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Solving the Blow-By Problem in a Two-Stage Gun[1]

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Abstract

Blow-by is a common occurrence in two-stage light gas guns. Although the blow-by is often inconsequential, it can sometimes present a serious problem. Various projectile designs have been tried to prevent blow-by, and a successful design is described. Computer calculations which clarify the dynamic performance of the design are presented, along with a parameter variation study to indicate the sensitivity of the design to certain geometric parameters.

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Introduction

In two-stage light gas guns, high-pressure hydrogen gas is used to propel the second-stage projectile to a hypervelocity [1]. Most of the researchers who use these guns are aware that some of the hydrogen blows past the projectile during most launches. Evidence for the blow-by has come from unexpected pre-shorting of electrical probes at the target by ionized blow-by gas, or from a slight pressure buildup just prior to the projectile impact.

Little has apparently been done to study or to prevent blow-by, probably because electrical probes can be shielded, and because the pressure buildup before impact is easily mitigated by even a short free flight of the projectile in an evacuated chamber before impact. However, when our experiments required a VISAR [2] laser beam to *see* the projectile nose during the launch, it was found that the blow-by gas is opaque, which posed a serious problem for continuous in-bore VISAR measurement of projectile velocity. It was also perceived that blow-by presented other problems for an experimental program aimed at understanding Taylor instabilities. Therefore, the present study of blow-by and methods for its prevention was undertaken.

The next section will present experimental data on the characteristics of the blow-by phenomenon, from which a blow-by scenario will be deduced to explain the observations. Efforts to prevent blow-by will then be described, including the development of a sabot design which solves the blow-by problem. Finally, computer simulations of the successful sabot design are presented to show why the design works, and to estimate the optimum geometrical parameters of the sabot.

The Blow-By Phenomenon

The blow-by shorting of electrical probes at the target several microseconds before impact, and the pressure build-up just prior to impact have already been mentioned. In a recent experiment in which blow-by gases were purposely trapped between the target and the projectile, the gas pressure reached 18 kbar at about 25 ns before impact at 6 km/s. The gun barrel had been evacuated before the shot, and a calculation of the compression of the residual gas in the barrel accounted for less than 1 per cent of the observed precursor pressure buildup.

Perhaps the most dramatic evidence of the timing and character of the blow-by has come from VISAR measurements of the in-bore projectile velocity history. A schematic of the experiment appears in Fig. 1, where it can be seen that any blow-by gas would, if opaque, snuff out the laser light which reflects from the projectile nose. Before showing a return beam measurement, it is helpful to discuss what the return beam intensity history should be in the absence of blow-by. First, the returned light intensity should increase as the projectile moves through the gun barrel because of the inverse square effect as the distance from the projectile to the VISAR decreases. Second, as the plastic sabot slides through the gun barrel, the friction raises the sabot surface temperature to the vaporization point, causing a trail of dense smoke to be left in the gas behind the projectile. Also, at the leading edge of the sabot, a small amount of the smoke generated there may remain ahead of the projectile. The accumulation of smoke ahead of the projectile can be expected to gradually attenuate the VISAR laser beam, counteracting the tendency for the beam intensity to increase due to the inverse square effect.

A typical return beam intensity history is shown in Fig. 2. The intensity begins to increase early in the launch, in agreement with our expectations based on the inverse square effect. Similarly, somewhat later, the intensity reaches a peak and slowly begins decreasing, indicating the gradual accumulation of smoke due to vaporization at the leading shoulder of the sabot, also as expected. At about 1100 μs after the start of the launch, however, the light intensity very suddenly drops to zero! The fall time of the intensity drop is less than 20 μs, far shorter than could be reasonably attributed to more smoke from the leading shoulder of the sabot. Thus, we suspect that a sudden loss of sealing (blow-by) occurred, carrying dense smoke from behind the projectile and extinguishing the laser beam. But what would cause such a sudden release of blow-by gas?

To answer this question, we consider what happens to the sabot during the launch. Initially, it is machined to a diameter slightly larger than the breech bore diameter, and it must be pressed into the breech to the firing position. (Failure to achieve a firm press fit has resulted in immediate blow-by before any significant projectile motion.)

Pressing the slightly oversized sabot into the barrel results in a small initial component of radial stress against the barrel wall.

When the driving gas pressure is applied, the projectile inertia leads to an axial compressive stress in the sabot. The sabot material has a large Poisson ratio, resulting in an increase in the radial stress at the sabot/barrel interface nearly equal to the increase in the driving gas pressure. However, this second component of radial stress must always be less than the driving gas pressure because of the finite sabot strength.

As the projectile slides through the barrel at ever higher velocity, the periphery of the sabot is eroded away and left behind as smoke. The erosion does not immediately preclude sealing, however, for although the press fit component of the interface pressure disappears, the Poisson ratio effect may maintain sufficient sealing pressure to prevent blow-by.

Shortly after peak pressure, however, the combination of increasing erosion and decreasing driving gas pressure allows some driving gas to penetrate between the sabot and the wall. This undoubtedly occurs first on one side of the sabot – it is quite unlikely to be perfectly symmetric (Fig. 3). At this point, the driving gas pressure suddenly slams the sabot away from the side of first gas infiltration, and gross blow-by occurs in a sudden burst. Even in the case of perfectly symmetric gas infiltration, the resulting gas-driven radial compression of the already-eroded sabot would immediately produce a large annular gap around the sabot, with consequent sudden blow-by.

The agreement of this scenario with observations, namely the occurrence of blow-by after peak pressure and the suddenness of the light extinction, tends to confirm its validity.

Designing Against Blow-By

Since it seems clear that blow-by is related to the erosion of the outside diameter of the plastic sabot, perhaps the first remedy that comes to mind is to hone the inside of the gun barrel to a much smoother finish in hopes of minimizing the erosion. This has been tried, but unfortunately it has little effect on the blow-by. The normal smoothness of our gun barrels is about 16 microinches, and the erosion rate is apparently affected very little by further smoothing.

Another approach would be to compensate for the sabot erosion by using a tapered gun barrel, such that the barrel continually squeezes the sabot in spite of the erosion (Fig. 4). This does indeed solve the problem [3], but it significantly complicates gun maintenance procedures.

Our approach has been to design a sabot which would continue to maintain the seal against blow-by even in the presence of considerable erosion during the launch. One should be able to make use of the driving gas pressure to force a sabot fin against the barrel wall, for example (Fig. 5). Calculations show that the driving pressure should easily expand the fin to maintain nearly the same pressure between the fin and the barrel wall, even after considerable erosion. Although there may be successful finned sabot designs, the ones we have tried have not worked well. Maintaining a sabot/barrel interface stress larger than the driving pressure is apparently required for a consistent seal.

Another idea made use of two sets of fins - - a twin finned sabot (Fig. 6). Here again, the designs we tried failed to prevent blow-by. Other unsuccessful designs we have tried will not be described. It is sufficient to note that ten designs were tested and found unacceptable before the workable design was found.

The successful design is shown in Fig. 7. It has a fin which is pressed against the barrel wall by a wedge ring that fits in the fin slot. Note that the wedge ring can slide forward to maintain the seal as erosion occurs. The side pressure exerted by the wedge ring is controlled by the driving pressure, the wedge angle, and the unsupported area ahead of the wedge; it does not rely solely on Poisson ratio effects as did some earlier designs. The wedge ring design requires friction to be small between the wedge ring and the slot in which it moves. This is accomplished by lubricating the surfaces with a medium vacuum grease. Measurements of the resulting coefficient of friction have been made under pressure conditions approaching those experienced during the launch. It was found that the friction coefficient is less than 0.012. The outside of the sabot and the inside of the barrel where the projectile is initially seated are also lightly lubricated with the same grease to prevent static friction from tearing off the fin at the start of the launch.

The measured VISAR return beam intensity history for a shot using the wedge ring sabot of Fig. 7 is shown in Fig. 8, where the typical blow-by history of Fig. 2 is reproduced for comparison. Note the similarity of the two traces up to the time of the very sudden light loss due to blow-by. No sudden light loss occurs with the wedge ring sabot, although there is a continuing gradual loss of light due to smoke from the leading shoulder of the sabot, as expected. A flash X-ray taken of the sabot just after exit from the muzzle of the gun showed the wedge ring still in its slot.

A sure way to prevent blow-by is to maintain a greater sabot pressure against the barrel wall than the driving pressure on the rear of the sabot. The wedge ring sabot does precisely that according to computer calculations discussed in the next section.

Analysis

The behavior of the wedge ring sabot during launch within a two-stage light gas gun is quite complex with several nonlinear processes occurring simultaneously. These include plasticity of the sabot and wedge ring, and frictional effects between the gun barrel and the sabot as well as between the wedge ring and the main body of the sabot. Analyses of such nonlinearities are among the capabilities of the transient dynamic finite element analysis code, PRONTO-2D [4], which was used in this study. Both the projectile geometry and loading were assumed to be axisymmetric. The finite element mesh used for the analysis is shown in Fig. 9. The driving gas pressure was applied to the base of the projectile, and the projectile was allowed to accelerate down the gun barrel. A simplified dual ramp pressure loading was applied in which the pressure increased linearly from zero to 276 MPa (40,000 psi) over the initial 0.3 ms, and then decreased linearly to 14 MPa (2,000 psi) over the next 1.4 ms, for a total duration of 1.7 ms.

The gun barrel was treated as a rigid surface because of the large difference in stiffness and strength between the polycarbonate sabot and the high strength steel barrel. The contact surface algorithm within PRONTO-2D calculates the normal forces required to prevent the nodes on the sabot surface from penetrating the rigid surface of the gun barrel. Friction forces are derived from a dynamic velocity dependent coefficient of friction (μ) calculated according to Equation 1.

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\, e^{-\gamma v_s}, \tag{1}$$

where μ_∞ and μ_0 are the high velocity and static coefficients of friction, respectively, γ is the decay constant, and v_s is the relative velocity of the contacting surfaces. In the results shown below, μ_0 was taken to be 0.3, μ_∞ was 0.03, while γ was 2.5 $\times 10^{-5}$ with v_s having units of m/sec. Erosion of the outside surface of the sabot is simulated by a slight taper of the rigid surface. The rigid surface increases its diameter by 0.02 mm for every meter of length. For the 8 m long gas gun barrel, 0.16 mm total diameter change was modelled.

The contact surfaces between the wedge ring and the main body of the sabot were assumed to have a constant friction coefficient, because no high surface velocities occur. Static testing indicated a coefficient of friction of less than 0.01 for polycarbonate on polycarbonate, lubricated by vacuum grease. This value, 0.01, was used for the results shown below.

A polycarbonate (Lexan) was used for both the wedge ring and the main body of the sabot. The compressive yield strength of polycarbonate is affected by both strain rate and by hydrostatic pressure. At a strain rate above $1 \times 10^{-3}\ s^{-1}$, the compressive yield strength of polycarbonate is about 120 MPa (17,400 psi) [5]. For a 345 MPa

(50,000 psi) hydrostatic compression, the yield strength increases by another 46 MPa (6,600 psi) [6]. A pressure dependent yield strength material model with zero strain hardening was used which takes the following form.

$$\sigma_y = a_0 + a_1 P + a_2 P^2, \tag{2}$$

where σ_y is the yield strength, a_0, a_1, a_2 are constants, and P is the hydrostatic pressure. The mechanical properties used for the results shown below are listed in Table 1.

Table 1. Mechanical Properties of Polycarbonate (Lexan)

Mechanical Property	S.I. Units	English Units
Young's Modulus	2,340 MPa	0.34×10^6 Psi
Poisson's Ratio	0.38	0.38
Shear Modulus	1,700 MPa	0.246×10^6 Psi
Bulk Modulus	3,260 MPa	0.472×10^6 Psi
Yield Strength a_0	120 MPa	17.4×10^3 Psi
Linear Pressure Constant a_1	0.132	0.132
Quadratic Pressure Constant a_2	0.	0.

As the pressure on the tail of the projectile increases, the wedge ring is driven into the fin slot at the same time as the projectile accelerates down the gun barrel. Fig. 10 displays the unmagnified deformed shape of the sabot tail and wedge ring at 0.3 ms, the time maximum pressure applied to the tail of the projectile after a travel of approximately 95 mm (3.7 in) down the barrel. Also shown in Fig. 10 are contour plots of the R-direction stresses in the sabot. Near the outside diameter of the sabot, the R-direction stress is a very good estimate of the interfacial pressure between the sabot and the gun barrel. It is assumed that blow-by will not occur if the interfacial pressure between the gun barrel and the sabot is greater than the driving pressure applied to the tail. The R-direction stresses in the sabot fin outboard of the wedge ring are greater than the driving pressure, indicating that blow-by should not occur at maximum driving pressure. However, experimental evidence shows that blow-by typically occurs after peak load. Fig. 11 repeats Fig. 10 at 1.7 ms, just before exit from the gun barrel, when the driving pressure has fallen to 14 MPa (2,000 psi). As was the case for maximum driving pressure, the R-direction stresses outboard of the wedge ring are still higher than the driving pressure. To indicate the behavior over the entire launch event, the R-direction stresses outboard of the wedge ring (elements 323 to 327 indicated in Fig. 9.) are shown as a function of time in Fig. 12. These stresses, representative of the interfacial pressure between the gun barrel and the sabot, are higher than the driving pressure throughout the launch. This indicates that blow-by will not occur.

A series of analyses were performed to determine the effect of various parameters on the behavior of the wedge ring seal. Only the major conclusions of these analyses will be mentioned here. There were no significant effects on the behavior of the wedge ring sabot of changing the wedge angle between 20° and 40°. The behavior was also unaffected by increasing the coefficient friction between the sabot and the wedge ring up to a value of 0.15. Likewise, changing the barrel static friction coefficient between zero and 0.3 or the barrel taper between zero and 0.02 mm/m (simulating sabot erosion) had no effect on the results.

Although the wedge ring sabot has been tested for blow-by prevention only twice at this writing, those two successes and the computer analysis described above generate a high level of confidence in the ability of the design to consistently prevent the blow-by phenomenon.

Conclusions

A projectile design which prevents blow-by in a two-stage light gas gun has been successfully tested. A computer analysis reveals information on the projectile's performance, and also indicates that successful performance is not overly sensitive to certain geometric design parameters. The new design should prove valuable in those cases where blow-by can be a problem.

Acknowledgments

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References

1. J. R. Asay, "The Sandia National Laboratories Shock Thermodynamics Applied Research (STAR) Facility," Sandia National Laboratories Report SAND81-1901, 1981.

2. L. M. Barker and R. E. Hollenbach, "Laser Interferometer for Measuring High Velocities of Any Reflecting Surface," J. Appl. Phys., Vol. 43, pp. 4669-4675, 1972.

3. A. J. Cable, private communication.

4. L. M. Taylor and D. P. Flanagan, "PRONTO 2D: A Two-Dimensional Transient Solid Dynamics Program," SAND86-0594, Sandia National Laboratories, Albuquerque, New Mexico, March, 1987.

5. W. A. Olsson, "Dynamic Compressive Strength of Vespel and Lexan," Memo to G. W. Wellman, Sandia National Laboratories, Albuquerque, New Mexico, March 2, 1989.

6. D. R. Mears and K. D. Pate, "Deformation and Fracture Characteristics of Polycarbonate Under High Pressure," Polymer Letters, Vol. 7, 1969, pp. 349-352.

Figure Captions

Fig. 1. Blow-by detecting experiment. The return light intensity suddenly drops to zero at the time of first blow-by because of smoke in the blow-by gas.

Fig. 2. Typical return light intensity history before correcting the blow-by problem.

Fig. 3. Sequence leading to blow-by. In (a), the press-fit projectile has just started moving in response to a rising driving gas pressure. In (b), the driving gas pressure reaches a maximum, the projectile accelerates rapidly, and friction vaporizes the outer skin of the sabot, leaving a trail of smoke. A small amount of smoke from the leading shoulder of the sabot gets ahead of the projectile. By (c), the decreasing driving gas pressure on the eroded sabot can no longer maintain sufficient contact pressure with the barrel, and blow-by suddenly occurs.

Fig. 4. Slightly tapering the launch tube to a smaller diameter at the muzzle compensates for sabot erosion and prevents blow-by [3].

Fig. 5. Finned sabot design. The pressure between the fin and the barrel tends to be approximately equal to the driving pressure.

Fig. 6. Twin finned sabot.

Fig. 7. Wedge ring sabot. The base pressure pushes the wedge ring forward, expanding the fins to maintain a higher contact pressure with the barrel wall than the driving pressure, even after considerable erosion.

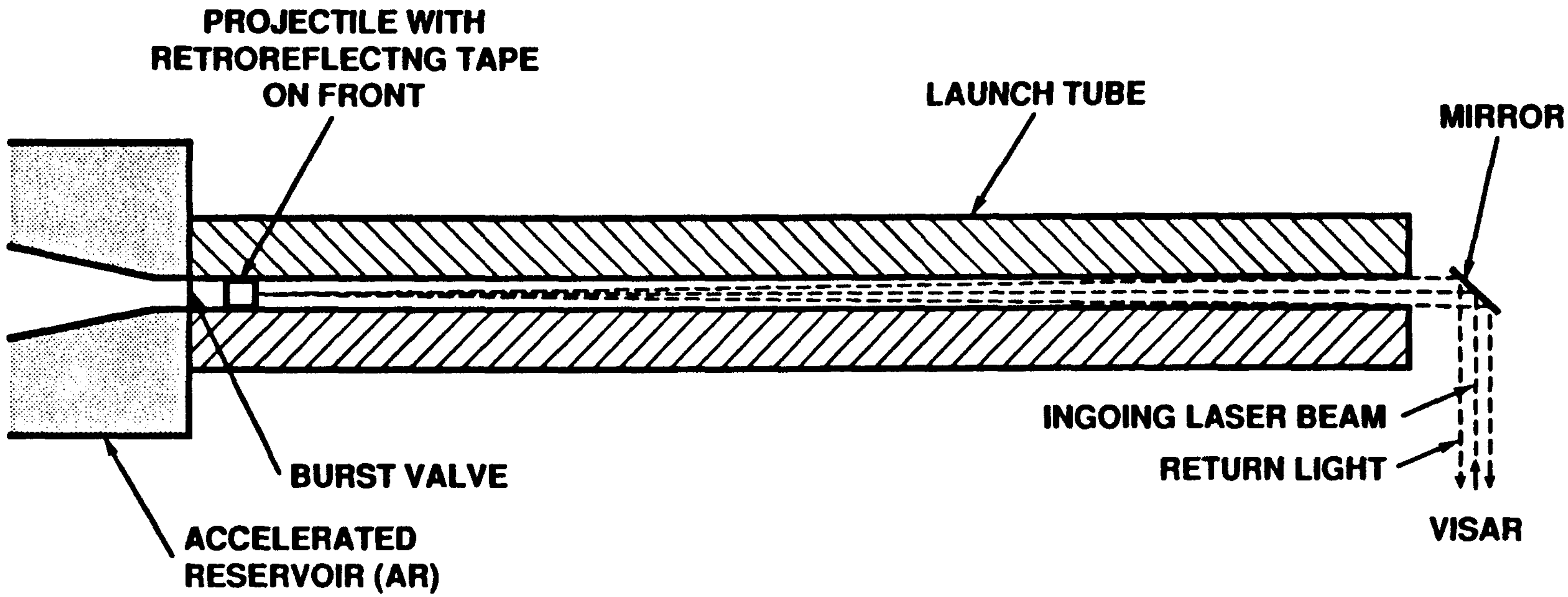
Fig. 8. Comparison of return light intensities for a normal projectile suffering blow-by and a projectile with the wedge ring sabot which prevents blow-by.

Fig. 9. Finite element mesh used for the projectile analysis.

Fig. 10. Contour plot of Radial-direction stresses on the deformed shape of the sabot tail at 0.3 ms. Note: compressive stress is negative.

Fig. 11. Contour plot of Radial-direction stresses on the deformed shape of the sabot tail at 1.7 ms. Note: compressive stress is negative.

Fig. 12. Comparison of the interface pressure between the gun barrel and the sabot to the applied driving pressure on the sabot tail.



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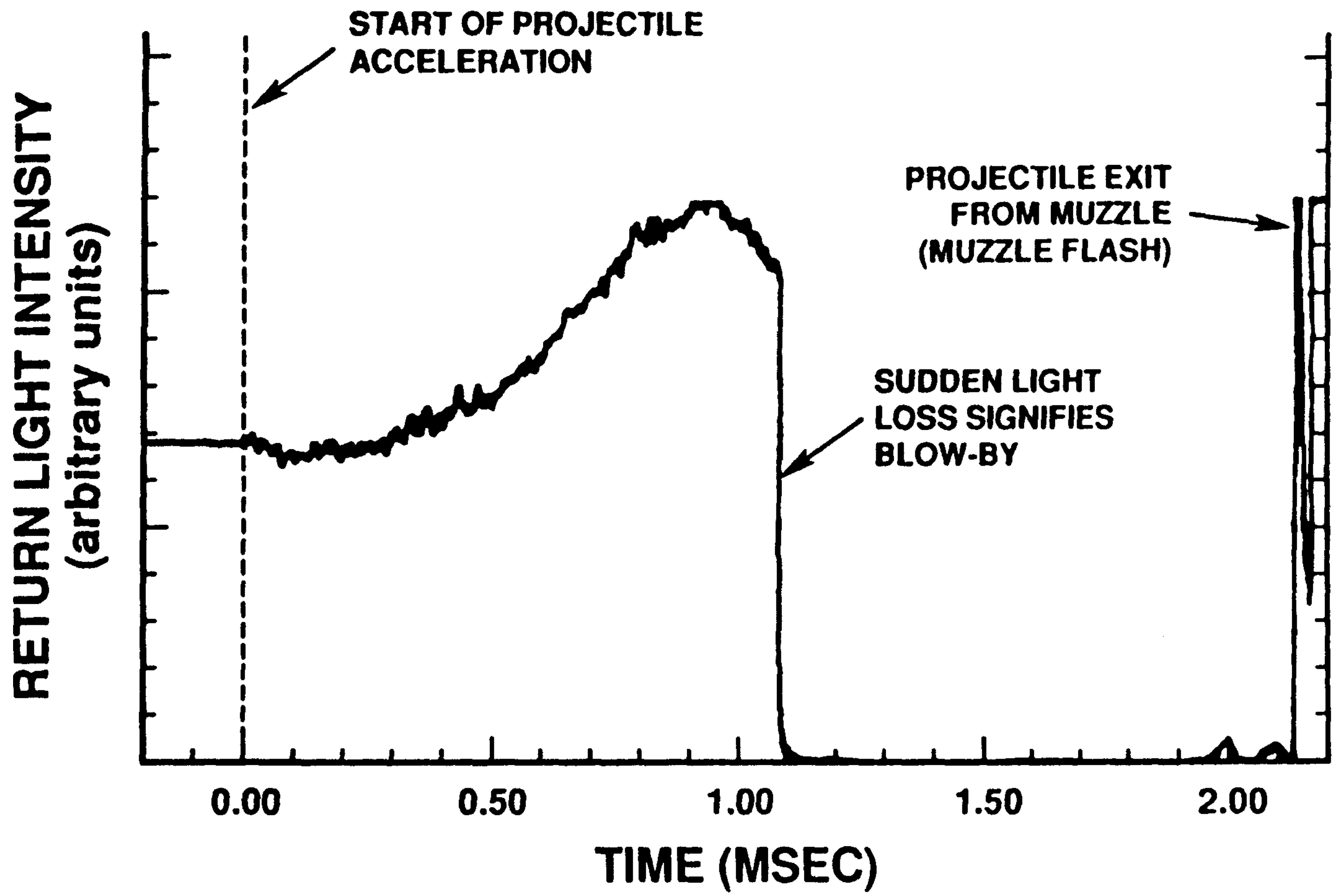

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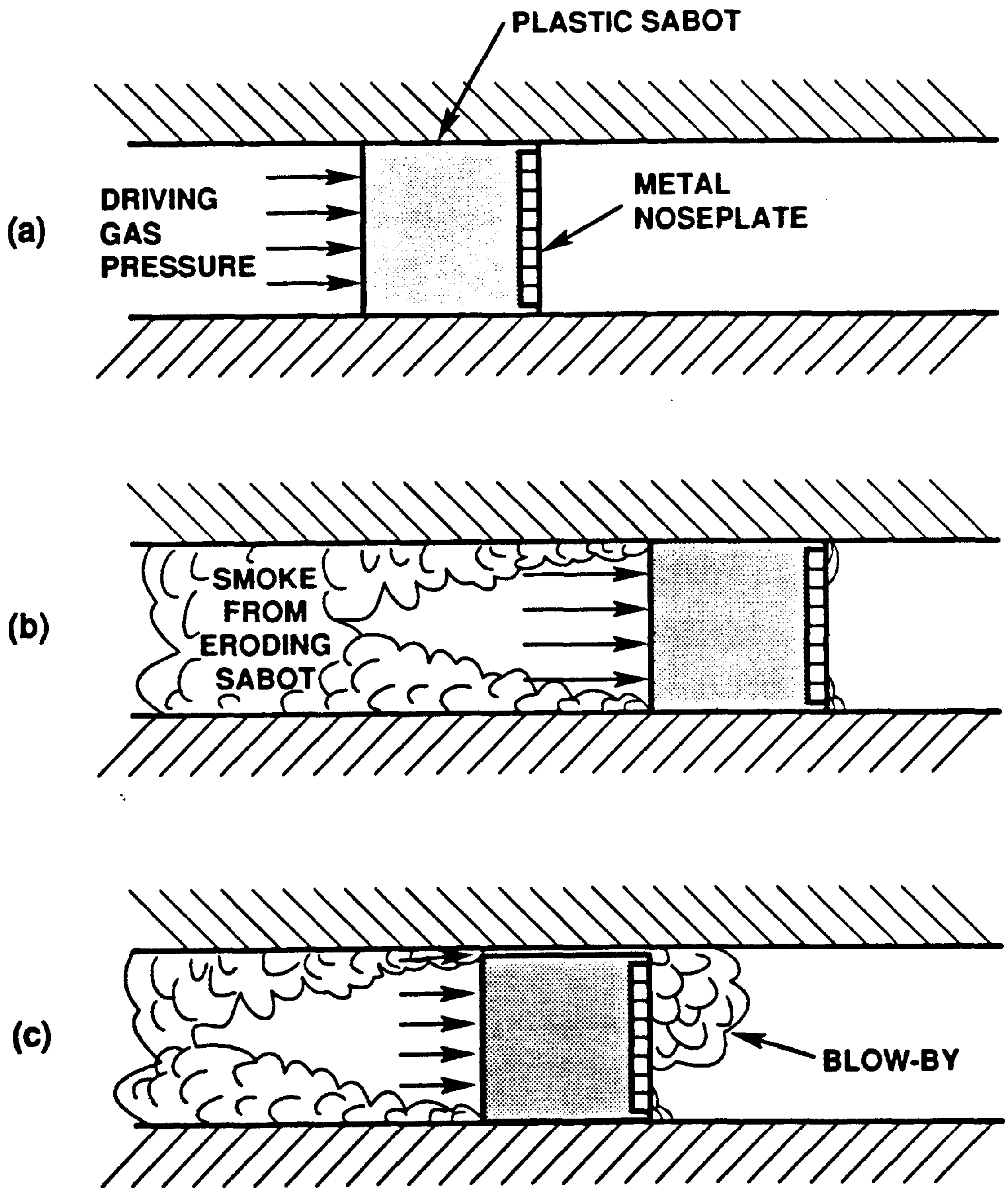

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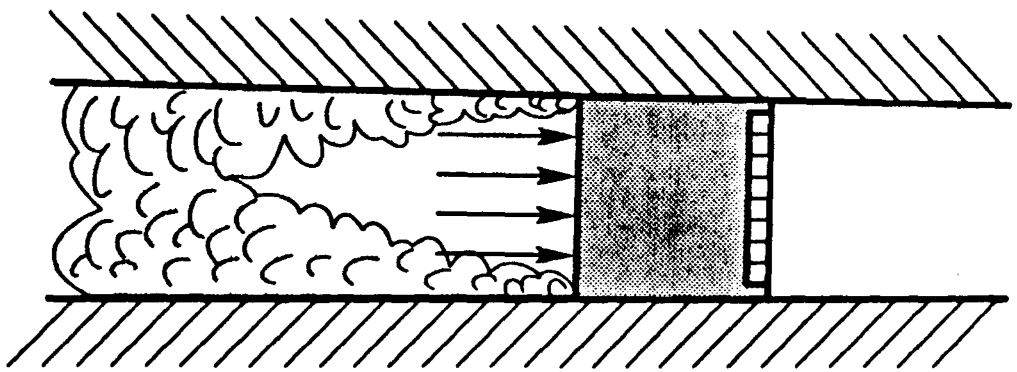

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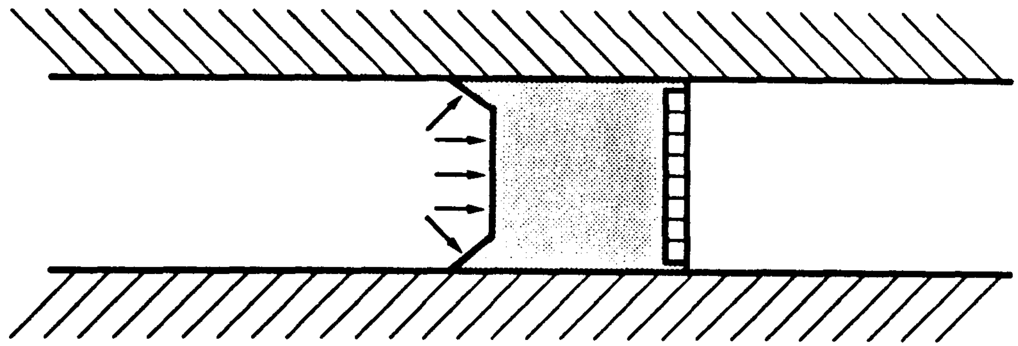

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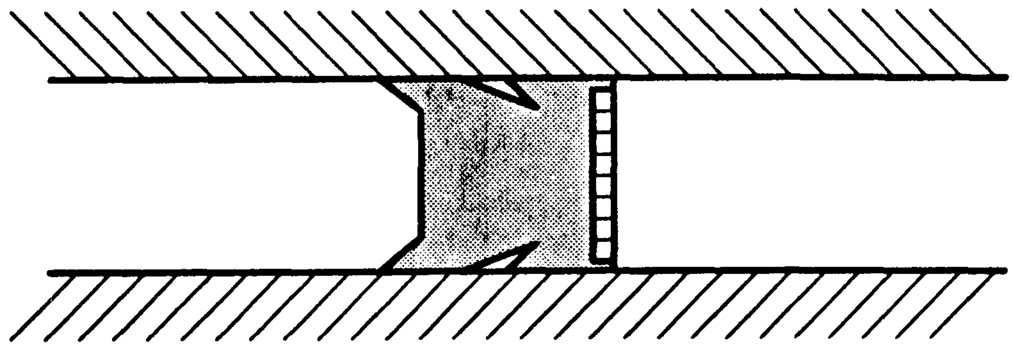

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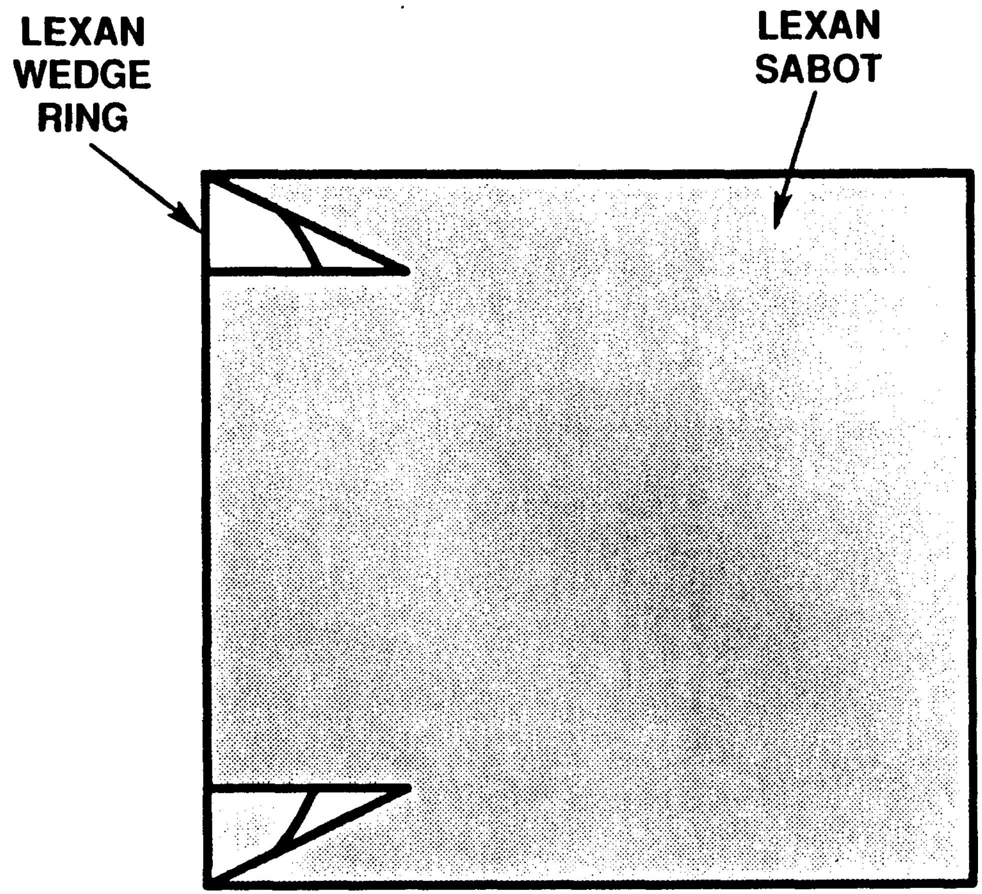

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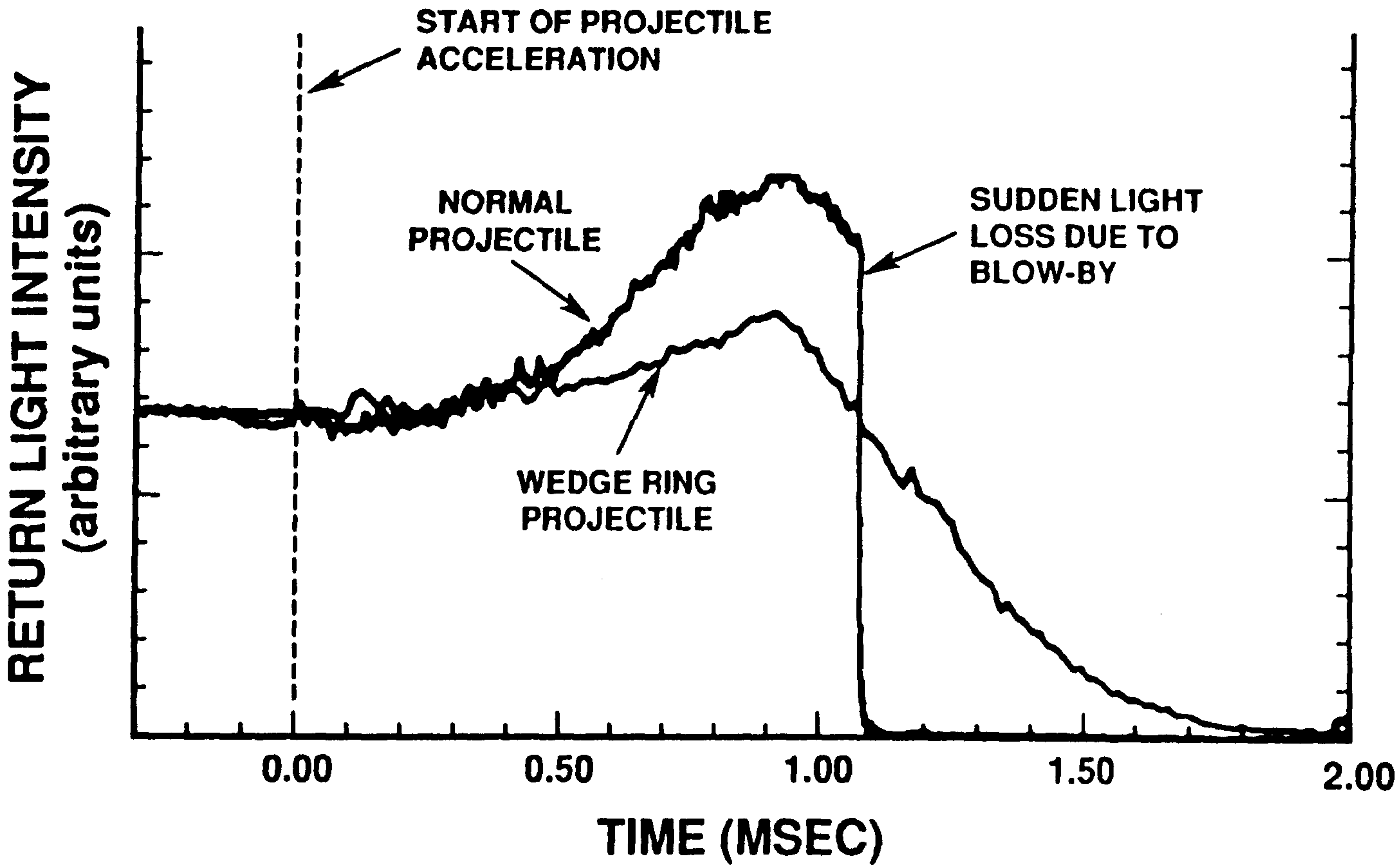

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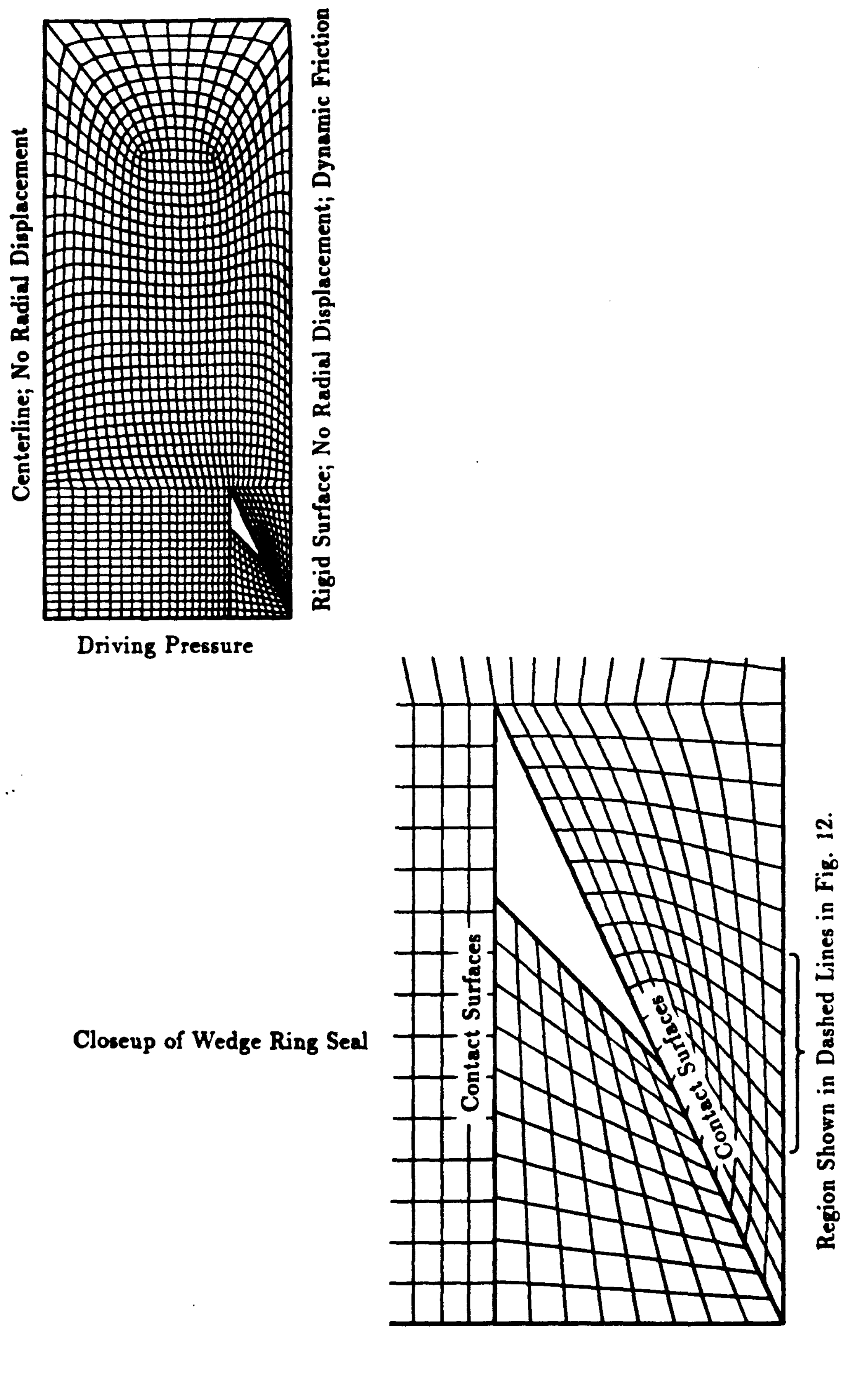

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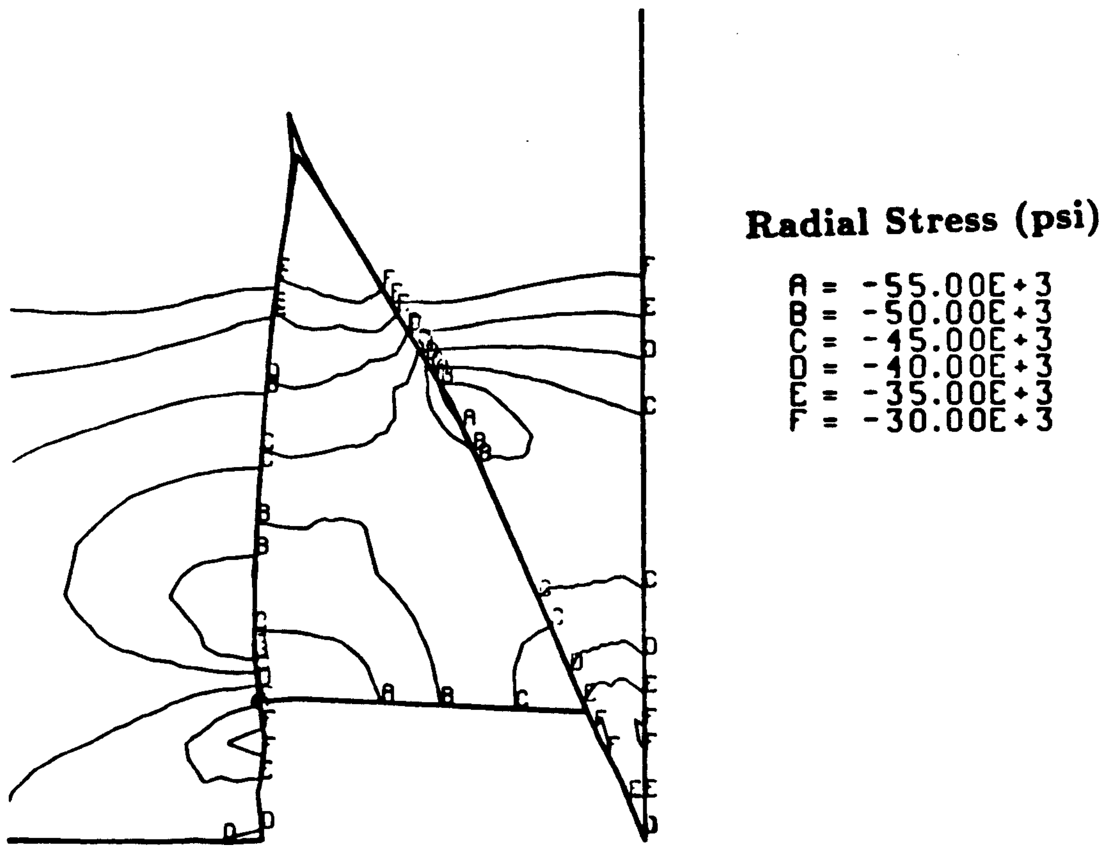

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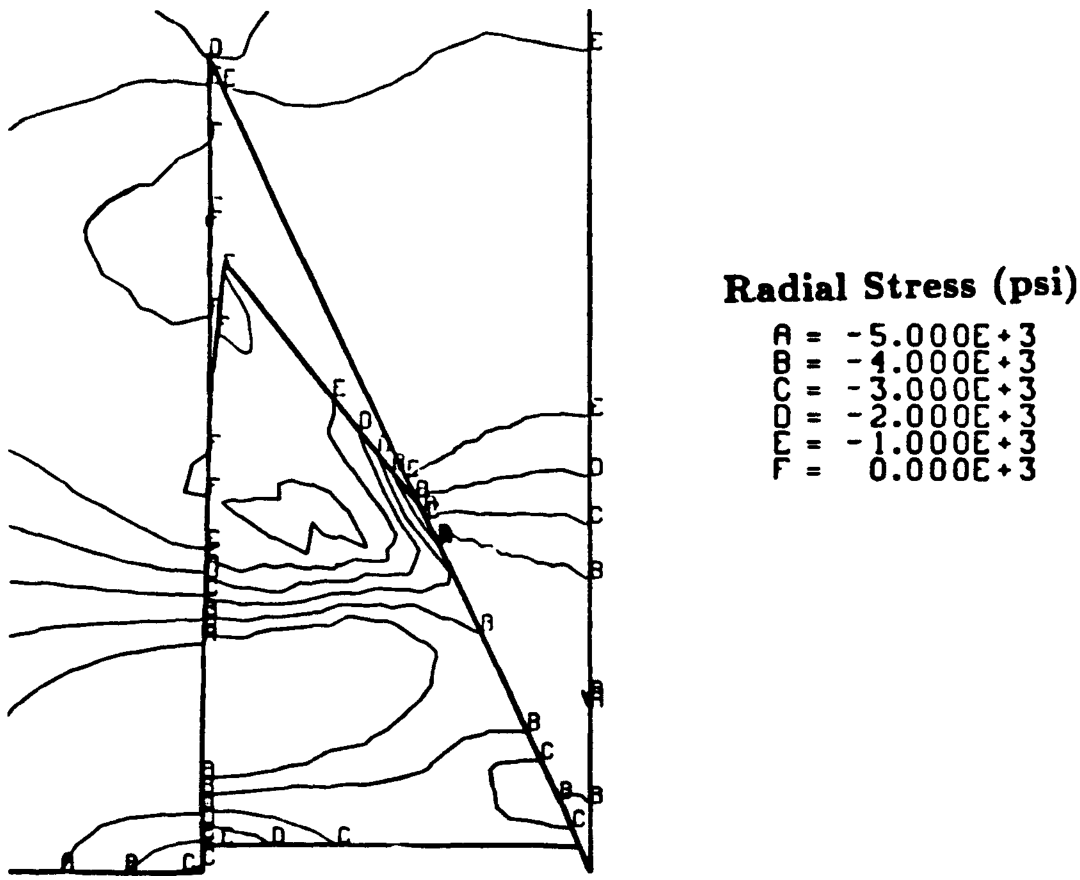

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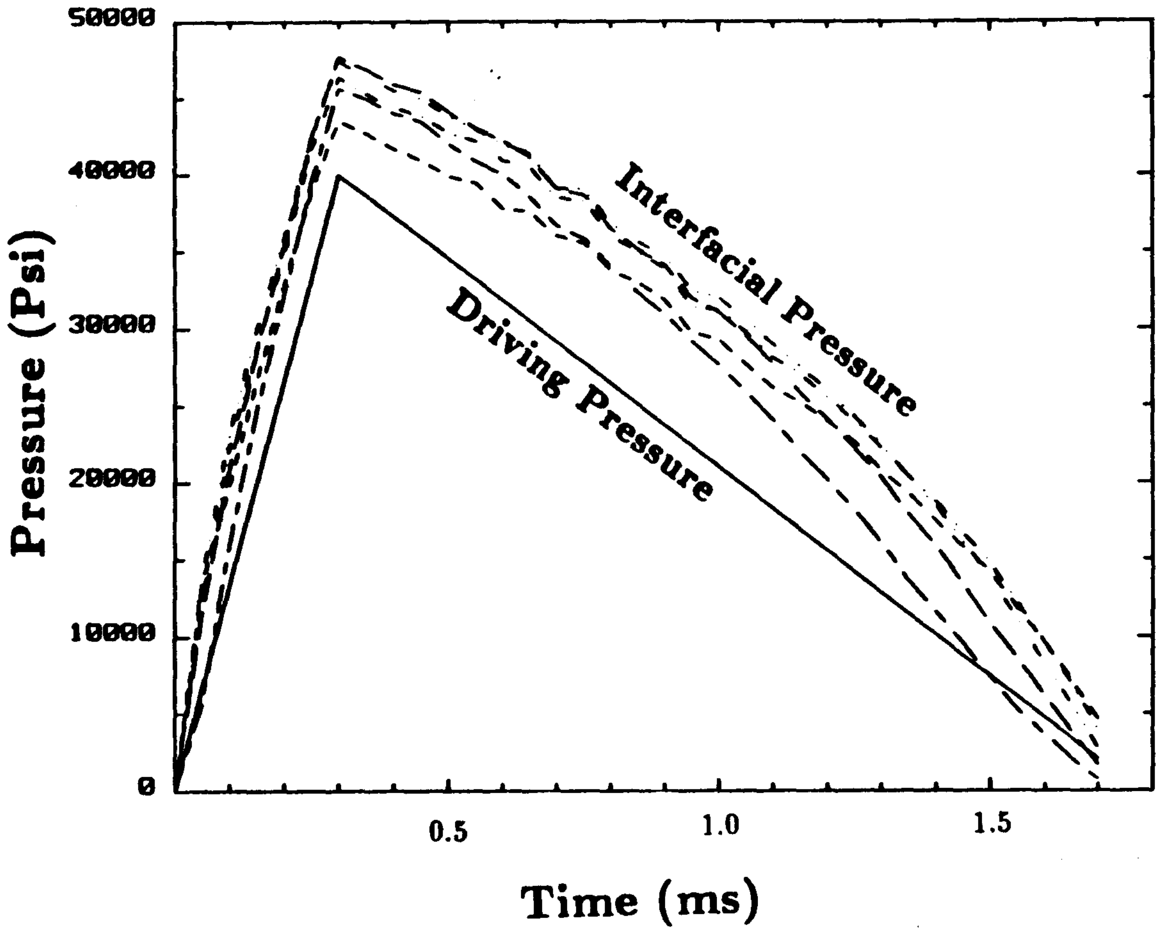

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