

FLOW-3D ANALYSIS OF PRESSURE RESPONSES IN AN ENCLOSED LAUNCHING SYSTEM

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ABSTRACT

The impingement of supersonic jets on various solid objects has been studied extensively, but most analytical studies have been limited to a two-dimensional (2-D) or axisymmetric code. Fewer yet have studied bounded, impinging, supersonic jets, and even then seldom with a three-dimensional (3-D) analysis. The 3-D flow code chosen for this study was FLOW-3D, a product of Flow Science, Inc.

This paper reports the results of our numerical analyses of four tests conducted with two configurations within an enclosed launching system. Details of the flow pressure, velocity, and temperature calculated by FLOW-3D for selected times and cross sections are stored, and the continuous pressure history is presented and compared with experimental data at various points. Velocity, temperature, and pressure histories to 300 ms were imposed at the throat of the nozzle to simulate actual test firings of the generic rocket motors located within the enclosed launching system.

The objectives are (1) to simulate the nozzle plume flow field (temperature, pressure, velocity, and density) of the plume of the enclosed launching system as the plume exits into the plenum and up through the uptake to the atmosphere and (2) to compare the pressure-time results with the data taken in each test. The scope of the flow field is from the exit of the nozzle through the entire enclosed launching system to the exit plane at the top.

INTRODUCTION

The Vertical Launching System/Gas Management System (VLS/GMS) shown in figure 1 serves as a vehicle to evaluate the computation tools used in the design refinement of the enclosed launching system. The initial design of the enclosed launching system required a high degree of engineering judgment; FMC Corporation, one of two contractors building the VLS for the U.S. Navy, simplified it and extensively refined it with thermal-hydraulic and structural computer codes.

The Naval Surface Weapons Center, Dahlgren Laboratory (NSWC/DL), studied the problem with the SHELL computer code, an axisymmetric 2-D code that predicts the velocity-, temperature-, and pressure-fields, and made significant advances (1). In 1985, Naval Systems Division of FMC Corporation continued those studies of the enclosed launching system with a modified version of SHELL. To retain the geometric complexity of the enclosed launching system in

the code predictions during its redesign, a more recent code, FLOW-3D (2), was then compared with experimental data (pressure). This comparison, for firings of generic missiles from the enclosed launching system, is the subject of this paper. Thus, the enclosed launching system design serves here merely as a vehicle to evaluate the calculation tool, FLOW-3D, for its suitability of use in design analysis. Data is available from pressure histories resulting from test firings of various rocket motors in two locations in an enclosed launching system. This paper reports the results of numerical analyses of the enclosed launching system undergoing test firings of generic missiles with slightly different nozzles. The missile is assumed to be restrained in place. The resulting flow and temperature fields are predicted as an integral part of the highly asymmetric 3-D cases of the rocket motor firings from, and near, a corner cell of an enclosed launching system.

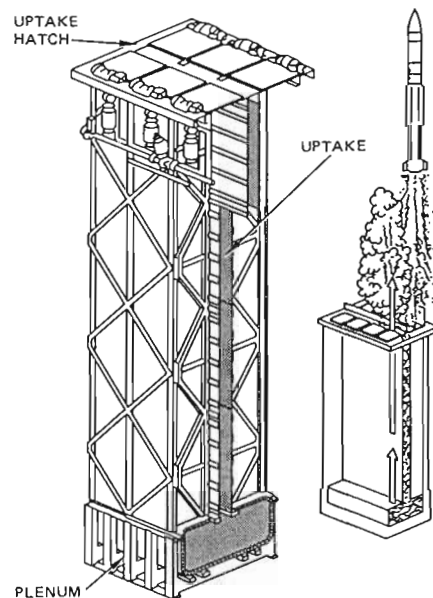


Fig. 1 Vertical Launching System/Gas Management System (VLS/GMS)

The comparison reported here focuses on the transient pressure at selected pressure transducer locations; ignored are the calculated transient velocity and temperature fields, although they may be interesting. The flow rate or velocity is not recorded; further, the thermocouples in place did not survive.

Descriptions of the enclosed launching system chosen for this study are given in references 1, 3, and 4. References 1, 3, and 4 also report the results of similar studies for near-identical systems. Reference 5 reports a study comparing FLOW-3D, SHELL, and Test 2b data for the system under consideration here. This paper is an update and expansion of reference 5 and is a report of significant improvement of the earlier FLOW-3D results obtained for Test 2b.

THE FLOW-3D COMPUTER CODE

FLOW-3D (2) is a descendant of the well-known Marker-and-Cell (MAC) finite-difference technique (6) and the Implicit-Continuous Fluid-Eulerian (ICE) technique (7). A series of simplified computer codes (SOLA) were developed to explore extensions and refinements of these techniques during 1975 through 1981. In 1981, a Flow Science, Inc., proprietary 3-D extension of the most successful of these codes, SOLA-VOF, was established as the basis of the present FLOW-3D code. Additions of new techniques for representing obstacles and new physical phenomena such as compressibility and heat transfer were made in a continuous series of code developments (i.e., SOLA-3D/FSI, SOLA-SLOSH, HYDR-3D). The culmination of this 11-year development is FLOW-3D, containing several physical modeling options and user conveniences.

Thus, a finite-difference method is used to construct a time-dependent solution of the fluid conservation laws for mass, momentum, and energy. The difference equations are based on a fixed Eulerian mesh of nonuniform rectangular cells. Variable porosities are assigned to mesh cell centers and cell faces to define curved obstacle boundaries and baffles embedded in the mesh. Free surfaces or material interfaces are defined by a fractional volume of fluid function. The fluid is then described at any instant of time by specifying the velocity, density, and internal energy of each cell. In the present analysis, the flow was considered to be composed of two nonreacting ideal gases (i.e., air and rocket motor exhaust products, completely mixed) emanating from the throat of the nozzle, completely burned (although incomplete combustion would have occurred in the real case).

The flow conditions at the rocket-motor nozzle throat, input into the code, are calculated from the averaged experimental data of the chamber pressures of the motors in Tests 1, 2a, 2b, and 2c. These chamber pressures are shown in figures 2 through 5 in which the four pressure sensor data in each refer to two sensors in each of two motor chambers.

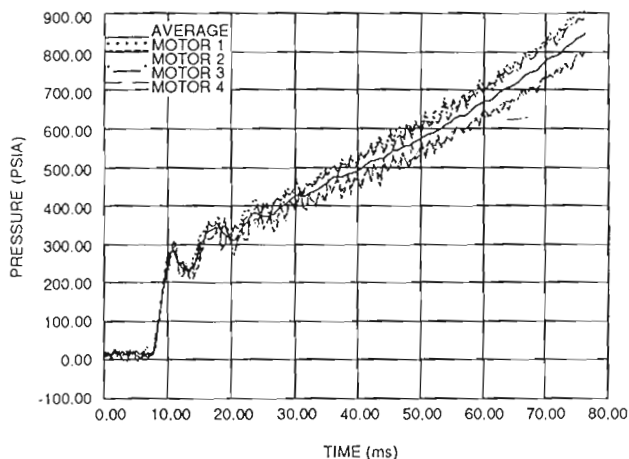


Fig. 2 Average Motor Pressure From Four Chamber Pressure Traces for Two Boosters, Test 1

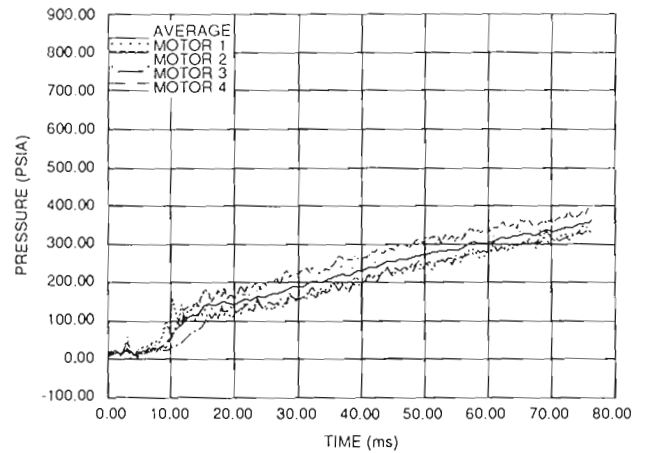


Fig. 3 Average Motor Pressure From Four Chamber Pressure Traces for Two Boosters, Test 2a

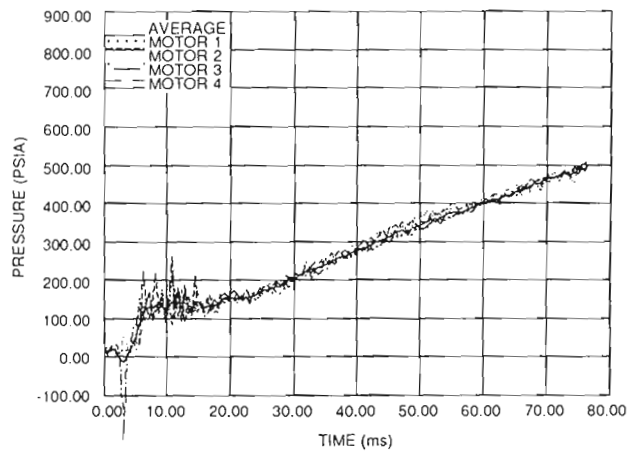


Fig. 4 Average Motor Pressure From Four Chamber Pressure Traces for Two Boosters, Test 2b

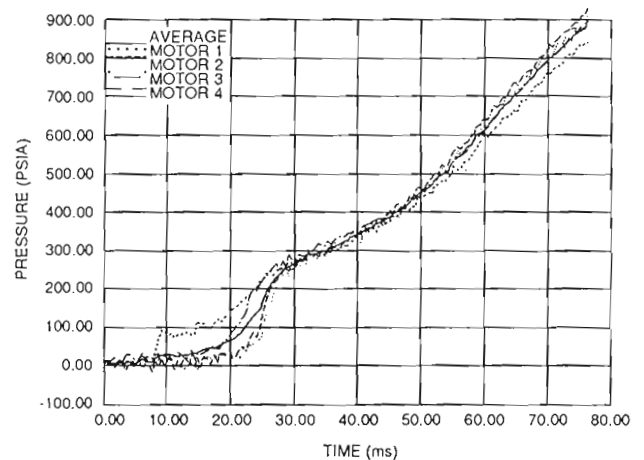


Fig. 5 Average Motor Pressure From Four Chamber Pressure Traces for Two Boosters, Test 2c

ANALYSIS

The present analyses used the FLOW-3D computer code described above to calculate the transient pressure environments due to the test firings of a generic booster in a launching module. The two basic actual grids used in the calculations are indicated in

figures 6 through 11 (four horizontal grid lines in the plenum and three vertical grid lines in the uptake are not indicated); the asterisks are centered between the grid lines.

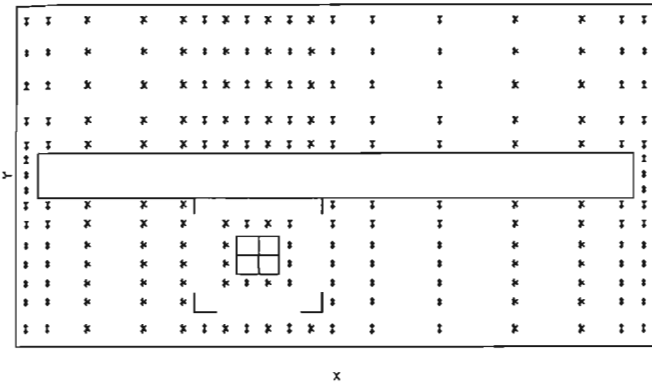


Fig. 6 Obstacle Plot, X-Y Plane at K=9, Test 1



Fig. 10 Obstacle Plot, Y-Z Plane at I=5, Test 2a-c

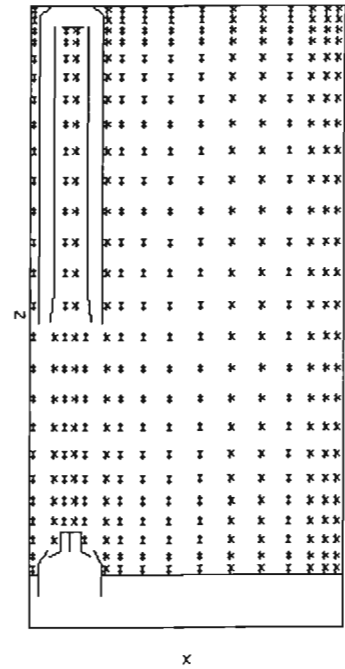


Fig. 11 Obstacle Plot, X-Z Plane at J=5, Test 2a-c

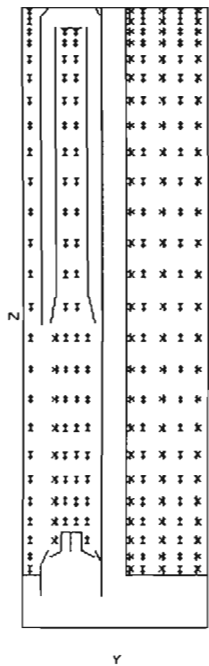


Fig. 7 Obstacle Plot, Y-Z Plane at I=9, Test 1

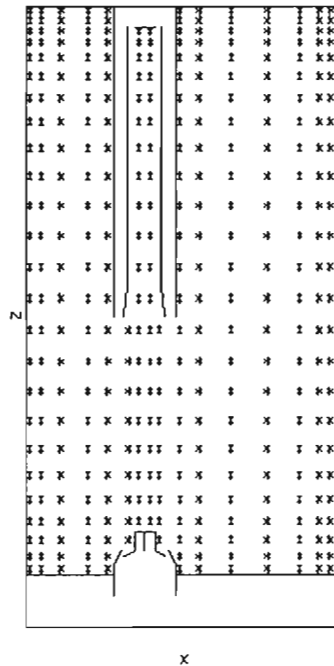


Fig. 8 Obstacle Plot, X-Z Plane at J=5, Test 1

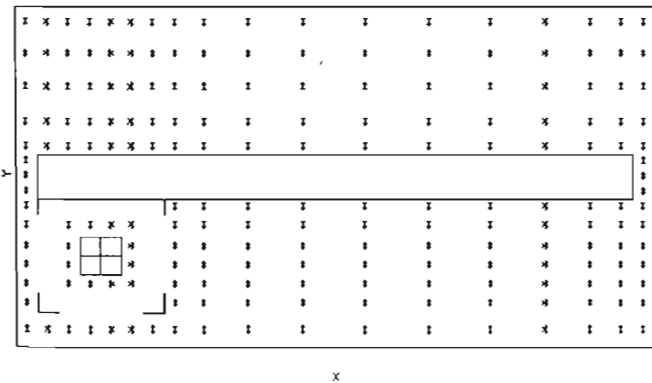


Fig. 9 Obstacle Plot, X-Y Plane at K=9, Test 2a-c

The analyses were performed for the three sequential cases listed in table 1 for Tests 1, 2a, 2b, and 2c: (1) a canister with an aft closure; (2) the canister, plenum, and uptake with the aft closure opened, but with the uptake hatch closed; and (3) followed again by the canister, plenum, and uptake, with the uptake hatch opened. The times were determined by sudden changes in voltages across break wires indicating a level of chamber pressure, initial opening of the aft closure, and initial opening of the uptake top hatch. The times inside the parentheses were estimated from the trace of pressure data and were used in the calculations.

Table 1. Sequential Occurrence

Condition	Time (ms)			
	Test 1	Test 2a	Test 2b	Test 2c
Ignition	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Flow begins from rocket-motor chamber with canister sealed (aft closed)	??? (11.0)	5.1 (3.1)	7.2 (7.2)	6.5 (6.5)
Aft is opened fully, but uptake hatch is closed	10.0 (16.0)	6.7 (13.0)	9.5 (11.5)	8.7 (11.7)
Uptake hatch is opened and remains open to end of test simulation	27.0 (38.0)	34.5 (38.0)	40.0 (40.0)	32.7 (32.7)

The aft closure is an important component of the enclosed launching system. Its main function is to protect the missile from the hot exhaust products of an adjacent missile firing. The aft closure consists of a steel core sandwiched between aluminum strips; the bottom and upper surfaces are protected by an ablative material and ablative rubber, respectively. The aft closure, precut diagonally to open into four distinct petals, is backed up by a steel grid that strengthens the closure and prevents it from opening inward. The aft closure rupture time for Test 2b was deduced to be

approximately 11.5 ms from a pressure-time record of a gauge located near the bottom of the canister (1); this is a minor disagreement with the break-wire data.

All experimental data, including the chamber pressures versus time for rocket motors, were taken from actual test data from Tests 1, 2a, 2b, and 2c of the VLS module. These tests are described in reference 8. The calculations were performed on the VAX 8600 computer at the FMC Corporation Advanced Systems Center, Naval Systems Division. With a variable step from 1 to 60 ms, depending on the state of the computation, a 60-ms run took about 12 central processing unit (CPU) hours on the VAX.

RESULTS

This section presents the results of the FLOW-3D analyses described in the previous section, along with the experimental data for the transient pressure at four locations in the canister, plenum, and uptake. All FLOW-3D results are compared with experimental data.

Continuous histories of the pressures are given here at selected transducer locations; the initial conditions were atmospheric pressure 101 kPa (14.7 psia) and temperature 296 K (73.1 °F). Considering the location in the canister adjacent to the missile and at an elevation one-sixth of the missile height below the top of the missile, we show Test 1, 2a, 2b, and 2c transient pressures in figures 12a through 12d for FLOW-3D. To explain the pressure history shown, consider that when the rocket motor ignites, exhaust products from the exit impinge upon the aft closure, accumulate in the bottom of the canister, and increase the pressure. The gases then move toward the top of the canister, while compressing the air ahead of them. The resulting pressure waves propagate into the air, which is initially at 101 kPa (14.7 psia). The aft closure rupture causes the hot exhaust products to rush out of the bottom of the canister. This motion of the gases causes a pressure wave to be propagated into the plenum and uptake, and a rarefaction wave to be propagated up the canister.

When the initial shock wave reflected from the forward closure is moving back down toward the bottom of the canister, the pressure behind the shock wave has increased considerably because of the reflection.

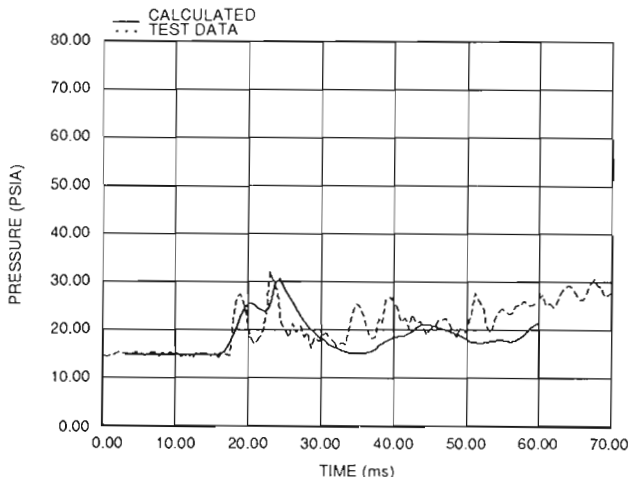


Fig. 12b Calculated and Experimental Pressures for AC-2, Test 2a

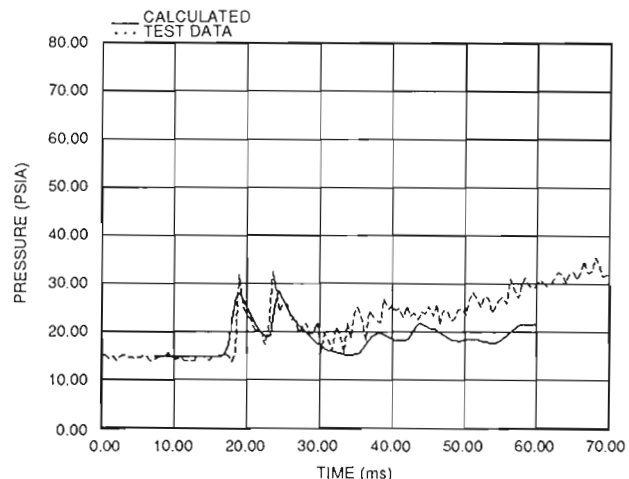


Fig. 12c Calculated and Experimental Pressures for AC-2, Test 2b

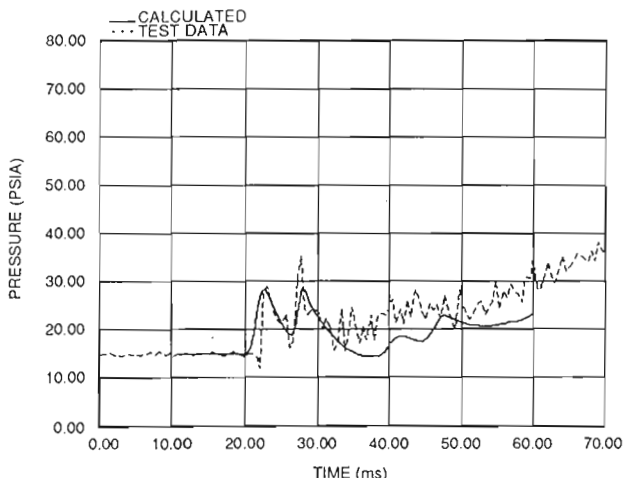


Fig. 12a Calculated and Experimental Pressures for AC-2, Test 1

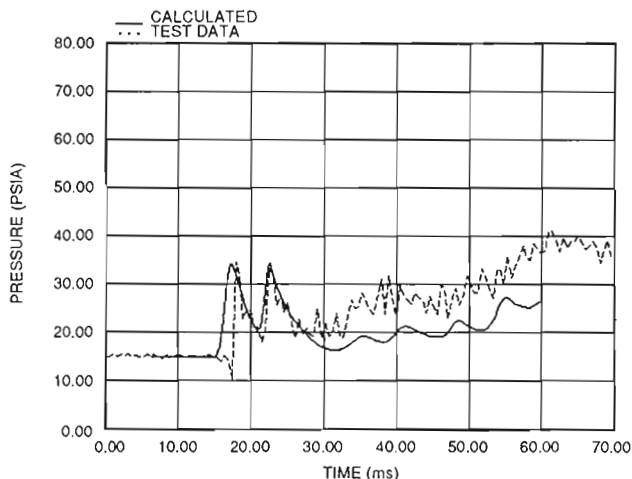


Fig. 12d Calculated and Experimental Pressures for AC-2, Test 2c

Comparison of Calculations With Experimental Data

The following comparison with experimental data will show that the initial shock wave and its reflection from the forward closure are the most significant events to consider concerning the effects of the transient wave environment upon the missile.

Figures 12a through 12d show FLOW-3D calculated pressure-versus-time plots at the location of experimental data taken from Tests 1, 2a, 2b, and 2c, respectively. The location is pressure sensor AC-2 at about 1 meter below the top of the canister. The FLOW-3D code calculated curves are solid; the experimental curves are dashed. The first two peaks shown by the calculated curves in figures 12a through 12d are caused by the initial and the reflected shock waves, respectively. The third and successive peaks are caused by the plenum waves because the aft closure has then opened. In general, good qualitative agreement is shown between the calculated FLOW-3D and the experimental values. Restricting the remainder of the discussion to Test 2b, primarily for brevity, we found, quantitatively, the calculated initial shock wave to be less than 3-percent higher (<3.5 kPa or <0.5 psi) than the first peak on the experimental curve. Because the pressure behind the initial shock wave increases upon reflection at the forward closure, the discrepancy between the calculated and the experimental reflected shock waves is slightly greater than that for the initial shock waves. The FLOW-3D computer code could be predicting slightly different pressure peaks because the true initial pressure peaks could arise from the chamber pressure peaks (averaged for use in the calculations, see figures 2 through 5). It should be noted that the nozzle flow area was increased, thereby increasing the mass-flow rate, to compensate for incomplete combustion. Pressure sensor AC-17 produced an interesting trace because of its location opposite the missile nozzles and near the aft closure, although the geometries and therefore the shock dynamics in that region were not closely modeled. Figures 13a through 13d show these pressure traces. The strengths of the canister waves are slightly underpredicted by the FLOW-3D calculations for a short period right after the aft closure opening. Perhaps the main reason for this underprediction is because the calculations assume that the aft closure opens instantly to its maximum position against the sills and remains there. This assumption gives a flow vent area of 0.1865 m² (289 in.²). However, if the aft closure petals, after hitting the sills, rebound to a position less than the maximum, or open slowly to its maximum position, the vent area would be reduced. This reduction would reduce the canister gases entering the plenum, thereby increasing the strength of the canister waves.

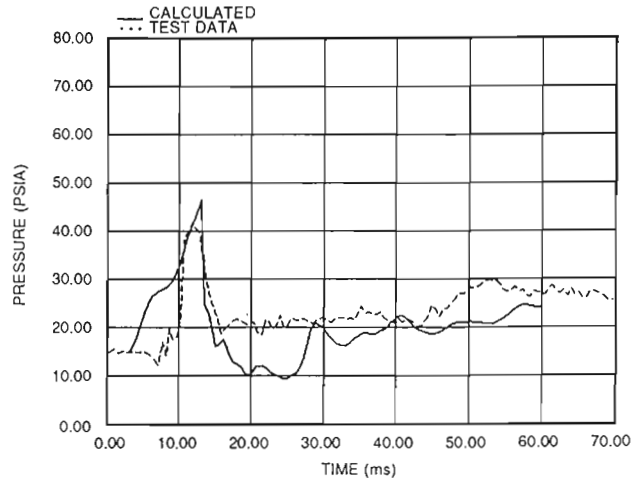


Fig. 13b Calculated and Experimental Pressures for AC-17, Test 2a

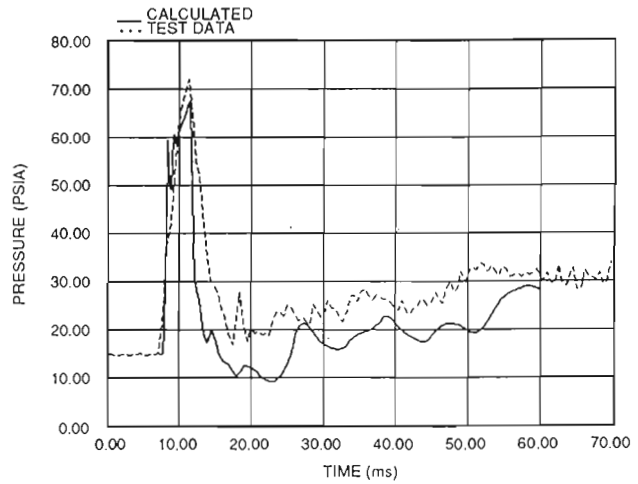


Fig. 13c Calculated and Experimental Pressures for AC-17, Test 2b

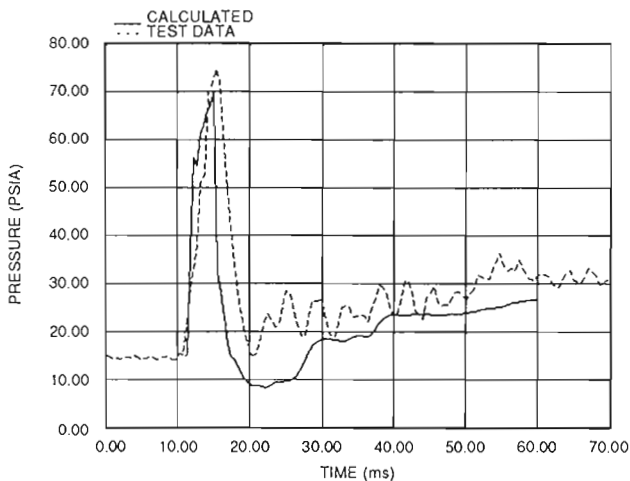


Fig. 13a Calculated and Experimental Pressures for AC-17, Test 1

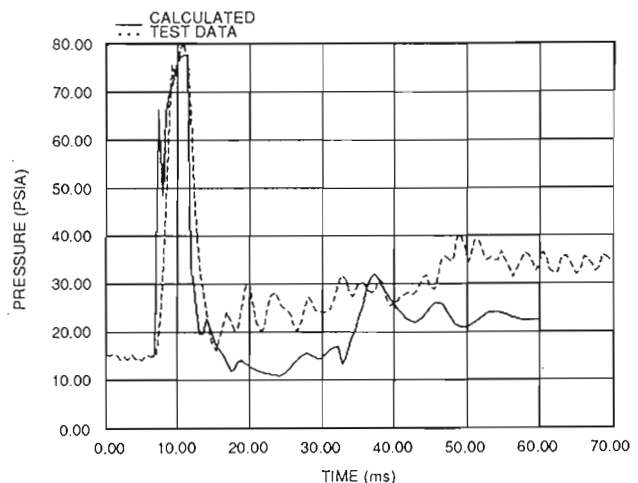


Fig. 13d Calculated and Experimental Pressures for AC-17, Test 2c

Figures 14a through 14d show the pressure history plots in the plenum area. Some of the pressure peaks are not shown in the FLOW-3D calculations. These peaks could be caused by the same reason of being unable to model the aft closure petal dynamic opening.

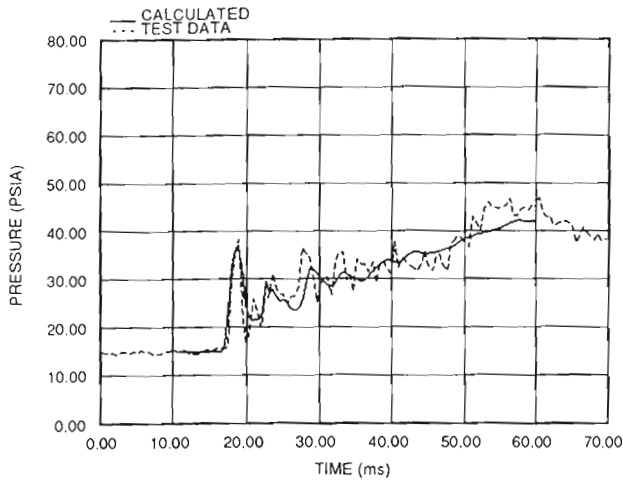


Fig. 14a Calculated and Experimental Pressures for PL-2, Test 1

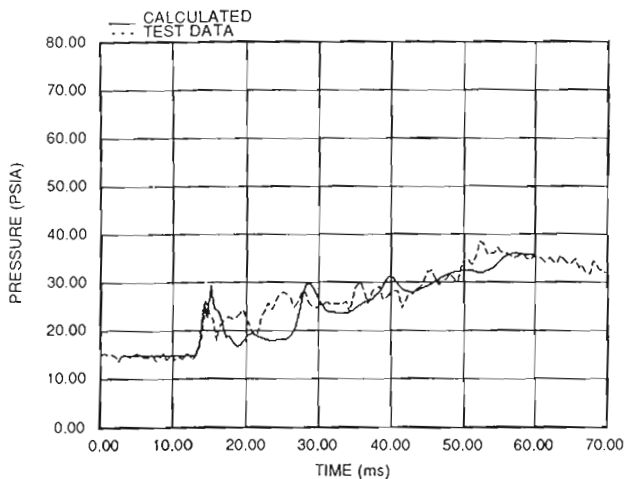


Fig. 14b Calculated and Experimental Pressures for PL-2, Test 2a

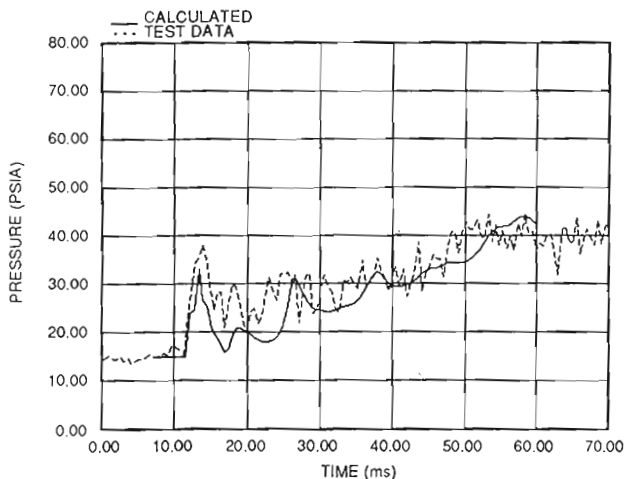


Fig. 14c Calculated and Experimental Pressures for PL-2, Test 2b

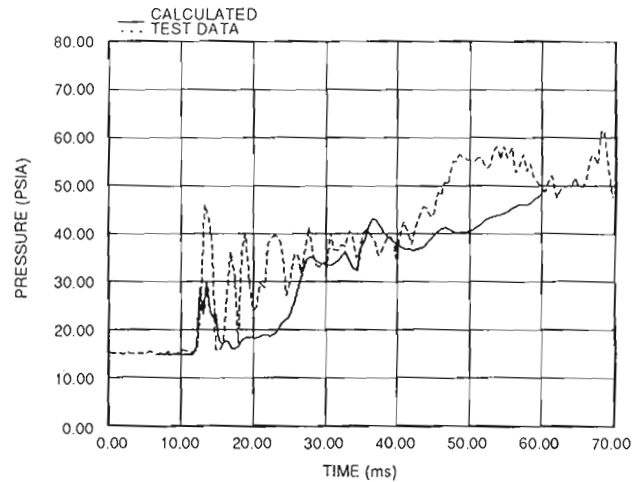


Fig. 14d Calculated and Experimental Pressures for PL-2, Test 2c

More careful modeling of the aft closure opening should bring the calculated and the experimental results into closer agreement. Even with the present assumptions, the calculations give an excellent qualitative description of the transient wave propagation. The strength of the initial shock wave is correctly predicted within 10 percent of the experimental value.

FLOW-3D could be under-predicting the peak pressure because of a flattening effect of the coarse grid and inexact locations of the pressure sensors with regard to the grid centers. Under- and over-predicting the overall pressure could be caused by lack of information about after-burning conditions. Regardless, the predictive ability of FLOW-3D for the times and magnitudes of the pressure peaks and the general pressure trends is excellent for the locations in the canister and the plenum. The predictive ability of FLOW-3D is nearly as good for the pressures in the uptake.

Figures 15a through 15d show the pressure history plots for sensor PU-8 (near the top) in the uptake section. The instantaneous opening time for the uptake hatch can be seen in the results where the PU-8 pressure drops suddenly. In general, FLOW-3D predicts the physical phenomena very well for all the test cases.

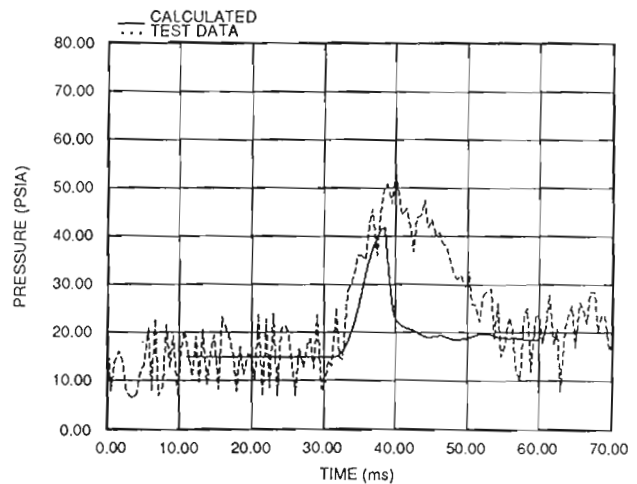


Fig. 15a Calculated and Experimental Pressures for PU-8, Test 1

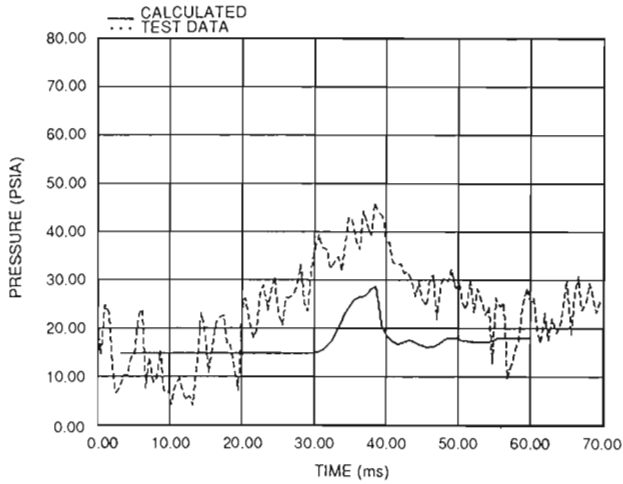


Fig. 15b Calculated and Experimental Pressures for PU-8, Test 2a

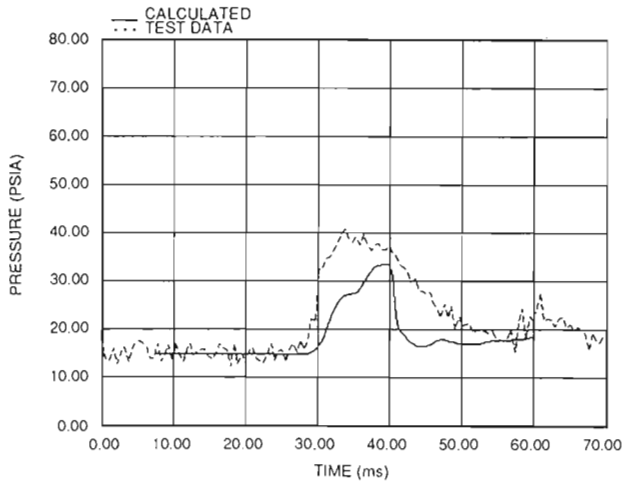


Fig. 15c Calculated and Experimental Pressures for PU-8, Test 2b

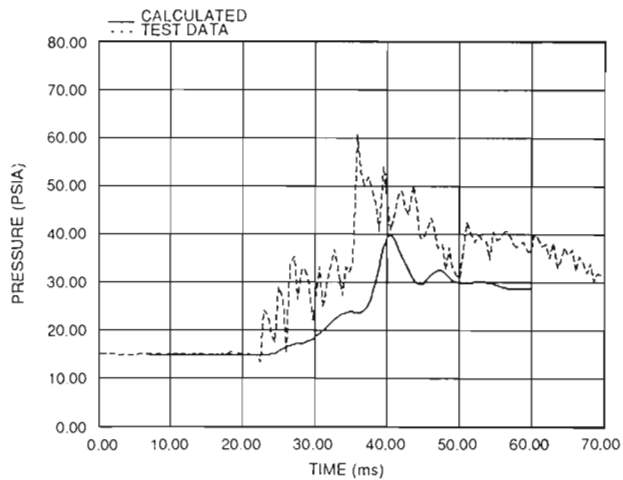


Fig. 15d Calculated and Experimental Pressures for PU-8, Test 2c

SUMMARY

The FLOW-3D computer code results for pressure have been compared with the test data for four tests of in-situ firings of restrained missiles located at two positions within an enclosed launching system. The comparisons of the data and predictions are generally reasonable, qualitatively, and are in good quantitative agreement for Test 2b, the test with the most trusted data and the best motor-chamber pressure data.

The dynamics of the aft-closure and -uptake hatch openings should affect the calculational results, perhaps significantly. No attempt was made to model the dynamics; the openings were modeled to be instantaneous. Even so, the comparisons for Test 2b were reasonable in each section of the system module (i.e., the canister, the plenum, and the uptake).

ACKNOWLEDGMENTS

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