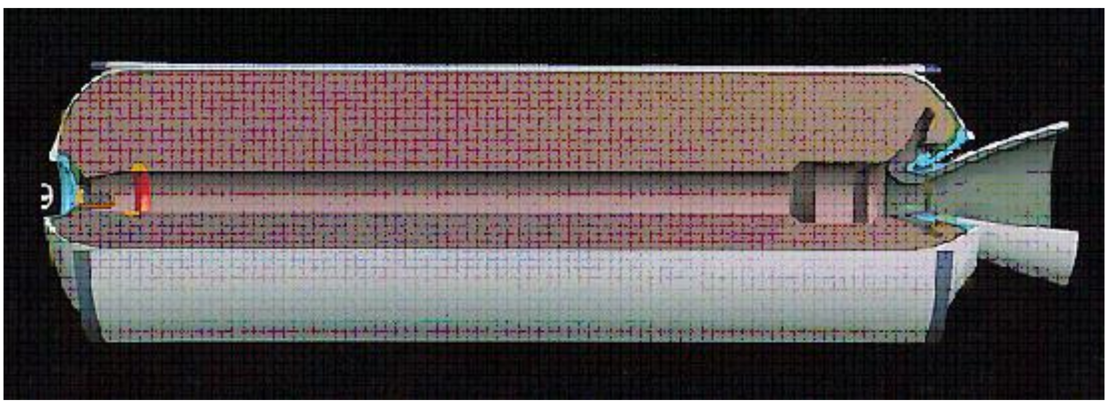

Figure 1. Typical solid rocket motor (SRM).

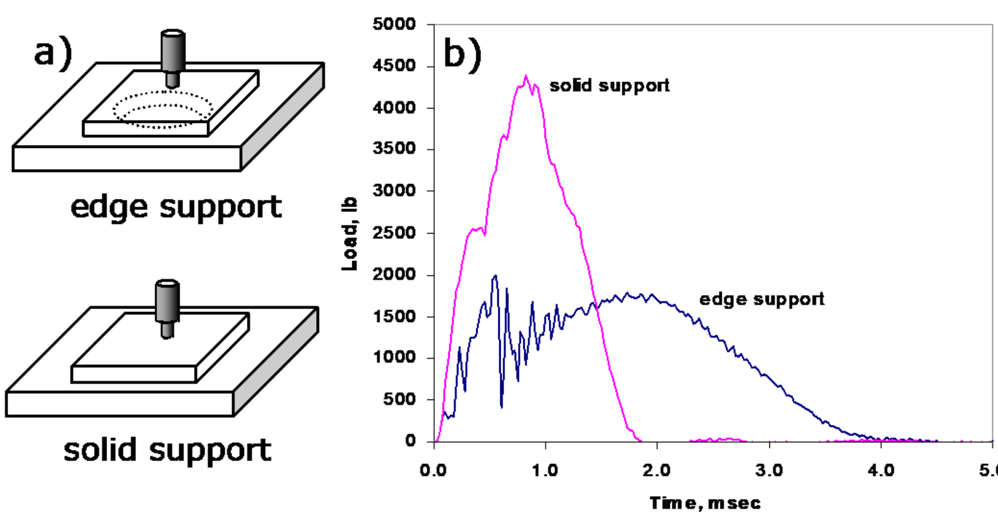

Figure 2. (a) Solid and edge support conditions; (b) Typical impulse curves for solid- and edge-supported coupons.

The solid-support conditions were achieved by placing a large steel specimen under the coupon. The edge support conditions were achieved by placing the coupon over a 3-inch diameter hole. These different support conditions were chosen to simulate impact on an empty motor (edge support) and on a loaded motor (solid support).

Of the eight coupons cut from each panel, four were impacted using solid support and impact energy levels of 10, 20, 30 and 40 ft-lb and the remaining four were impacted using edge supports and the same energy levels. These test conditions were applied to coupons cut from each of the panels for a total of five sets with eight coupons in each set. Most of the impacts left an almost undetectable (by eye) dent on the coupon's surface, with a diameter of approximately 3/8". No other damage was visually detected. The only exceptions were coupons damaged with edge support conditions and an impact energy level of 40 ft-lb. Near-surface fiber breakage was visible in these cases.

The composite response to impact loading with solid and edge support conditions and different energy levels is shown in Figure 2b. One can see that these two responses are distinctly different. Edge support conditions lead to lower amplitude, longer duration impulses. Also, edge support impulse curves exhibit a significant load drop at about 1,500 pounds that is associated with material damage. This load drop occurred for all considered impact energy levels. Gardiner and Pearson [1] demonstrated that this load drop is caused by the formation of interply delaminations that result from shear stresses caused by the plate flexure. The solid-support impulse curve shows small periodic load drops that may be attributable to localized matrix cracking and fiber breakage

Before damaging the coupons, ultrasonic wave velocities and attenuations were measured in each coupon to characterize porosity. The results of these measurements are summarized in Figure 3. A higher degree of porosity leads to a reduction in the velocity and an increase in the attenuation. The five sets of coupons were ordered from low-to-high porosity based on the wavespeed and attenuation measurements.

From impulse curves for different porosity levels it was found that for solid-supported coupons the increase in porosity results in lengthening of the impulse response. For edge-supported coupons the increase in porosity leads to the dampening of ringing after the load drop.

ULTRASONIC MEASUREMENTS

Determination of Lateral Damage Size

To determine the lateral damage size, the coupons were immersed in a water tank and scanned in the through-transmission mode. Two 2-MHz, 0.5-inch diameter focused transducers with the 2-inch focal length were used as a transmitter and a receiver. For solid-supported coupons the 2 x 2-inch area surrounding the point of impact was scanned with a step size of 0.02 inch. Edge-supported coupons were scanned over a 3.3 x 3.3-inch area with a 0.1-inch step size. It was found that the size of the damaged area for solid supported coupons expectedly increases with an increase in impact energy level, but is well contained within a 0.5-inch diameter circular area. Figure 4 compares C-Scans for solid supported coupons with impact energy of 40 ft-lb and edge supported coupons with impact energy of 10 ft-lb. The lateral damage extent is much higher for the edge-supported coupons. This is an expected result, because edge supported coupons absorb the majority of the impact energy, while for the solid supported coupons the support plate absorbs part of the energy. The size of the damaged area for edge-supported coupons increases with an increase in the impact energy level as well. At the impact of 40 ft-lb almost the entire panel is damaged and one can see the delaminations reaching the edge of the panel.

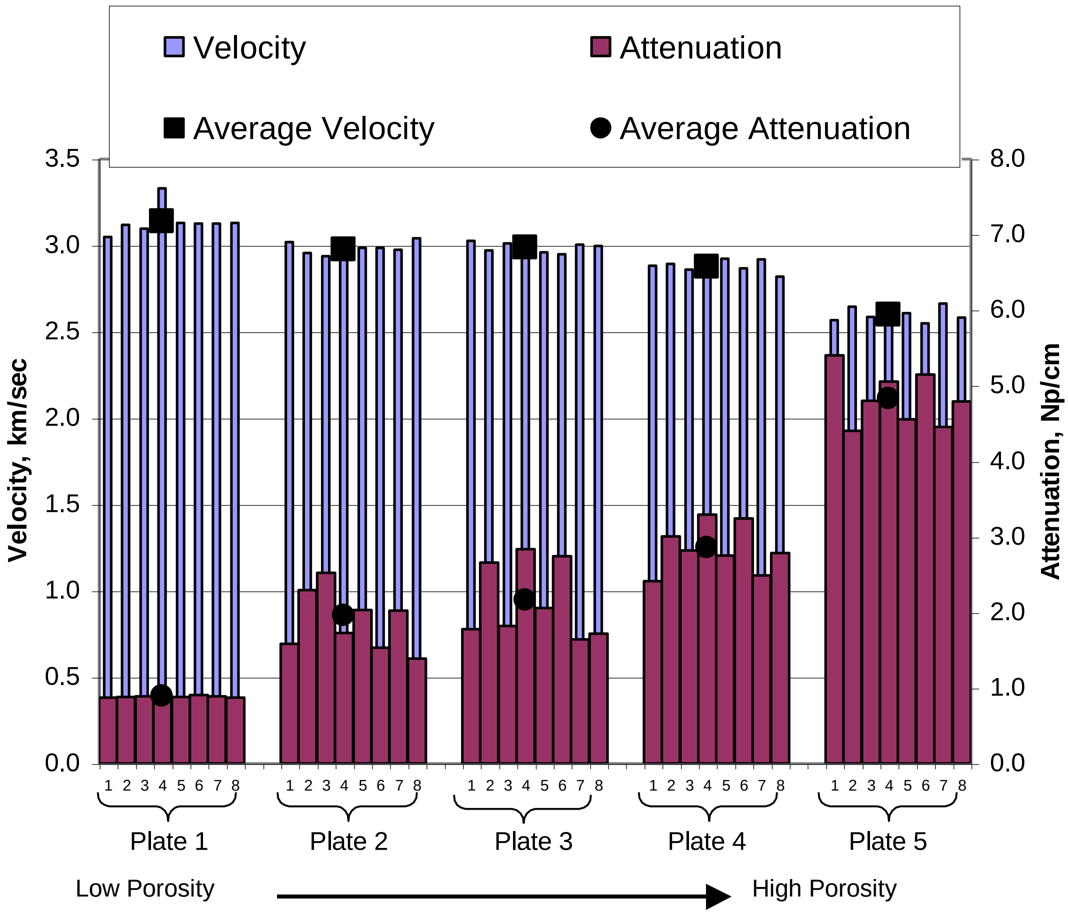

Figure 3. Ultrasonic wave velocities and attenuations of the undamaged coupons.

The image resolution decreases with porosity increase because of the increase in in the background noise level of the signal. The comparison of C-scan images of lowest and highest porosity coupons for both solid and edge supports show that higher porosity significantly reduces the image resolution. Lateral damage size was determined from through-transmission C-scan images. The results for all coupons are summarized in Figure 5. No clear correlation was found between porosity and damage size. This can be attributed to the inhomogeneous condition of the composite specimens. There is a variation in the damage between the coupons since impacts occur at points of higher and lower fiber concentration.

Determination of In-depth Damage Size

For determination of in-depth damage information the coupons were scanned in a pulse-echo mode. The same 2-MHz focused transducer was used as both transmitter and receiver. The measurements were performed from both the impact and the back sides of the plates.

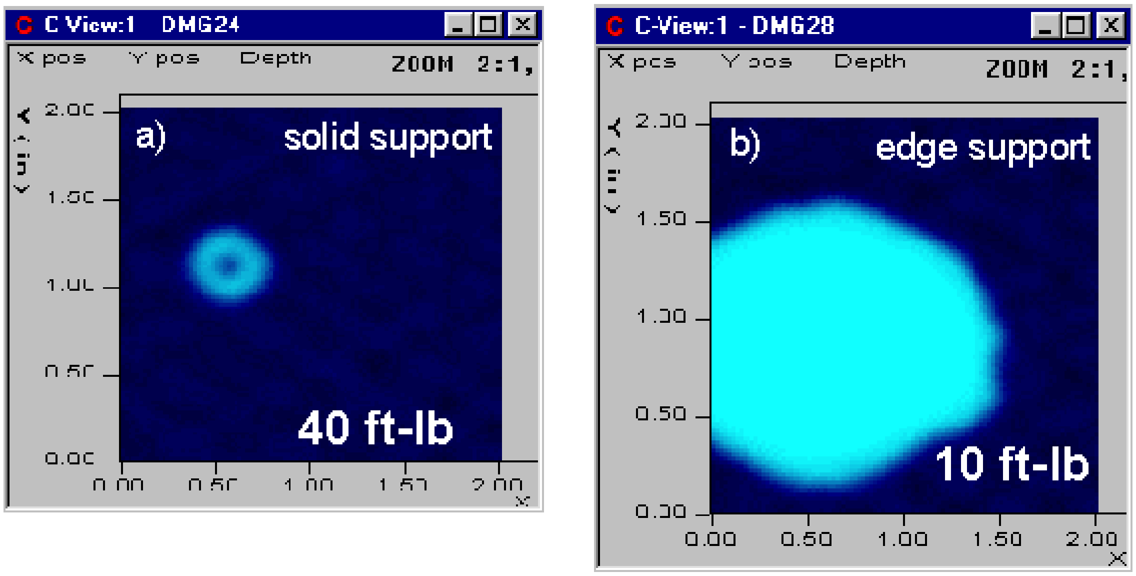

Figure 4. Through-transmission C-Scans of (a) solid- and (b) edge-supported coupons of low-porosity, impact damaged with energy of 40 and 10 ft-lb. respectively.

From backside measurements for edge-supported coupons it was observed that ultrasound is reflected from layers close to the back (opposite to impact) surface of the plate. This means that delaminations most likely occur in layers through the entire thickness of the composite plate. It was found that for solid supported coupons only a small in-depth region is damaged. The depth size of the region was determined from waveforms collected from the backside of the coupons. The results for low-porosity plates are shown in Table 1. The lack of clear dependence between impact energy level and the depth of the damaged region could be a result of the material inhomogeneity and non-uniform thickness. The depth of the damaged region is around 0.06 inch for solid-supported coupons and almost the entire plate thickness (0.25 inch) for edge-supported coupons.

Impact Energy, ft-lb	Damage region depth, in.
10	0.0636
20	0.0626
30	0.0598
40	0.0668

Table 1. Depth of the Impact-Damaged Region for Solid-Supported Low-Porosity Coupons

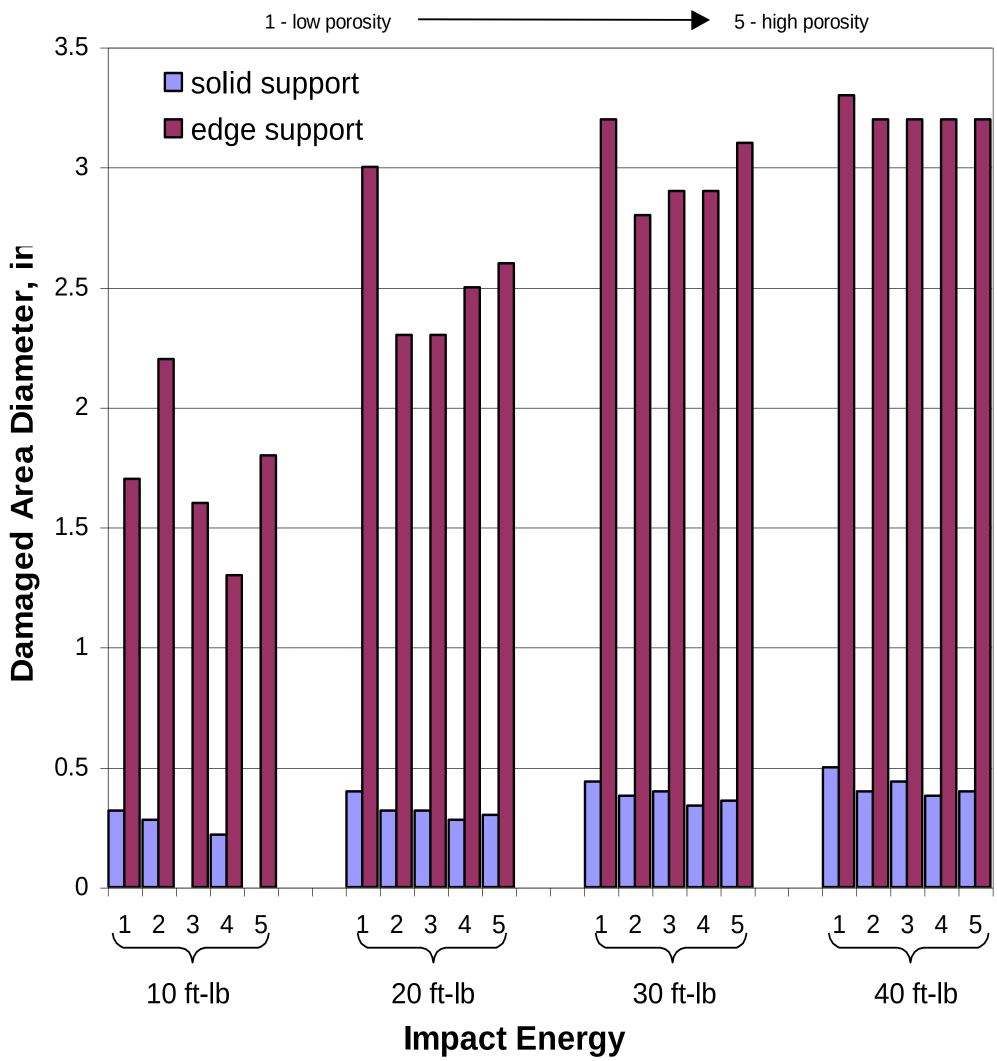

Figure 5. Lateral size of the damaged region calculated from through-transmission C-scans

EDDY CURRENT MEASUREMENTS

Eddy current C-Scans were collected on the same coupons. An HP 4192A Impedance Analyzer was used to drive the coil and to measure its complex electrical impedance. 3/8" radius coil was attached to the scanner and kept in constant contact with the surface of the coupons by a spring loaded fixture. A single frequency of 2 MHz was used in these measurements.

For the coupons, which were impact damaged using solid support, the electrical impedance only changed slightly when the coil was scanned over the damaged area. For the edge-supported coupons the changes were much more pronounced. Figure 6 shows a C-Scan of the reactance for the edge-supported coupon impacted with 40 ft-lb. One can see that in addition to the small circular region of higher reactance around the point of impact, there is also a line of higher reactance, which follows the –45°-fiber direction. It was believed that the fibers were broken in this direction. To verify this hypothesis, the epoxy resin was baked off by putting the coupon into an oven at 800° F for one hour. The coupon was then deplied layer by layer. Photographs were taken after the removal of each layer. The photograph of the first 90° layer (fourth layer) is shown at Figure 7. One can see that there is fiber breakage in the –45° direction which corresponds to the indication on the C-scan eddy current image of Figure 6.

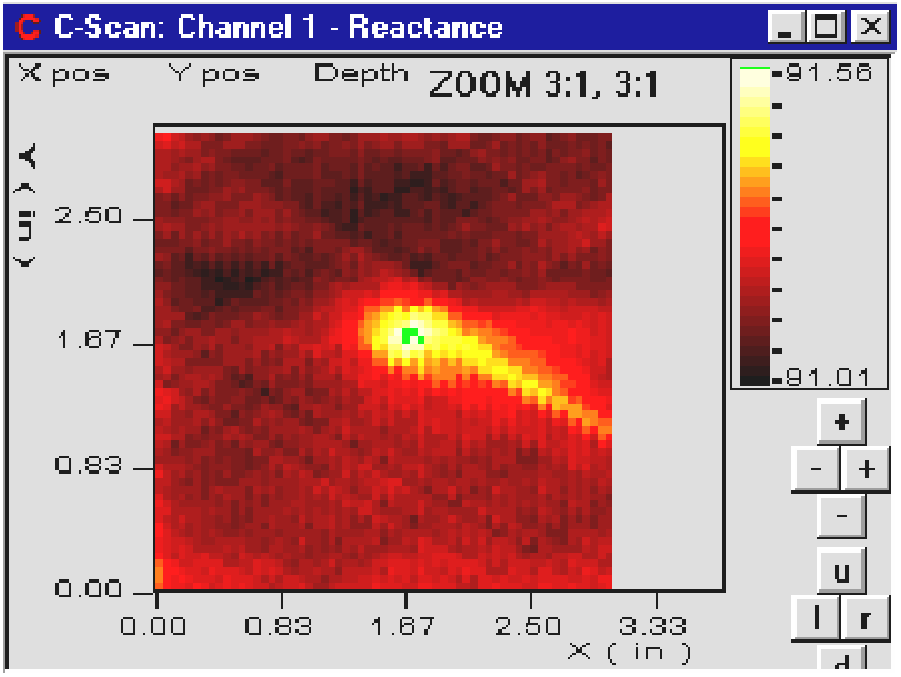

Figure 6. Eddy current scan image of the coupon impact-damaged with edge support and energy level of 40 ft-lb.

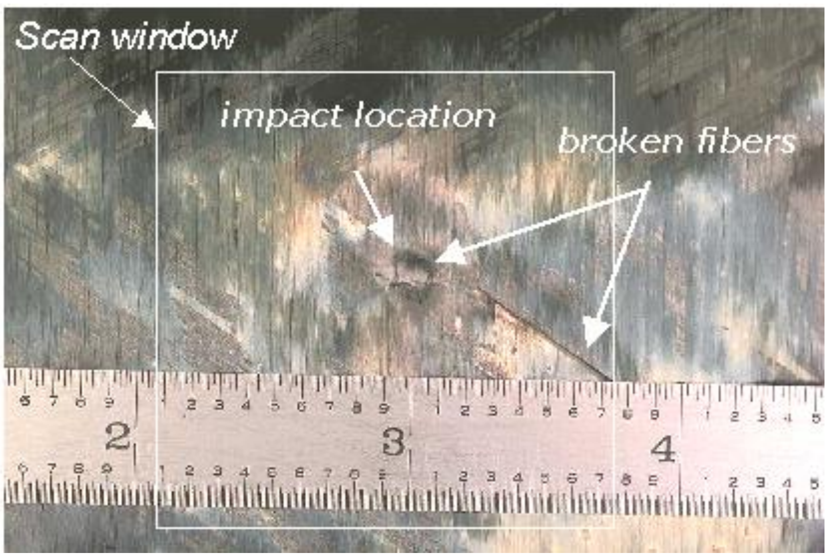

Figure 7. Photograph of deplied 4th layer (90° direction) of the coupon impact-damaged with edge support and energy level of 40 ft-lb

SUMMARY AND CONCLUSIONS

The results of this study have demonstrated that ultrasound and eddy current provide the complimentary information about the impact damage in carbon fiber composites. Normal incidence ultrasonics is primarily sensitive to matrix cracks and delaminations. Eddy current is primarily sensitive to fiber damage. The combination of these techniques is needed for a complete nondestructive characterization of impact damage in composite rocket motor cases.

REFERENCES

1. D. S. Gardiner and L. H. Pearson, Experimental Techniques, 22-28 (November 1985).
2. L. H. Pearson, Thiokol Report TWR-40286, Thiokol Propulsion (1992).