STUDY OF EXPLOSIONS IN THE NASA-MSC VIBRATION AND ACOUSTIC TEST FACILITY (VATF)

by

Wilfred E. Baker
Sandor Silverman
Tom D. Dunham

FINAL REPORT

Contract NAS9-7749
SwRI Project 02-2309

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

March 1968

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO   HOUSTON

SOUTHWEST RESEARCH INSTITUTE
8500 Culebra Road, San Antonio, Texas 78228

STUDY OF EXPLOSIONS IN THE NASA-MSC VIBRATION AND ACOUSTIC TEST FACILITY (VATF)

by

Wilfred E. Baker
Sandor Silverman
Tom D. Dunham

FINAL REPORT

Contract NAS9-7749
SwRI Project 02-2309

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

March 1968

Approved:

H. Norman Abramson, Director
Department of Mechanical Sciences

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

This report presents the results of a study of the effects of bursting of helium pressure bottles in the Apollo Service Module (S/M) while the spacecraft is undergoing vibration or acoustic testing at the Manned Spacecraft Center of NASA. The work was conducted by personnel of the Department of Mechanical Sciences at SwRI, in accordance with requirements of Contract No. NAS9-7749 from NASA-MSC.

The problem which we are studying here is well described in the Statement of Work for the Contract, included as an appendix. Two 40.2-in. diameter titanium alloy pressure spheres located in the Apollo Service Module (S/M) are considered to be potential explosion hazards during vibration and acoustic tests to be conducted in the Vibration and Acoustic Test Facility (VATF). We were to assess the damage potential of these vessels to the Spacecraft Vibration Laboratory (SVL), the Spacecraft Acoustic Laboratory (SAL), and to adjacent areas; to determine the maximum pressures which can be tolerated in the vessels consistent with present facility design criteria; and to suggest methods for modifying or safeguarding the facilities to minimize damage to structures and operating personnel.

The SVL is a 60 × 60 × 100-ft laboratory with the spacecraft mounted vertically in the center. The pressure spheres in the S/M are located about 55 ft from the floor. The primary framework of the laboratory building is of structural steel. A number of balcony-type steel work platforms surround the spacecraft at various levels. The building walls are composed of 6-in. thick, precast, exposed aggregate, reinforced concrete panels (PEAF panels) which are attached to the steel framework with 3/4-in. diameter steel bolts inserted into tee-slots in the panels. The PEAF panels are not load bearing, and they are designed only for wind loads. These panels cover the complete west and south sides of the SVL, the upper part of the north side above a 40-ft high door, and the upper part of the east wall above the control room roof level at 30 ft. The door is in three sections and slides horizontally on rails. The wall of the control room facing into the SVL is made of ceramic tile blocks, and contains a double glass viewing window and a heavy double steel door.

The design of the SAL is quite similar to the SVL, and the spacecraft is similarly located. Primary differences are that the wall panels are 8 in. thick and that the spacecraft is surrounded by a steel shroud during a test.

II. NARRATIVE ACCOUNT OF PROBABLE EFFECTS OF PRESSURE VESSEL FAILURE

We are not primarily concerned with the probability that failure of a pressure vessel will occur, but, instead, postulate that a failure does occur and are then concerned with the effects of the failure. On rupture of one vessel, the sudden release of the stored energy in the compressed gas will generate an explosion within the S/M which will be intense enough to rupture the adjacent vessel. Because of the near certainty of failure of the second vessel after rupture of the first, the energy source for estimating blast effects must be assumed to consist of both vessels rather than one. A blast wave will then emanate from a point which we can assume to be located midway between the two vessels, and will impinge on various internal components of the S/M, on its external skin, and on the aft heatshield of the Command Module (C/M). The S/M itself will be completely demolished and converted into missiles of indeterminate size which will be projected out into the laboratory*. The C/M will be projected upward, probably at rather low velocity, and will then fall into the laboratory. It is also quite likely that the aft heatshield of the C/M would be ruptured. If the explosion occurred within the spacecraft while under test in the SAL, some of the blast energy would be absorbed in acceleration of part of the steel shroud around the spacecraft, also converting it to missiles. In either laboratory, some of the missiles could conceivably penetrate or perforate outside walls, doors, and the walls to the control room.

Only a relatively small amount of the blast energy will be absorbed in converting hardware to missiles, so that a strong shock wave will propagate through the laboratory and load the walls, roof, etc. This shock will be moving much faster than the missiles and will therefore precede them. The strength of the shock attenuates rapidly with distance from the source but still may be strong enough to seriously damage wall panels, doors, windows in the control room, etc. Before striking walls, etc., the shock wave must diffract around platforms, beams, etc. in many cases and may be modified enough that prediction of the actual time history of wall loading is nearly impossible to predict. An upper limit to the loading can be obtained, however, by ignoring the presence of internal structural elements and considering interaction of an unimpeded blast wave with the wall.

If the wall panels or doors fail, then the panels, or doors, or parts of them could be projected outward from the building, constituting

*Empirical data on effects of internal explosions in aircraft show that 1 lb of TNT detonated within the fuselage of any known aircraft will completely demolish the fuselage.

a missile hazard near the building. Conceivably, a PEAF panel located above the control room roof could fall on the roof and penetrate into the control room. The double glass viewing window between the SVL and the control room will almost certainly be blown into the control room, and the ceramic tile wall there may also fail. Even though PEAF panels and doors may be projected outward, they will move much more slowly than spacecraft fragments and, therefore, will be impacted by these fragments before moving an appreciable distance.

In short, it appears that from a qualitative sense, a very severe explosion hazard does exist. In the following sections of this report, we will make such quantitative estimates as are possible.

III. ESTIMATES OF BLAST ENERGY

When a pressure vessel containing compressed gas bursts, the stored energy in the gas drives a compression wave into the surrounding atmosphere which rapidly "shocks up" to form a blast wave very similar to that generated by a conventional explosive charge. Close to the compressed gas sphere source, the overpressures will be somewhat lower and the durations somewhat longer than for the explosive source, but, at greater distances, blast waves for sources of equal energy will be identical. The primary problem in estimating blast effects for the bursting pressure spheres is then the problem of determining the "TNT equivalent". Once this is known, blast wave parameters can be estimated at almost any distance from the energy source by using compiled blast data for TNT.

A very good estimate of the upper limit of TNT equivalent for any vessel filled with a compressed gas can be made by assuming that the gas expands isentropically from the initial pressure and specific volume at bursting to a final pressure equal to the atmospheric pressure, and computing the change in internal energy of the gas in such an expansion (see Refs. 1 and 2). The energy change in such a process is

$$E = \frac{1}{\gamma - 1}(p_1 V_1 - p_2 V_2) \tag{1}$$

where γ is the ratio of specific heats for the gas in the vessel, p_1 is initial absolute pressure, V_1 is total vessel volume, p_2 is atmospheric pressure, and V_2 is total volume after expansion to atmospheric pressure. The isentropic expansion dictates that

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} \tag{2}$$

Combined with Eq. (1), this gives for the blast equivalent energy

$$E = \frac{p_2 V_1}{(\gamma - 1)}\left[\left(\frac{p_1}{p_2}\right) - \left(\frac{p_1}{p_2}\right)^{1/\gamma}\right] \tag{3}$$

The heat of explosion for TNT is about 1800 Btu/lb, or 1.4×10^6 ft-lb. This energy value divided into the above equation for E yields the blast equivalent in pounds of TNT.

Let us emphasize that the estimate obtained in this manner is an upper limit because a reversible and loss-free thermodynamic process has been assumed. In spite of this, it is undoubtedly reasonably accurate and does not overestimate by much. Note that a higher estimate would have been obtained if only the initial internal energy, represented by the first term in Eq. (1), were used. Note also that the expansion of the gas, if the pressure vessel is originally at ambient temperature, involves considerable cooling.

An equation for computation of TNT equivalent, and a table of energy equivalents per cubic foot of tank volume for various tank pressures, is given for bursting pressure vessels in Reference 3. We believe that this equation is incorrect and yields much too high estimates of blast energy. It cannot be derived in any rational manner, and it involves superfluous parameters. A brief comparison of energy equivalents from the table in Reference 3 and those calculated from Eq. (3), assuming compressed air, is given in Table 1. Note that the estimates

TABLE 1. COMPARISON OF TNT ENERGY EQUIVALENTS PER CUBIC FOOT OF VOLUME

Tank Pressure, psig	Energy Equivalent, lb of TNT	
	AFM 127-200	Eq. (3)
10	0.001238	0.000876
1,000	0.4150	0.180
30,000	22.53	6.85

from Reference 3 are consistently too high. We will use Eq. (3) throughout this study.

As noted earlier, we will assume that both pressure spheres in the S/M fail nearly simultaneously. Energy equivalent is then obtained for 100, 75, 50 and 25 percent of full pressurization of 3650 psig and for laboratory line pressure of 180 psig. Gas in the spheres will be assumed to be nitrogen with $\gamma = 7/5$. Initial volume is

$$V_1 = 2 \times \frac{4}{3} \pi r^3 = 2 \times \frac{4}{3} \pi \times 20.1^3 = 6.80 \times 10^4 \text{ in}^3$$

Final pressure $p_2 = 14.7$ psia, and initial pressure p_1 is 3665, 2755, 1840, and 928 psia. Energies from Eq. (3) are then given in Table 2.

TABLE 2. ENERGY EQUIVALENT FOR BURSTING SPHERES

% of Full Pressure	E, lb of TNT
100	29.26
75	21.50
50	13.84
25	6.40
4.9 (line pressure)	1.03

In the SAL, some of the blast energy is converted into kinetic energy of the shroud, reducing the energy which drives a shock wave into the laboratory. For each of the initial explosive energies, an estimate can be made of the velocity with which shroud segments are projected (see next section of the report) and the mass of all segments is known. Kinetic energy, therefore, can be easily calculated as

$$E_k = \frac{1}{2} MV^2 \quad (4)$$

Now,

$$M = 156 \times \pi \times 13.0 \times \frac{12}{4} \times \frac{0.283}{386}$$

$$= 14.00 \frac{\text{lb sec}^2}{\text{in.}}$$

For the velocities shown in Table 7, the kinetic energies, E_k, and reduced total energies, E', available for blast loading of walls are given in Table 3. By comparison of E and E' (Tables 2 and 3), one can see that the decrease in energy available for blast due to accelerating shroud segments is almost negligible, particularly when one realizes that blast parameters are a function of the cube root of this energy.

TABLE 3. ENERGIES E' FOR BLAST LOADING OF SAL

% of Full Pressure	E_k, lb of TNT	E', lb of TNT
100	0.955	28.30
75	0.610	20.89
50	0.282	13.56
25	0.102	6.30

IV. BLAST LOADING

The blast wave generated by vessel rupture impinges on the inner parts of the S/M, diffracts around them, and then loads the S/M outer skin. It also impinges on the aft heatshield of the C/M. After disruption of the S/M structure, the wave then loads the PEAF panel walls and doors in both laboratories. For tests in the SAL, the wave loads and disrupts the shroud surrounding the spacecraft before loading laboratory walls and doors. Before predicting response of these various portions of structure, etc., we must estimate the blast loading.

A. Wall Loading

The geometry shown in Figure 1 indicates loading on part of the wall at the same level as the explosion sources in the S/M. The PEAF panel in the center of the wall is shown since it is the most heavily loaded.

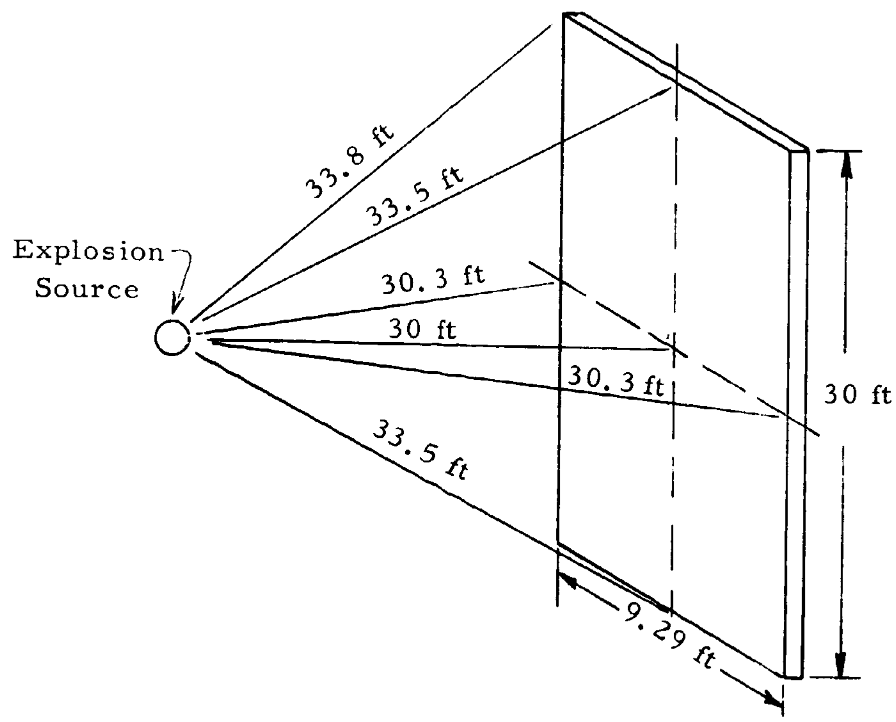

FIGURE 1. GEOMETRY OF BLAST SOURCE AND PEAF PANEL

The shock front will arrive first at the center of the panel, with curvature as shown in the sketch. But, arrival at all other parts of the panel will occur such a short time later that differences in time-of-arrival can be neglected. Also, differences in blast wave amplitude and duration will be small, because the difference in distance from the source to the nearest and furthest points on the panel is small (30.0 ft to 33.8 ft).

Accordingly, the wall loading will be approximated by a pressure pulse striking the panel surface normally of the form*

$$p(t) = P_r e^{-t/T} \tag{5}$$

where the amplitude P_r is peak reflected overpressure obtained from a source of compiled blast data, and the "duration," T, is adjusted so that the blast wave has a reflected impulse, I_r, which also agrees with experimental data. This is done by setting

$$T = I_r / P_r \tag{6}$$

The amplitude and duration will be obtained for a mean distance of the explosion source from the panel, say 32 ft. Values of P_r, I_r, and T are given in Table 4 for explosive sources equivalent to 100, 75, 50, 25, and 4.9 percent pressure in the vessels. Blast data are from Reference 4.†

TABLE 4. BLAST LOADING OF WALL

E, lb of TNT	$E^{1/3}$, $lb^{1/3}$	$R/E^{1/3}$, $ft/lb^{1/3}$	$I_r/E^{1/3}$, psi-ms/$lb^{1/3}$	P_r, psi	I_r, psi-ms	T, ms
29.26	3.08	10.40	12.82	16.56	39.5	2.38
21.50	2.78	11.50	11.49	13.52	31.9	2.36
13.84	2.40	13.33	9.78	10.18	23.4	2.30
6.40	1.857	17.23	7.44	6.62	13.8	2.09
1.03	1.029	31.1	3.90	2.72	4.01	1.475

B. Loading of S/M Skin and Acoustic Shroud

The S/M skin consists of light honeycomb in the form of a cylinder 13 ft in diameter, and, for tests in the SAL, it is surrounded by a concentric steel shroud with relatively small clearance. The blast source will load the S/M skin, cause it to fail, and, for tests in the SAL, then load the steel shroud. For this loading, the important parameter is the reflected impulse, I_r, which can be determined from Reference 4 for R = 6.5 ft. Loading is essentially the same for skin and shroud, as given in Table 5.

*A triangular pulse is also a good approximation, but response calculations are simpler with the exponential form.

†Data from numerous other sources could be used. However, caution should be exercised since some sources, such as EM 1110-345-413 entitled "Design of Structures to Resist the Effects of Atomic Weapons, Weapons Effects Data," dated 1 July 1959, have an unwanted "ground reflection factor" of 2 incorporated in the data. See, for example, Figure 3.5 of this manual.

TABLE 5. BLAST LOADING OF S/M SKIN OR ACOUSTIC SHROUDS

E, lb of TNT	$R/E^{1/3}$	$I_r/E^{1/3}$	I_r, psi-ms
29.26	2.11	88.0	278
21.50	2.34	80.0	222
13.84	2.71	63.0	151
6.40	3.50	49.0	91.0
1.03	6.32	22.1	22.7

C. Loading of Command Module (C/M)

The bursting pressure spheres will apply a blast loading to the aft heatshield of the Command Module (C/M). The mean distance from the blast source midway between the two pressure vessels to the aft heatshield is R = 5.54 ft. Again, the important blast parameter is I_r. Table 6 gives this parameter for the range of energy releases.

TABLE 6. BLAST LOADING OF C/M

E, lb of TNT	$R/E^{1/3}$	$I_r/E^{1/3}$	I_r, psi-ms
29.26	1.80	109.0	335
21.50	1.99	95.0	263
13.84	2.31	78.1	188
6.40	2.98	55.5	103

V. FRAGMENTATION EFFECTS

Light components of structure or those of large area presented to the blast wave will be disrupted by the blast wave and accelerated to some maximum velocity to become missiles which can penetrate or perforate walls or doors of the building. The sizes and shapes of these missiles are nearly impossible to predict, except for relatively strong items joined with weak joints. The velocities can be predicted from the impulse-momentum theorem which gives

$$V = I_r/m \tag{7}$$

where m is mass per unit area presented to the blast.

For tests in the SVL, the S/M skin will be so severely loaded as to be immediately converted into high-speed fragments. Under the assumption that this light honeycomb structure has a value for m of about 2×10^{-5} lb sec^2/in^3, the resulting velocities are calculated from Eq. (7), and are listed in Table 7. The shroud around the spacecraft consists of 1/4-in. steel segments, joined by weak wooden vee-joints, which should fail immediately under the blast loading. Mass per unit area for the shroud is then

$$m = \frac{0.283 \times 0.25}{386} = 1.832 \times 10^{-4} \text{ lb sec}^2/\text{in}^3$$

and velocities for these segments are also given in Table 7.

TABLE 7. VELOCITIES FOR S/M SKIN AND ACOUSTIC SHROUD

E, lb of TNT	I_r, psi-ms	V, ft/sec Skin	V, ft/sec Shroud
29.26	278	1168	126.2
21.50	222	925	100.9
13.84	151	629	68.6
6.40	91.0	379	41.4
1.03	22.7	94.5	12.4

The skin would undoubtedly be fragmented into small pieces, and the size of these pieces and the manner in which they would strike walls, doors, etc. is quite indeterminate. No rational estimates of penetration or perforation effects can be made for the skin fragments.

A section of the shroud would most probably be projected horizontally, nearly normal to its surface and would be considerably slowed by air drag before reaching the wall. But, it is quite possible that the segment will rotate and strike the wall either edge-on or end-on, the most critical case for possible wall penetration being the latter.

A Navy empirical formula for penetration, D, of a slab by fragment or projectile impact is given in Reference 5. Perforation of thin slabs occurs for thicknesses of 2D.

$$D = KA_p \log_{10}(1 + V^2/215,000) \quad (8)$$

In this formula

D = depth of penetration in feet;

K = 4.76×10^{-3} ft^3/lb for reinforced concrete;

A_p = sectional pressure, i.e., missile weight divided by impact area, lb/ft^2, and

V = striking velocity in ft/sec.

Assuming that a shroud segment is equal in length to the S/M (156 in.) we have

$$A_p = 0.283 \times 156 \times 144 = 6360 \ lb/ft^2$$

Thickness of slab, which would be perforated 2D in inches, is computed for each blast source energy and listed in Table 8. Note that no perforation is predicted for even the greatest energy release, so that there appears to be no problem for fragments passing through the walls.*

TABLE 8. PERFORATION OF WALL SLAB BY SAL SHROUD

V ft/sec	V^2	$\left(1 + \frac{V^2}{215,000}\right)$	$\log_{10}(\ )$	2D, in.
126.2	15,900	1.0740	0.0309	1.82
100.9	10 150	1.0472	0.0205	1.24
68 6	4,700	1.0218	0.00946	0.573
41.4	1,710	1.00795	0.00345	0.209
12.4	153.7	1.000715	0.000310	0.0187

*Fly speck on paper caused an initial error in the estimation of the distance 2D. This erronous value was the one communicated to NASA personnel at the meeting attended by the first two authors.

VI. RESPONSE TO BLAST LOADING

A. Response of PEAF Panels

1. Bending Response

The PEAF panels (Precast Exposed Aggregate Facing) are concrete reinforced panels. Those panels closest to the blast source have dimensions of approximately 111.5 × 396 inches. The panels are connected to the structural steel frame of the building by means of nine bolts. The 6-in. thick panel in the SVL is shown in Figure 2. For the purposes of computing the response of the panel-to-blast loading, the panel is idealized as a beam, simply supported at both ends and in the middle (Figure 3a). The response of this beam is desired. Further simplifications are possible since EI is constant; the lengths of both sections are equal and the blast source is located almost directly over the center support. Thus, the response of the beam shown in Figure 3b must be found. It is assumed that the system is elastic and that deformations are small. The response computed under the foregoing assumptions is conservative in that the actual system is stronger than that analyzed.

For the beam shown in Figure 3b, the response to a time-dependent pressure is given by the following system of equations (Ref. 6):

$$w(x,t) = \sum_{n=1}^{\infty} \phi_n(x) \left[(A_n \cos \omega_n t + B_n \sin \omega_n t) + \frac{1}{m_n \omega_n} \int_0^t Q_n(\tau) \sin [\omega_n (t - \tau)] d\tau \right] \quad (9)$$

$$\phi_n(x) = \left(ch \frac{\lambda_n x}{\ell} - \cos \frac{\lambda_n x}{\ell} \right) - K \left(sh \frac{\lambda_n x}{\ell} - \sin \frac{\lambda_n x}{\ell} \right) \quad (10)$$

$$K = \frac{ch\, \lambda_n - \cos \lambda_n}{sh\, \lambda_n - \sin \lambda_n} \quad (11)$$

$\lambda_1 = 3.9266$

$\lambda_2 = 7.0686$

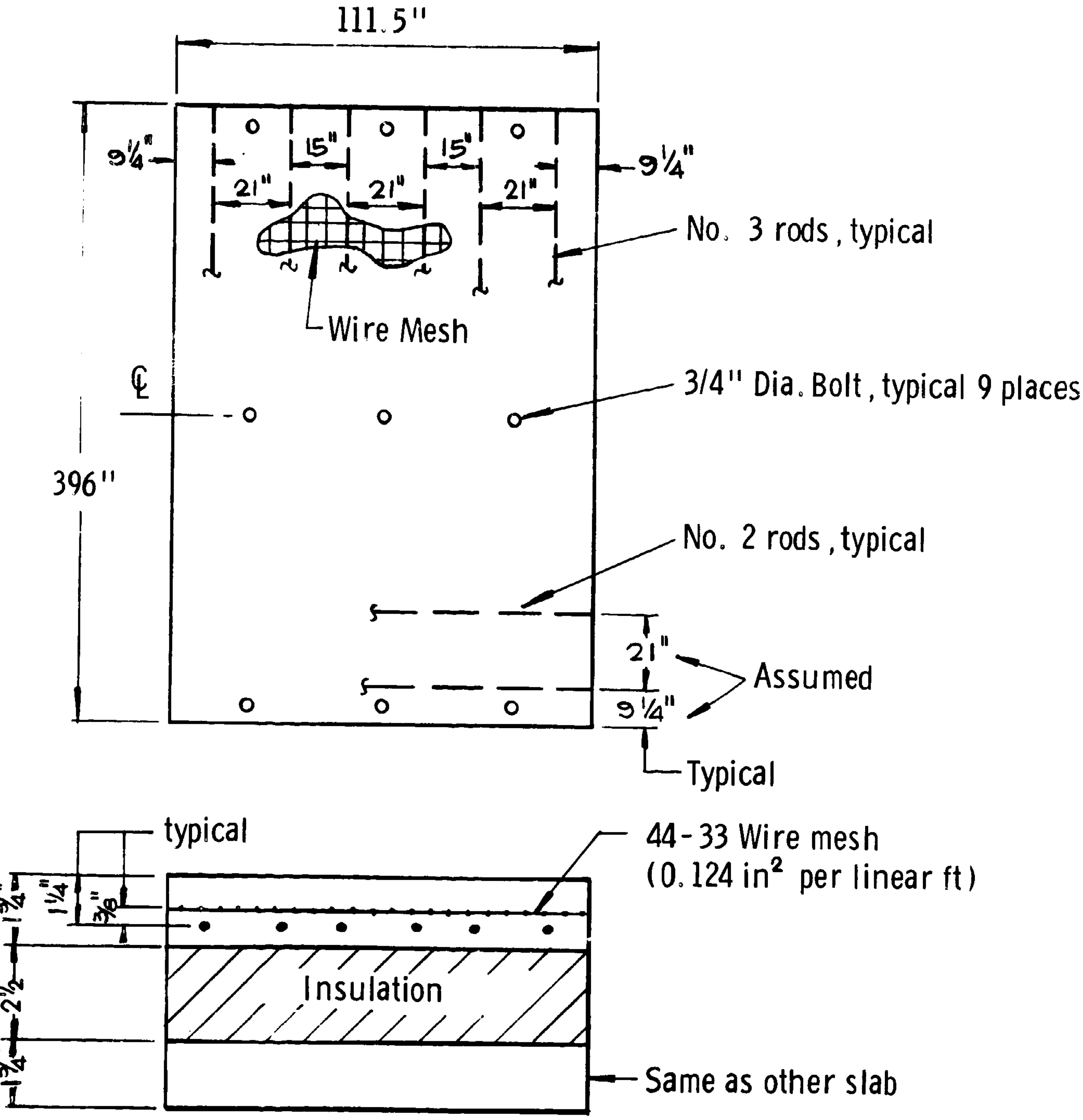

Figure 2. Six-Inch Thick PEAF Panel In SVL

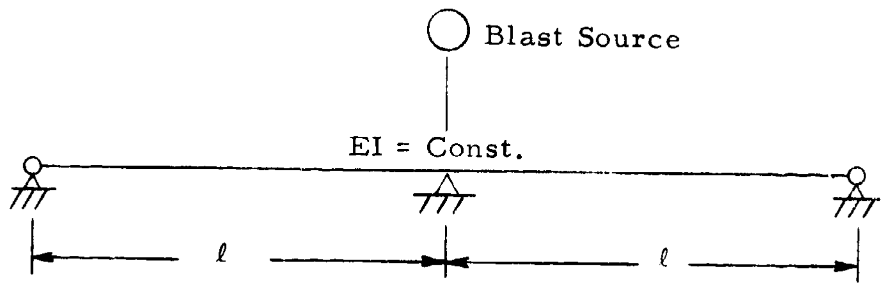

Figure 3a

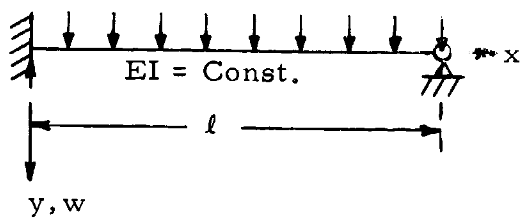

Figure 3b

FIGURE 3. ASSUMED MODEL FOR PEAF PANEL RESPONSE

$$\lambda_3 = 10.2102$$

$$\lambda_4 = 13.3518$$

For large n

$$\lambda_n = (4n + 1)\frac{\pi}{4}$$

$$\omega_n = \frac{\lambda_n^2}{\ell^2}\sqrt{\frac{EI}{\mu}}$$

$$\left.\begin{aligned} A_n &= \frac{1}{m_n}\int_0^{\ell} w_0 \mu \phi_n \, dx \\ B_n &= \frac{1}{m_n \omega_n}\int_0^{\ell} \dot{w}_0 \mu \phi_n \, dx \\ m_n &= \int_0^{\ell} \mu \phi_n^2 \, dx \end{aligned}\right\} \qquad (12)$$

$$Q_n(\tau) = \int_0^{\ell} p(x,t)\phi_n \, dx \qquad (13)$$

In the foregoing equations,

ℓ	- length of beam
μ	- beam mass per unit length of beam
EI	- bending rigidity of beam
w	- displacement of beam in y direction
ϕ	- mode shape
m_n	- generalized mass
$Q_n(\tau)$	- generalized force
dot $(\cdot)$	- derivative with respect to time

For the case of a blast load given by $p(x,t) = P_r e^{-t/T}$ where, for a given tank pressure, P_r and T are constants (see Table 4), we have the following:

$$Q_n(\tau) = \frac{P_r \ell}{\lambda_n} e^{-\tau/T} \underbrace{[(sh\,\lambda_n - \sin\lambda_n) - K(ch\,\lambda_n + \cos\lambda_n) + 2K]}_{K_2}$$

$$I = \int_0^t Q_n(\tau) \sin[\omega_n(t-\tau)]\, d\tau \qquad (14)$$

$$= \frac{P_r \ell K_2}{\lambda_n} [I_1 \sin\omega_n t - I_2 \cos\omega_n t] \qquad (15)$$

$$I_1 = \frac{e^{-t/T}\left(-\frac{1}{T}\cos\omega_n t + \omega_n \sin\omega t\right) + \frac{1}{T}}{\left(\frac{1}{T^2}\right) + \omega_n^2} \qquad (16)$$

$$I_2 = \frac{e^{-t/T}\left(-\frac{1}{T}\cos\omega_n t - \omega_n \sin\omega t\right) + \frac{1}{T}}{\frac{1}{T^2} + \omega_n^2} \qquad (17)$$

For a concrete beam, the computation of EI poses a problem in that it is not possible to calculate an "exact" rigidity. From Reference 7, we have for the 6-in. thick PEAF panels

$$E = 1.8 \times 10^6 + 0.5 \times 10^3 f'_c \approx 3 \times 10^6 \text{ psi}$$

$$I = 1860 \text{ in}^4$$

$$EI = 5.58 \times 10^9 \text{ lb-in}^2$$

where it has been assumed that the compressive strength of the concrete in the PEAF panel, f'_c, is about 2500 psi. Reference 8 presents an alternate technique for obtaining the rigidity:

$$E = 3.3 \times 10^4 (f'_c)^{5/8} = 4.39 \times 10^6 \text{ psi}$$

$$I = 1142 \text{ in}^4$$

$$EI = 5.02 \times 10^6 \text{ lb-in}^2$$

The agreement between the answers is surprisingly good.

The details of the 8-in. thick PEAF panels in the SAL could not be determined because no drawings were readily available. Assuming that each of the precast slabs composing the PEAF panel is the same as the 6-in. thick panel (see Fig. 2) and assuming that the panels are separated by an additional 2 in., we can obtain from Reference 8

$$EI = 1 \times 10^{10} \text{ lb-in}^2$$

and from Reference 7

$$EI = 1.085 \times 10^{10} \text{ lb-in}^2$$

The value 1×10^{10} lb-in^2 was used in the calculations.

The maximum allowable moment in the beam may be estimated by assuming that the entire moment is obtained from the reinforcing steel, which is stressed to yield. Thus the bending strength of the beam attributable to the compressed concrete is ignored. This calculation is very realistic for the PEAF panels as they are very much under-reinforced, and the bars yield before the concrete becomes appreciably stressed. For the 6-in. thick panel, the allowable moment is about

$$M_A = 300,000 \text{ in.-lb}$$

and for the 8-in. thick panel

$$M_A = 358,000 \text{ in.-lb}$$

To obtain these values, it was assumed that the yield strength of both the wire mesh and reinforcing steel was 33,000 psi. The net force for the entire 111.5-in. cross section was 21,800 lb for the reinforcing steel and 38,000 lb for the mesh. For the 8-in. panel, the compressive and tensile forces are separated by about 6.25 in. for the mesh and 5.5 in. for the reinforcing steel. Multiplying the mesh force by its lever arm and adding it to the product of the reinforcing steel force and its lever arm yields the allowable moment listed above.

Once the deflection w(x, t) is found, the shear force, S, and bending moment, M, may be calculated by differentiation:

$$EI \frac{dw}{dx} = M$$

$$EI \frac{d^2w}{dx^2} = S$$

At the supports, the shear force is equal to the reactions, and thus the bolt loads may be obtained. These loads as well as the bending moments must be below allowable values or else it is assumed that the panel fails. The allowable shear stress for a concrete reinforced beam is (Ref. 7, p 139)

$$0.03 \, f_c' = 75 \text{ psi}$$

The shear force in the panel should be much less than that corresponding to this stress since the panel is not designed as a structural member and does not have sufficient shear-reinforcing steel.

Equations (9) through (17) were programmed on a computer. It was found that the moment in the 6-in. thick PEAF panel exceeded the allowable moment for all cases shown in Table 4. Thus, it may be concluded that these panels fail in bending. The 8-in. thick panels survived only the last case shown in Table 4. That is, for the one case, the moment did not exceed the allowable. The bolt loads were within 1000 lb/bolt, and the shear stresses were much less than allowable values.

2. Bolt Loads

It is apparent from the preceding parts of this report that the expected blast loading on the PEAF panels in the SVL causes the panels to fail in bending, even for 25-percent pressure, assuming that the supporting bolts do not fail in tension and that the tee-slots by which these bolts fasten the panels to the framework of the building do not pull out of the panels. Data from MSC indicate that in the SVL the tee-slots are not attached to the panel reinforcing rods and can only take a load of about 1000 lb/bolt without pulling out of the panel. In the SAL, these slots are welded to the panel reinforcement, and one can assume that the bolts will probably develop their full tensile strengths before failure. Critical blast pressures can be easily estimated for tee-slot or bolt failure.

For panels in the SVL, the maximum allowable load is that which will pull the nine tee-slots out of the panel, or

$$F_A = 9 \times 1000 = 9000 \text{ lb}$$

Panel area is

$$396 \times 111.5 = 4.41 \times 10^4 \text{ in}^2$$

Allowable, statically applied pressure is, therefore,

$$p_A = 9000/(4.41 \times 10^4) = 0.204 \text{ psi}$$

Equating this to P_r for the blast loading, we obtain from Reference 4 that $R/E^{1/3} = 330$ since $R = 32$ ft, $E^{1/3} = 0.0970$, and $E = 9.11 \times 10^{-4}$ lb. The vessel pressure corresponding to this value of E is so small as to be essentially negligible. If we accept the limitation above, then we must conclude that no pressurization should be allowed in the vessels during test in the SVL.

For panels in the SAL, the maximum allowable load is that which will fail the bolts in tension. A handbook value for allowable load on a conventional 3/4-in. NC steel bolt is 53,000 lb. Failure load for a mild-steel bolt will be somewhat higher, perhaps by a factor of 1.5. So,

$$F_A = 9 \times 1.5 \times 53,000 = 882,000 \text{ lb}$$

Allowable static pressure on a panel is then

$$p_A = 882,000/(4.41 \times 10^4) = 20 \text{ psi}$$

Again equating this to P_r for blast loading, we get $R/E^{1/3} = 9.55$. Blast energy is then $E = 37.5$ lb. Since this is greater than the maximum possible blast equivalent for the bursting pressure vessels, we see that bolt failure will not occur in the SAL.* Allowable vessel pressure in the SAL should then be dictated by panel failure in bending or shear under the blast loading.

3. Rigid-Body Response

If the bolts holding the PEAF panels in the SVL fail or pull out of the panels, as is probable, then these panels will be projected horizontally out from the building and will fall to the ground or onto the roof of the control room adjacent to this laboratory. Velocities can be calculated from Eq. (7). The mass per unit area of the 6-in. PEAF panels is

$$m = \frac{25,600}{396 \times 111.5 \times 386}$$

$$= 1.5 \times 10^{-3} \text{ lb sec}^2/\text{in}^3$$

Reflected impulse I_r can be obtained from Table 4 for various energy releases. The resulting velocities from Eq. (7) are given in Table 9. Each panel falls under the effect of gravity as it is projected so that it will strike the ground at some distance from its initial position, dependent on its initial height above the ground. The bottoms of the central panels, which are most heavily loaded, are about 45 ft above the ground, while the panels above the control room roof are initially about 12 ft up. For initial horizontal projection, the distance projected is

$$d = V\sqrt{2h/g} \tag{18}$$

where h is height above ground. These distances are also shown in Table 9 for panels above the ground and the control room roof. They can be seen to be negligible.

TABLE 9. VELOCITIES AND PROJECTION DISTANCES FOR PEAF PANELS IN THE SVL

E, lb of TNT	I_r, psi-ms	V, ft/sec	Projection Distances, d, ft: Ground	Projection Distances, d, ft: Control Room Roof
29.26	39.5	2.20	3.69	1.90
21.50	31.9	1.77	2.96	1.53
13.84	23.4	1.30	2.18	1.12
6.40	13.8	0 766	1.28	0.662
1.03	4.01	0.222	0.372	0.192

*In this estimate, the dynamics of the panel bolt system is ignored. The dynamic stress can be about two times greater than the static stress.

C. Response of Doors

We were not able to make numerical computations of door response under blast loading because we could not determine exact construction details or weights from data available at MSC. But, we believe that the guideways at the tops would fail as the doors are blast loaded and that the doors would essentially rotate about their bottom edges and fall outward without being projected any appreciable distance from the building. This estimate is based on the calculations of rigid-body response of the PEAF panels and the assumption that the doors are of somewhat comparable mass per unit area exposed to the blast.

D. Motion of Command Module and Abort Rocket under Blast Loading

Under reflected blast loading from the bursting pressure spheres, the C/M will be impulsively loaded and projected upwards. The mean distance from the blast source midway between the two pressure vessels to the aft heatshield of the C/M is R = 5.54 ft. The important blast parameter is reflected impulse I_r. Under this impulse, the module will have an upward velocity imparted to it which can be calculated from Eq. (7). The C/M plus appurtenances weighs about 26,000 lb and has an area presented to the blast equal to a circle 13 ft in diameter. Then, mass/unit area is

$$m = \frac{26,000}{386} \times \frac{4}{\pi \times 13^2 \times 144} = 3.53 \times 10^{-3} \text{ lb sec}^2/\text{in}^3$$

The upward velocity will cause the C/M to rise against gravity to a height given by

$$h = V^2/2g \qquad (19)$$

The blast loading, upward velocity, and height of rise are given for the four postulated energy releases in Table 10. Even under the most

TABLE 10. RESPONSE OF C/M TO BLAST LOADING

E, lb of TNT	I_r, psi-ms	V, ft/sec	h, ft
29.26	335	7.90	0.97
21.50	263	6.20	0.60
13.84	188	4.33	0.29
6.40	103	2.43	0.092

severe loading, the C/M can be seen to rise an insignificant amount before falling back into the wreckage of the S/M.

E. Containment Vessel

It may prove desirable to build a vessel which will completely contain any explosion which might occur. This structure must necessarily enclose in an airtight manner the vehicle being tested. To date, only the response to internal blast of spherical vessels has been determined in a rigorous manner. Both the loading on the walls and the end closures of cylindrical containment vessels pose serious problems to the analyst. For the present facility, it is felt that a cylinder is ideal (geometrically) and that a carefully designed vessel need not be rigorously* analyzed. Realistic, approximate solutions are possible.

To see if a cylindrical containment vessel is feasible, assume that it is fabricated from 60,000-psi yield steel and has a diameter of 30 ft. The equation of motion for axisymmetric radial motion is†

$$\ddot{w} + \frac{E}{\rho a^2} w = p(t) \tag{20}$$

where w is the radial displacement, ρ the mass density, a the cylindrical shell radius, E the modulus of elasticity, and p(t) the blast pressure loading. The solution to this equation for the case of a blast load may be found in Reference 9. The maximum displacement is given by

$$w_{max} = \frac{P_r a^2}{hE} \sqrt{A^2 + B^2} \tag{21}$$

where A and B are defined in Reference 9. The shell circular frequency is

$$\omega = \frac{1}{a}\sqrt{\frac{E}{\rho}} = 1.124 \times 10^3 \text{ rad/sec}$$

For the maximum tank pressure considered in this report, we have the following blast properties:

---

*By this, the authors mean a solution which satisfies the shell equations of motion, both in the cylindrical portions and end closure portions of the vessel.

†To get this equation, add inertia and loading terms to expression for hoop stress in segment of circular ring and express stresses in terms of displacements.

$$P_r = 114 \text{ psi}$$

$$I_r = 91 \text{ psi-ms}$$

where I_r is the impulse corresponding to the reflected pressure. For an equivalent impulse, the duration of a triangular blast wave, T, may be obtained from

$$\frac{P_r T}{2} = I_r$$

and

$$T = 1.6 \text{ ms}$$

Thus $\omega T = 1.8$, and, from Reference 9

$$\sqrt{A^2 + B^2} \approx 0.8$$

The maximum displacement and stress are

$$w_{max} = \frac{0.8 P_r a^2}{hE}$$

$$\sigma_{max} = \frac{0.8 P_r a}{h} = E\epsilon = E \frac{w}{a}$$

Assuming that σ_{max} is 60,000 psi, shell thickness is

$$h = 0.27 \text{ in.}$$

This is a relatively thin shell, so it is therefore concluded that a cylindrical containment vessel completely enclosing the vehicle being tested is generally feasible.

VII. DISCUSSION AND RECOMMENDATIONS

Some conclusions can be drawn as a result of this study of explosion of pressure vessels in the Apollo spacecraft while being tested in the vibration and acoustic test facility at NASA-MSC. The first conclusion is that blast effects of such an explosion would be quite severe, resulting in extensive damage to the building and possible danger to personnel outside the building from wall panels, doors, etc., which would be blown out. This conclusion is not particularly surprising, because the laboratories were not designed as blast-resistant structures but, instead, were designed only for dead loads and wind pressure. A second conclusion is that, although various parts of the spacecraft and surrounding equipment would be disrupted and converted to missiles, it is highly improbable that these missiles would perforate walls or doors and constitute a hazard to personnel outside the facility. However, failure of the walls may cause chunks of concrete and other debris to be projected into the immediate vicinity. We have also concluded that several conceivable effects of the explosion are negligible. The C/M and escape tower, located immediately above the pressure vessels in the S/M, cannot conceivably be projected any appreciable distance upward and, therefore, cannot impact the roof in either laboratory. Also, any static pressure rise within either laboratory from release of the gas in the pressure vessels will be so small as to be entirely negligible.

Another conclusion appears almost redundant. This conclusion is that no one should be allowed within either laboratory while the vessels are under full pressure, or even under any partial pressure in circumstances which could lead to catastrophic vessel failure. The events occurring within the laboratory in event of vessel failure would be so violent as to render injury or death to persons there almost certain.

The most important recommendation is that no tests be run in either laboratory with the pressure vessels at or near full pressure. A second recommendation is that no attempt be made to convert the facilities, including the control room, to explosion-proof test areas by modifications such as sandbagging, erection of local barricades within the laboratories, etc., unless NASA is willing to undertake major modifications to the facilities. The PEAF panels which constitute the outer walls and the main doors to each laboratory are far too weak both as structural members and in their attachments to the frame of the building to be safeguarded by barricades or sandbags. The roof of the control room also appears to be too weak to survive the loads it might experience. A possible alternative to major facility modification is to surround the spacecraft by a cylindrical containment vessel within the building. This is shown here to be generally feasible in an engineering sense but may prove prohibitively expensive or may seriously interfere with the tests being conducted in the laboratories.

In closing, let us reiterate a basic assumption of this study. Throughout this report we have assumed that vessel failure would occur regardless of pressure in the vessel at time of rupture, and we have studied the effects of such failure. We have not attempted to ascertain the probability of a failure nor of less severe failure than complete and instantaneous bursting.

REFERENCES

1. Baker, W. E., and R. R. Mills, Jr., "Evaluation of Shock and Missile Hazard from a Bursting Pressure Vessel," ER-3192, Aircraft Armaments, Inc., Cockeysville, Maryland, August 1963.

2. Muzzall, C. E. (ed.), "Compendium of Gas Autoclave Engineering Studies," Report Y-1478, Union Carbide Corp., Nuclear Division, Y-12 Plant, Oak Ridge, Tennessee, November 1964.

3. (Author unknown), Air Force Safety Manual AFM 127-200.

4. Goodman, H. J., "Compiled Free-Air Blast Data on Bare Spherical Pentolite," BRL Report No. 1092, Aberdeen Proving Ground, Maryland, February 1960. (AD 235278).

5. Trexel, C. A., "Tests and Design of Bombproof Structures of Reinforced Concrete," Navy Dept., (1941).

6. Young, Dana, "Lateral Vibration of Beams: Classical Theory," Handbook of Engineering Mechanics, W. Flügge (ed), Section 61.4 (1st ed.), McGraw-Hill Book Co., (1962).

7. Ferguson, P. M., Reinforced Concrete Fundamentals, John Wiley and Sons, pp 11 and 437, (1960).

8. Urquhart, L. C., C. E. O'Rourke, and G. Winter, Design of Concrete Structures, McGraw-Hill Book Co., p 27, (1958).

9. Baker, W. E., W. O. Ewing, Jr., and G. E. Bunnewith, "The Elastic and Plastic Response of Cantilever to Air Blast Loading," Proceedings of the Fourth U. S. National Congress of Applied Mechanics, p 853, ASME, New York, (1962).

APPENDIX

STATEMENT OF WORK FOR SOUTHWEST RESEARCH INSTITUTE

"Study of Explosions in the NASA-MSC Vibration and Acoustic Test Facility (VATF)"

1.0 General - The MSC Vibration and Acoustic Test Facility (VATF) is a facility composed of three (3) laboratories, a control room, shop, and offices. Two laboratories require special consideration due to potential explosion hazards; these are 1) the Spacecraft Vibration Laboratory (SVL) and 2) the Spacecraft Acoustic Laboratory (SAL). Each laboratory is approximately 60' x 60' wide and 100' high and can accommodate a fully integrated Apollo Spacecraft for testing. The walls of each laboratory are composed of precast exposed aggregate panels with reinforcement. The panels are approximately 10 feet wide by 30 feet long with a 6 inch thickness in the SVL and an 8 inch thickness in the SAL.

During testing, the Apollo Spacecraft is positioned in the center of the laboratory so that the distance from the spacecraft centerline to the nearest wall is approximately 30'.

On board the Apollo Spacecraft, there are located pressurized vessels which have a high damage potential (in the event of an explosion) to both the spacecraft and the laboratory. The vessels which appear to offer the most serious problems are the two (2) helium pressure spheres which are located interior to the Service

Module. These spheres are made of titanium alloy, have a 40.2-inch inner diameter, a 0.366-inch thick shell, and are pressurized during test to a nominal 3650 psi.

2.0 Purpose of Study - The purpose of this study is the following:

1) To assess the damage potential of pressurized vessels to the Spacecraft Vibration Laboratory, the Spacecraft Acoustic Laboratory and to adjacent areas.

2) To determine the maximum pressures which can be used consistent with present facility design criteria.

3) To suggest methods for modifying or safeguarding the facilities to insure that damage to the structure and operating personnel will be minimal in the event of an explosion.

3.0 General Guidelines - The following are general guidelines which can be used for the purposes of this study:

1) The source of the explosion, if one occurred, would be centered in the middle of each facility at a height of approximately 55 feet from the floor.

2) In the Spacecraft Vibration Laboratory, the Apollo Spacecraft will be exposed to the building's interior environment. In the Spacecraft Acoustic Laboratory the spacecraft will be

enclosed in an acoustic shroud system - details of which may be obtained from the VATF.

4.0 Schedule

a) Quick look at present situation and opinion as to hazard from which safety precautions may be developed by MSC. (100%, 50%, 25% pressurization).

b) Detailed study and submission of a report of recommendations.

END

DATE

FILMED

FEB 24 1970