STS-93 SSME NOZZLE TUBE RUPTURE INVESTIGATION

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INTRODUCTION

STS-93 was launched on July 23, 1999. There was an anomaly at the end of the launch in that the main engines shut down 0.16 second early because sensors detected a low level of oxidizer in the LOX tank (actually the duct from the tank to the vehicle). This resulted in a cutoff velocity for the vehicle that was 16 ft/sec low. It should have been 25872 ft/sec. The OMS engines were subsequently used to achieve the proper orbit. An investigation was immediately initiated into the cause of this LOX tank low level cutoff.

It was noticed during the launch that the turbine temperatures for Main Engine 3 (E2019) were approximately 100°F higher than the preflight prediction. Linear Engine Model matching of the data indicated that a nozzle leak best fit the data. Post launch review of the data showed, that at approximately five seconds into the start, numerous parameters indicated small anomalous shifts. These shifts were all consistent with a rupture of nozzle tubes.

Post launch review of the films showed that just after Space Shuttle Main Engine (SSME) ignition and just prior to liftoff a streak is seen in the exhaust plume of E2019. Just after liftoff the streak can be seen emanating from the nozzle wall. This photo confirmed that a leak was coming from the nozzle tubes. Based on the photo, the axial location of the leak was estimated to be 28" from the aft end of the nozzle and in line with nozzle coolant feed line #1. The streak continued to be visible during the launch.

Almost immediately upon landing a visual inspection was made of the nozzle. It was confirmed that three nozzle tubes were ruptured at the suspected location (Figure 1). The focus then turned to the cause of the tube ruptures. Prior to landing, a hardware review revealed that two main injector LOX posts had been deactivated prior to the flight. This is done by inserting pins in the orifices located in the interpropellant plate of the main injector. Therefore, once the engine was available, a high priority was to inspect for these pins. Indeed one of two pins was missing. A pin is approximately 0.9" long by 0.1" in diameter, weighs 1.5 grams, and is gold plated (Figure 2). Also, there was a ding in the Main Combustion Chamber (MCC) in line with this post at a location 2.5" upstream of the MCC throat. The tube ruptures are located approximately 30° in the azimuthal direction from the post with the missing pin.

The ruptured tubes were sectioned from the nozzle and subjected to an evaluation in the Materials laboratory. The key finding from this investigation was that the gold discoloration at the dents was indeed gold and had a chemical composition consistent with that of the gold plating used on the pins. The same gold was also found at the dent in the MCC wall. The other significant finding was that the rupturing of the tubes occurred during the impact and dent formation. It was not a delayed event. This evaluation confirmed that the ejected pin caused the tube ruptures.

As a result of this conclusion, the following aerothermal questions were generated with regard to the pin.

- What is the trajectory of the pin?
- What is the velocity of the pin as it impacts the nozzle?
- What is the probability that an ejected pin will impact the nozzle?
- What is the probability that the pin will damage the nozzle if it hits the nozzle?
- Was this the worst damage that the pin could cause?
- Would the pin hit the nozzle if it is ejected from a different location on the face of the injector?
- How much damage can the pin do to the MCC?

At first it would seem to be a difficult task to answer these questions for a seemingly random event. However, it was found that a relatively simple computer model using basic flow principles could be developed to provide reasonable first order answers to these questions.

TRAJECTORY CALCULATION METHODOLOGY

In order to attempt any type of trajectory analysis for the pin, the combustion gas flow field must be defined. This information was generated when the chamber and nozzle contours were initially developed. These parameters are

- The combustion chamber and nozzle contour profiles.
- The combustion gas Mach number.
- The combustion gas velocity.
- The combustion gas static pressure.
- The combustion gas static temperature.
- The combustion gas density.

With this information, a simple model can be set up for calculating the pin trajectory. The fundamental equation for this model is the equation for the drag force on the pin.

$$F = C_D * A_N * \rho(V_G - V_P)^2/2$$

Using this fundamental equation, the following procedure is used to calculate the axial component of the pin trajectory.

1. The initial coordinates of the pin are selected (axial and radial location).
2. An initial pin velocity (speed and angle or, equivalently axial and radial components of velocity) is selected.
3. Values for the axial and radial drag coefficients are selected.
4. Values for the pin area normal and parallel to the combustion chamber axis are determined.
5. An incremental axial position is selected (initial $X + \Delta X$).
6. The combustion gas density and axial speed are determined for the average axial position (initial $X + \Delta X/2$).
7. An initial guess is made for the pin axial speed after it has traversed the axial length increment.
8. The average axial speed of the pin for the axial increment is calculated by taking the average of the starting and ending speeds.
9. From the relative axial speed and the density, the pressure $[\rho(V_{GX}-V_{PX})^2/2]$ acting on the pin in the axial direction is calculated.
10. The average axial force over the axial length increment is calculated from the axial pressure acting on the pin, the drag coefficient, and the pin area normal to the chamber axis.
11. From the initial axial speed, the average force, the pin mass and the axial length increment, the time for the pin to traverse the axial length increment is determined.
12. From the initial axial speed, the time increment, the mass of the pin, and the average axial force on the pin, the axial speed of the pin at the end of the axial increment is calculated.
13. Using this axial speed at the end of the axial increment, Steps 8 through 12 are repeated until the axial speed converges.
14. Steps 5 through 13 are repeated until the desired final axial position is reached.

Once the axial component of the trajectory has been calculated, the radial component can be calculated using the following similar procedure.

1. Starting at the initial position of the pin and the initial axial increment, the average radial component of the combustion gas velocity is determined.
2. An initial guess is made for the pin radial speed after it has traversed the axial length increment.
3. The pin radial speed at the average axial position is calculated by averaging the starting and ending radial speeds.
4. From the relative radial speed and the density, the pressure $[\rho(V_{GR}-V_{PR})^2/2]$ acting on the pin in the radial direction is calculated.

5. The average radial force over the axial length increment is calculated from the radial pressure acting on the pin, the drag coefficient, and the pin area parallel to the chamber axis.
6. From the initial radial speed, the time increment, the mass of the pin, and the average radial force on the pin, the radial speed of the pin at the end of the axial increment is calculated.
7. Using this radial speed at the end of the axial increment, Steps 3 through 6 are repeated until the radial speed converges.
8. Using the average radial speed and the time for traversing the axial increment, the change in radial position is calculated and added to the radial position at the start of the increment to get the radial position at the end of the increment.
9. Steps 1 through 8 are repeated until the desired final axial position is reached.

Using this procedure, starting parameters can been iterated to determine the values required to impact the nozzle as a specific location.

DRAG COEFFICIENT

To make the above calculations, the drag coefficients for the pin in both the axial and radial directions must be determined. The drag coefficient is a function of the Mach number, the Reynolds number, the object shape, and the orientation of the object within the flow field. The Reynolds number for the pin as it travels in the combustion gas flow field is calculated to be in the range from 10^3 to 10^5. The two extreme positions for the pin orientation are for the pin axis to be either normal or parallel to either the axial or radial component of the combustion gas velocity.

For the pin axis normal to the flow field, the pin can be approximated as a cylinder in cross flow. The drag for this configuration has been studied extensively for an infinitely long cylinder and is available as a function of Reynolds number in standard texts. For this configuration in the Reynolds number range of interest, the drag coefficient is between 0.9 and 1.2. For a cylinder of finite length the drag coefficient will be lower. For a cylinder with an aspect ratio of 9:1 (approximately that of the pin), the drag coefficient is approximately 2/3 that for an infinitely long cylinder. Applying this ratio to the infinitely long cylinder results gives a drag coefficient range from 0.6 to 0.8. The area of the pin normal to its axis is approximately 0.09 in^2. This will result in a maximum drag coefficient times area of 0.072 in^2.

For the pin axis parallel to the flow field, the pin can be approximated as either a square ended cylinder or a projectile depending on which way the pin is oriented. The projectile will have the lower drag coefficient. The minimum drag coefficient for a projectile is 0.2. Multiplying this by the pin approximate cross sectional area of 0.015 in^2 gives a minimum drag coefficient times area of 0.003 in^2.

The pin could also be rotating and/or tumbling. Rotation can create lift. However, calculations indicate that the pin would have to develop a significant rotation rate to generate an appreciable lift. It is not expected to do this. Any tumbling will cause the drag coefficient times area value to vary with time. The calculated range of values for the drag coefficient times area (0.003 in^2 to 0.072 in^2) are intended to provide a general range of the values that can be expected for the pin as it is traveling through the combustion gas flow field.

TRAJECTORY TO MCC IMPACT

Once the pin dislodges from the orifice it will travel down the LOX post until it exits the injector. From the LOX pressure and the geometry, the force on the pin can be estimated and the velocity calculated. From the Materials evaluation it is known that the tubes ruptured when the pin hit them. The data indicates that the tubes ruptured at approximately five seconds after ignition, which is one second into 100% power level operation. Therefore, the pin was dislodged during 100% power level operation. From a number of calculations it was determined that a reasonable estimate for the velocity of the pin as it exits the post is 100 ft/sec. The pin initial radial position will be approximately 0.4" from the MCC wall. Most likely it will be traveling with the pin axis parallel to the flow. Its drag coefficient times area in the axial direction should be close to the minimum calculated value 0.003 in^2. In the normal direction it will be close to the maximum value of 0.072 in^2.

A parametric analysis was made to determine the conditions required for the pin to impact the MCC at a location 2.5" forward of the throat. Parameters varied were the axial drag coefficient times area, radial drag coefficient times area, initial velocity, and exit angle from LOX post. The following conclusions were made from this parametric analysis.

- The most significant result was that the minimum initial trajectory angle for the pin had to be approximately 10° in order for the pin to impact 2.5" forward of the throat. This minimum angle was independent of the combination of other conditions required. Any angle less than 10° will cause the pin to impact more forward of the throat.
- For an initial velocity less than 100 ft/sec, the axial drag coefficient times area becomes smaller than what appears to be a minimum realistic value. This would imply that the 100 ft/sec is a reasonable value for the initial speed of the pin when it exits the LOX post.
- A pin in one of the outer two rows of elements (rows 12 or 13, which are most likely to have a pin) of the main injector will have a very high probability of striking the MCC.
- The impact angle of the pin relative to the MCC wall is shallow (less than 10° with a typical value of 5°). This is consistent with the observed damage to the MCC.

- The velocity of the pin when it hits the MCC is primarily a function of the initial velocity. This is because the acceleration of the pin is relatively small up to the time it hits the MCC. The axial velocity at impact is less than 50 ft/sec greater than the initial velocity for the range of conditions analyzed.
- The time from expulsion of the pin to impact with the MCC will be a function of the axial velocity which, in turn, is a primarily a function of the assumed initial velocity. For an initial velocity of 100 ft/sec, the time is approximately 10 milliseconds.

TRAJECTORY FOR NOZZLE IMPACT

After the pin impacts the MCC, it continues traveling in the combustion gas flow field until it impacts the nozzle at a location 28" forward of the aft manifold. It is not known precisely how the impact of the pin with the MCC affects the pin trajectory. It can be expected than there will be a reduction in the pin velocity as a result of it hitting the MCC. The shallow impact angle should mean that the pin trajectory angle when it leaves the MCC will be similar to that of the MCC at the point of impact (25°-25'). It is known that the pin impacted the nozzle at an azimuthal angle 30° from the MCC impact point. This could imply that the impact with the MCC gave the pin a velocity component in the azimuthal direction.

A parametric analysis was also made for the trajectory of the pin from when it grazed the MCC to when it impacted the nozzle. Parameters varied were the axial drag coefficient times area, radial drag coefficient times area, initial speed and angle after grazing the MCC. The following conclusions were made from this analysis.

- For reasonable values of the initial speed and angle after grazing the MCC, these parameters do not significantly affect the trajectory (Figure 3).
- The pin velocity at impact is on the order of 800 to 900 ft/sec. This is roughly an order of magnitude less than the combustion gas velocity. A structural analysis estimated that axial and radial components of the velocity of 600 ft/sec are required to produce the observed damage to the nozzle tubes. The calculated velocities are consistent with this structural evaluation.
- The pin impacts the nozzle at an angle of typically 13° to 15° relative to the nozzle wall.
- The time from impact with the MCC to impact the nozzle is on the order of 20 to 30 milliseconds depending on the assumed set of conditions.

PROBABILITY OF PIN HITTING THE NOZZLE

Using the trajectory calculation model, the combination of conditions required for the pin to hit the nozzle can be determined. This is done by first determining the combination of conditions (radial and axial drag coefficient time area) that will result in the pin hitting at the aft end of the nozzle. This set of conditions represents the dividing line between impacting and not impacting the nozzle (Figure 4). Any combination of axial drag coefficient times area and radial drag coefficient times area below the line will result in the pin hitting the nozzle.

Next the range of axial drag coefficient times area and radial drag coefficient times area that can occur for the pin can be determined. This was discussed earlier. The minimum axial drag coefficient times area that can be expected is 0.003 in^2. For this condition the radial drag coefficient times area would be at its maximum value of 0.072 in^2. The maximum value for axial drag coefficient times area would be the 0.072 in^2 value. For this condition the radial drag coefficient time area could range from the minimum of 0.003 in^2 to the maximum of 0.072 in^2 depending on the pin orientation. These ranges result in a triangular region of possible axial and radial drag coefficient times areas (Figure 4). If there is an equal probability of any point within the triangle, then the probability of the pin hitting the nozzle is the ratio of the hit area of the triangle to the total area of the triangle. This ratio is 0.13, which is equivalent to a one in eight chance of the pin hitting the nozzle.

However, rather than an equal probability of any condition within the triangle occurring, there is a probability distribution for both the axial and radial components. The pin will probably want to align its axis to that of the nozzle centerline. This would cause a skewed probability distribution where the axial drag coefficient times area would most probably be at the low end of its range and the radial drag coefficient times area would most probably be at the high end of its range.

A log normal distribution applied to both the axial drag coefficient times area and the radial drag coefficient times area can be used to approximate this expected skewness (Figure 4). When these probability distributions are factored into the calculation, the probability of the pin hitting the nozzle increases to approximately one in four.

PROBABILITY OF PIN RUPTURING A NOZZLE TUBE

Starting with a set of conditions that results in the pin impacting the nozzle at the aft end, the axial drag coefficient times area can be incrementally reduced to result in the pin impacting farther and farther forward in the nozzle. The velocity of the pin at the various impact locations is a part of the trajectory calculation. As expected, the impact velocity of the pin decreases as the impact location moves forward. Simplistically, there should be a minimum velocity required to rupture a tube since the square of the velocity is proportional to the kinetic energy of the pin. In reality, other factors need to be considered such as pin orientation at impact, the radial and axial components of the velocity, the tube geometry at the impact location (tube diameter and wall thickness decreases going forward in the nozzle), and the tube temperature (increases going forward in the nozzle).

Lines of constant velocity can be determined and then overlaid on the parametric analysis results (Figure 4). The area within the triangle between a constant velocity line and the line of demarcation between hitting and not hitting the nozzle, is the set of conditions that will result in the pin impacting at or greater than a given velocity. Again, by factoring in the probability distributions, the probability of the pin impacting the nozzle at or greater than a given velocity can be determined (Figure 5). For example, if the threshold velocity for rupturing a tube is assumed to be 700 ft/sec, then the probability of an ejected pin rupturing a tube is 0.10 or one in ten. This compares with the experience of one in eighteen ejected pins rupturing nozzle tubes. Therefore, despite the simplifications and assumptions that went into the model, it appears to be able to make reasonable probability assessments.

CONCLUSIONS

In summary, a simple generic model for determining the trajectory and other conditions of an object in the combustion chamber and nozzle hot gas flow field of a rocket engine has been developed. This model (process) can be used for any analysis of a rocket engine where it is desired to estimate the implications of a solid contaminant that has been introduced into the combustion gas flow field.

For the specific case of the LOX post deactivation pin that was ejected during the launch of STS-93, it was found that the results of the model were consistent with the hardware observations. Additionally, the model was used to make probability predictions, which were also consistent with hot fire experience.

NOMENCLATURE

A_N = Area normal to flow

C_D = Drag coefficient

F = Force

LOX = Liquid oxygen

MCC = Main Combustion Chamber

OMS = Orbiter Maneuvering System

SSME = Space Shuttle Main Engine

STS = Shuttle Transportation System

V_G = Velocity of combustion gas

V_{GR} = Component of combustion gas velocity in radial direction

V_{GX} = Component of combustion gas velocity in axial direction

V_P = Velocity of particle

V_{PR} = Component of particle velocity in the radial direction

V_{PX} = Component of particle velocity in the axial direction

X = Axial position

ΔX = Axial position increment

ρ = Density

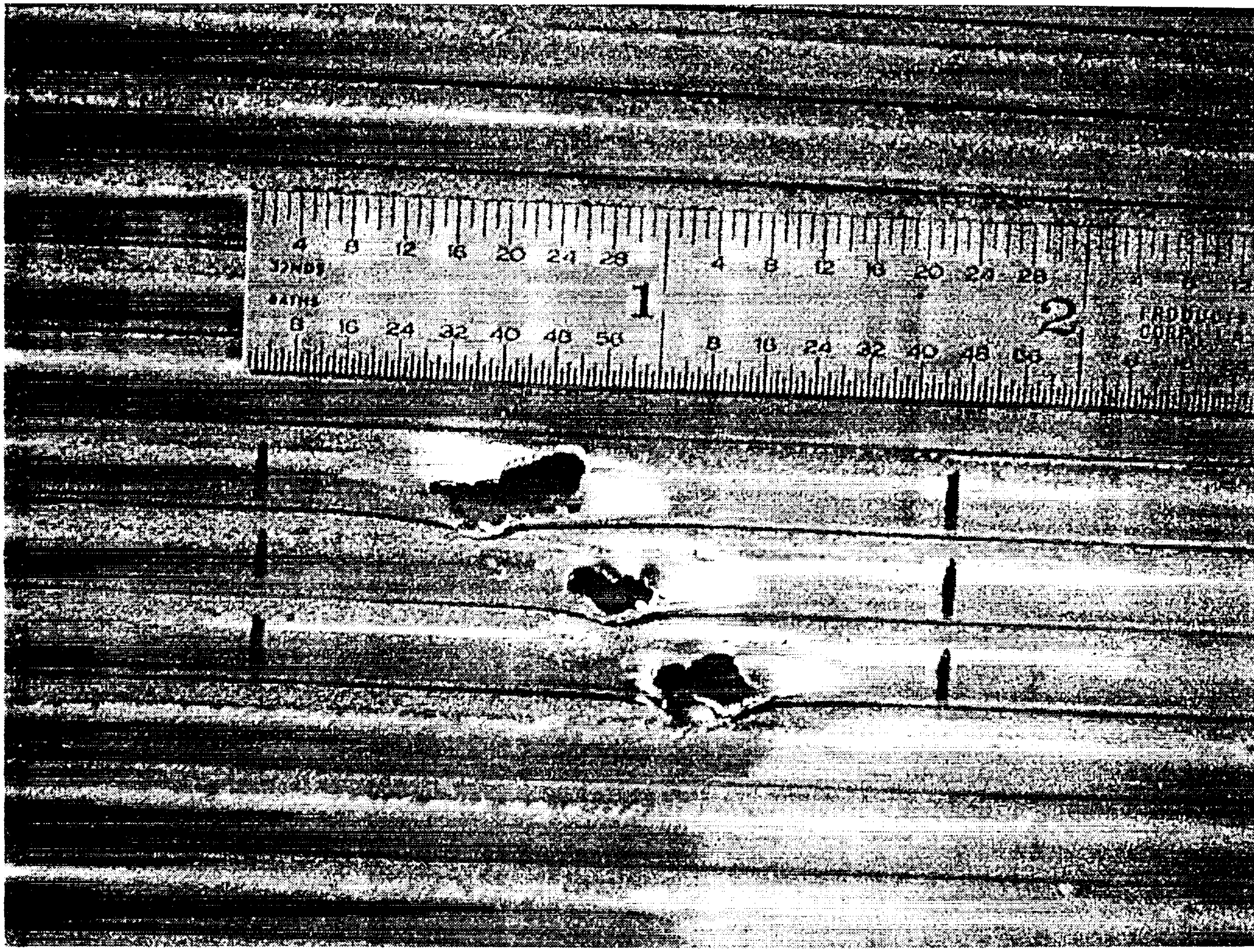

Figure 1. Nozzle Tube Ruptures

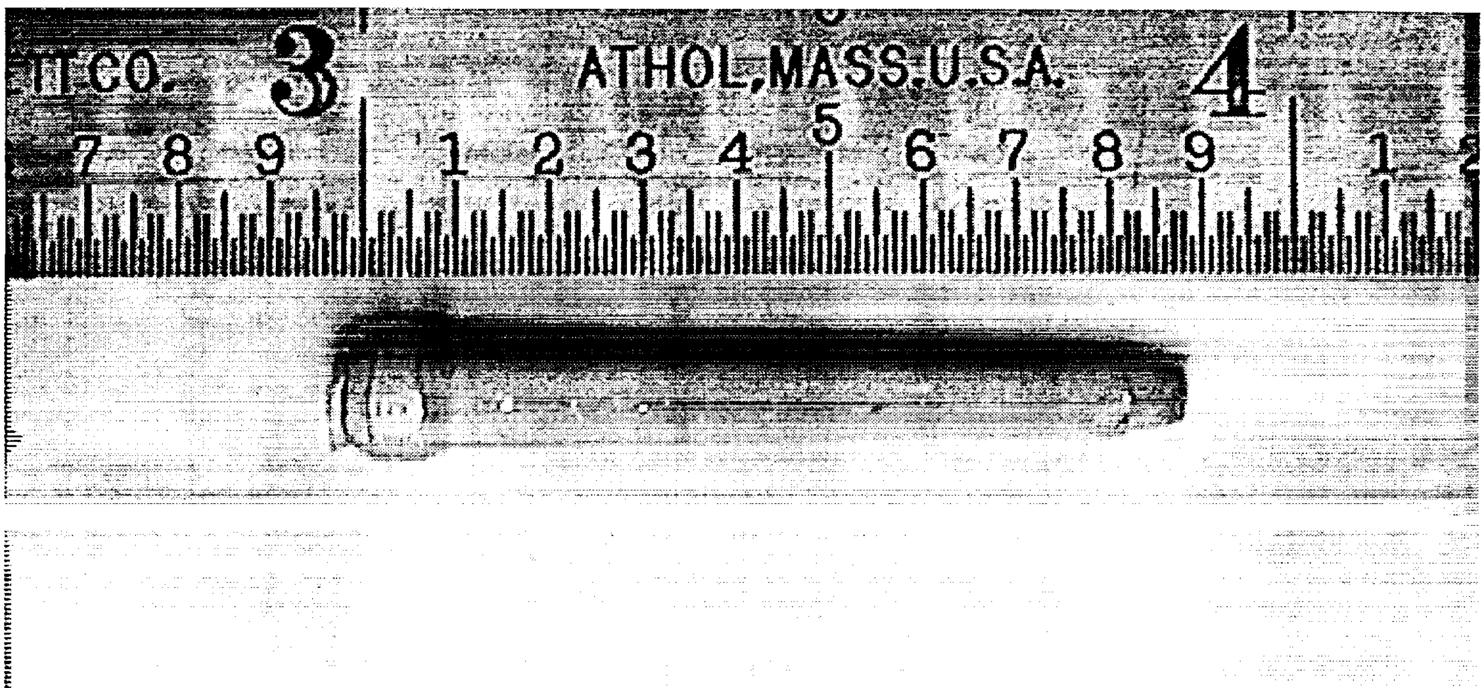

Figure 2. LOX Post Deactivation Pin

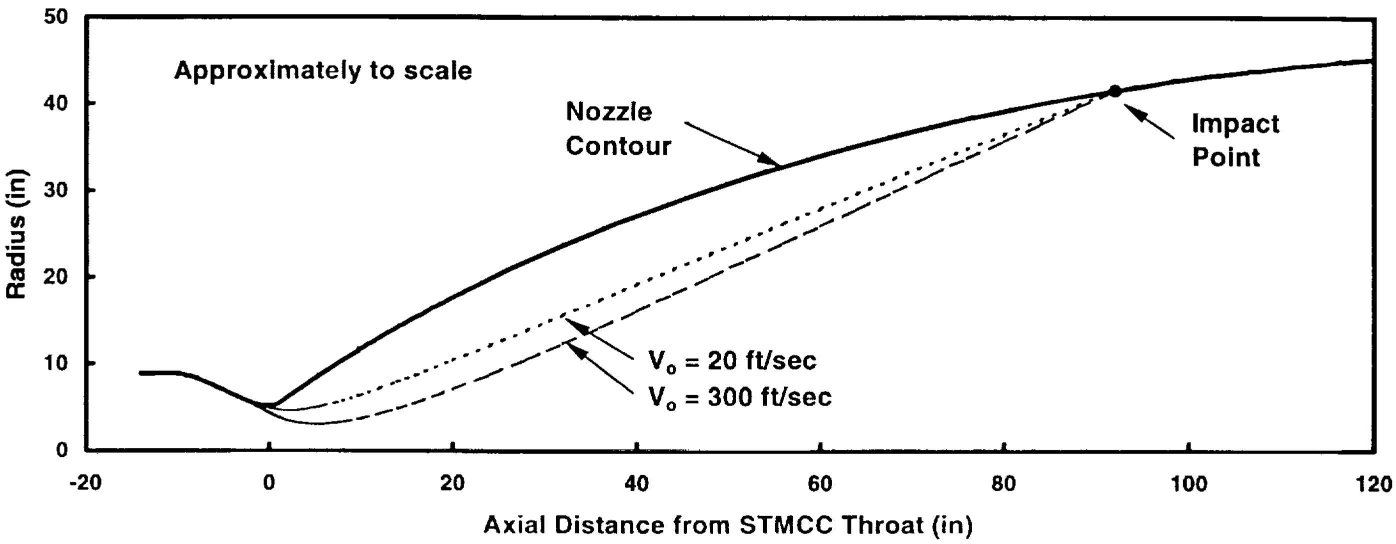

Figure 3. Example Pin Trajectories

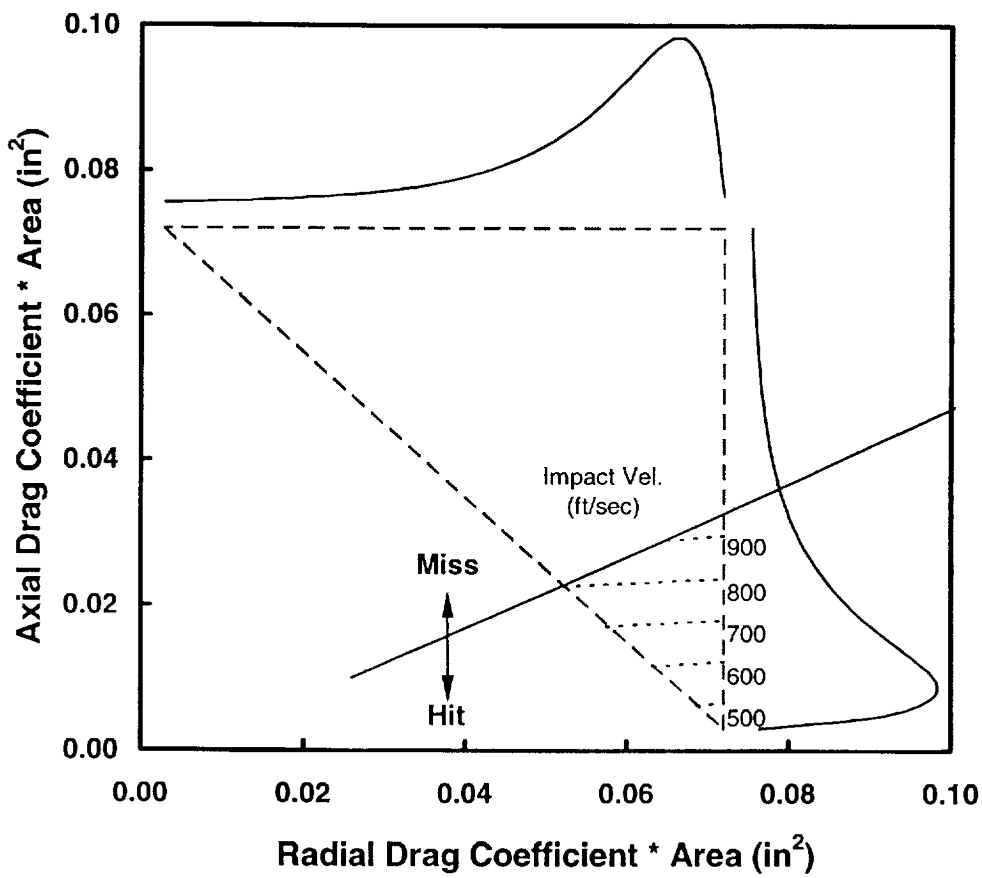

Figure 4. Flow Conditions for Pin Impacting Nozzle

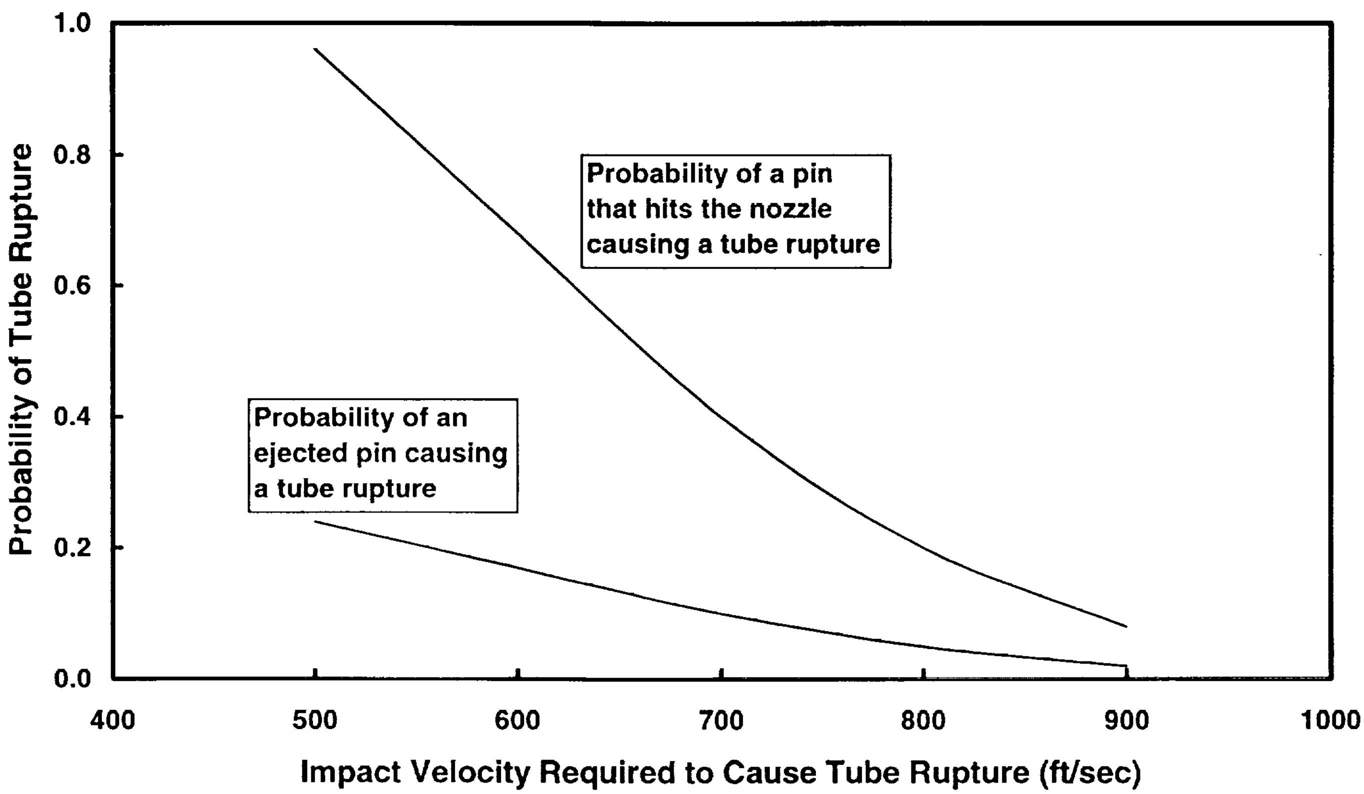

Figure 5. Probability of Tube Rupture