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NUCLEAR PRODUCTION DEPARTMENT

January 21, 1982

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D.C. 20555

Attention: Mr. Harold R. Denton, Director

Dear Mr. Denton:

SUBJECT: Grand Gulf Nuclear Station
Units 1 and 2
Docket Nos. 50-416 and 50-417
File 0260/0756
Report on the Effects of Hydrogen Detonation as the Result of a Hydrogen Generation Event
AECM-82/32

The enclosed report documents the ability of the Grand Gulf Nuclear Station (GGNS) containment to withstand the effects of local detonations. This analysis was conducted due to serious concern on the part of the Nuclear Regulatory Commission (NRC) regarding this issue. The results of this analysis satisfactorily resolve this area and no further work is planned by Mississippi Power & Light Company (MP&L) with regard to the effects of local detonations.

It should be noted that MP&L does not believe that there is a potential for transition to detonation during hydrogen burns resulting from operation of the GGNS Hydrogen Ignition System (HIS). This is based not only on our judgement but on the evaluation conducted by Bernard Lewis and Bela Karlovitz of Combustion and Explosives Research, Inc. (COMBEX), who concluded that there was no potential for transition to detonation. The results of the COMBEX evaluation are being submitted separately.

Yours truly,

L. F. Dale
Manager of Nuclear Services

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RMS/SHH/JDR:lm
Attachment

cc: (See Next Page)

AE5R1

cc: Mr. N. L. Stampley (w/a)
Mr. G. B. Taylor (w/a)
Mr. R. B. McGehee (w/a)
Mr. T. B. Conner (w/a)

Mr. Richard C. DeYoung, Director (w/a)
Office of Inspection & Enforcement
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

A Description of the Investigations Into the Nature and Effects of Assumed Hydrogen Detonations in the Grand Gulf Containment

January 1982

Table of Contents

1.0 Introduction

The purpose of this study is to calculate the potential effects of hydrogen detonations on the Grand Gulf containment building. In this report, the probability of such an event occurring is not addressed. In fact, based upon a review of the available literature and discussions with recognized experts, it is concluded that detonations will not occur for two reasons: 1) the hydrogen ignition system will prevent the buildup of detonatable concentrations of hydrogen; and 2) the Mark III containment geometry and environment are not amenable to inducing a transition to detonation. In spite of the conclusions regarding the possibility of detonation, this report conservatively evaluates the potential consequences of such an event.

The practice of attempting to calculate consequences resulting from phenomena which are not well understood is analagous to the original treatment of in-vessel steam explosions. In WASH-1400, an in-vessel steam explosion leading to containment failure was felt to be of major importance among those events producing a significant radioactive release. The investigators based their judgement on the results of several small-scale experiments and accidents (BORAX, SL-1, etc.). Based on this limited knowledge of steam explosions, the authors took the most conservative approach and assumed similar results could be obtained in the large-scale reactor vessel environment. It was acknowledged that a great deal of uncertainty was associated with this scenario.

Recognizing that so little was known about steam explosion phenomena, the NRC initiated research on this phenomena. With the advent of the Zion/Indian Point severe accident studies in 1979, this research was accelerated. In a recently released Sandia Report (Reference 6), it was concluded that the in-vessel steam explosion scenario postulated in WASH-1400 was much less probable, and much less significant, than originally thought.

A similar situation now exists with regard to the potential impact from hydrogen detonations. True, laboratory experiments in shock tubes (and other apparatus) have produced detonations with significant pressure pulses. If the results of these detonations obtained in the laboratory were assumed scalable to containment dimensions and geometries, then concern might be warranted, but the available evidence indicates that large-scale hydrogen detonations of a magnitude sufficient to threaten containment integrity will not occur. The probability of, and consequences from, hydrogen burning still tend to dominate the small fractional risk associated with hydrogen gas generation.

There are no easily defined scenarios for modelling hydrogen gas detonations in a Mark III containment. Therefore, a procedure was developed which extrapolates from the available theoretical and experimental data to obtain a conservative pressure-time history. However, the degree of conservatism can only be determined in a broad, qualitative sense.

2.0 Significant Conclusions from Literature Review

The first step in this study was to conduct a review of available literature on gas detonations and shock waves. This review, which encompassed a wide variety of references (1-5), led to confirmation of some previously held judgements, as well as some insights important to the issue at hand. The most significant aspects are briefly discussed below, with further elaboration presented in subsequent sections of this study.

a. Shock tube geometries are not found in the Mark III containments. As expected, the available experimental data on hydrogen detonations does not translate very well to the Grand Gulf containment. Most experiments are conducted under very precise conditions, usually in shock tubes. The volumes in a containment are too large and unconfined to accommodate such detonations and the initial atmospheric conditions are generally not as favorable for detonation as the experiments. It is a major conservatism to assume that the results of these tests are applicable or scalable to the containment environment.

b. Blast Waves and detonation waves have different properties. Simply stated, a blast (shock) wave is a compression wave moving at supersonic speeds through a non-reacting medium (air). Blast waves are generated by the detonation of an explosive charge, such as TNT. A detonation wave can be modelled as a shock wave travelling through a combustible gas (hydrogen and air) with a chemical reaction occurring behind the wave front. The detonation wave may be generated by a spark, a small explosive charge, or a combustion wave degenerating into a detonation wave. The last case is the hardest to obtain, requiring very precise geometry and conditions. This is further explored in Section 3.2.

c. Wave reflection is very important. This study is ultimately concerned with the interaction between the detonation wave and the containment wall. The basic scenario examined is one in which the pressure pulse generated by the detonation wave is the primary threat to the containment boundary. The temperature spikes which accompany a detonation are of very short duration, and are, therefore, not a threat to the containment integrity. Assuming for the moment that detonation waves behave the same as blast waves, this objective is simplified to determining the impulse imparted to the wall. The impulse is defined as the area beneath the pressure-time history curve.

   As a shock wave propagates through air, the air in the shock front is compressed. If the surface of an object in the path of the shock wave is parallel to the direction of propagation, this surface will be exposed to the same pressure (the static pressure) as the compressed air. On the other hand, if the surface is an obstacle standing in the way of the shock wave, then the impact of the air mass may result in a pressure many times greater than the static pressure. The static pressure is frequently called the incident or undisturbed pressure, whereas the pressure resulting from impact of the air mass is the reflected pressure.

This evaluation is concerned primarily with the reflected pressure and its corresponding impulse, which can also be many times greater than the static impulse.

d. Spherical waves versus plane waves. Most of the actual test data reported in the literature comes from shock tube experiments. In a shock tube, the shock wave experiences one-dimensional propagation, a plane wave. However, most actual shock waves are not one-dimensional, but three-dimensional or spherical. In the case of a reactor containment, any postulated shock wave would probably have characteristics closer to a spherical wave than a plane wave.

The distinction between spherical and plane waves is important when calculating the impulse generated during wave reflection. For plane shock waves, the reflected impulse may be, at most, twice the incident impulse. But for spherical shock waves, the reflected impulse may be many times higher than the incident impulse. Section 3.2 presents a thorough discussion of the differences.

e. The difference between spherical detonation waves and blast waves is important. The discussion in the preceding sections (2.c and 2.d) assumed that detonation waves behaved much the same as blast waves. In actuality, this is not true, and the differences between the two can be significant. While Section 3.0 of this report gives a detailed discussion of this point, the major difference can be summarized as follows: the peak reflected pressure of a spherical detonation wave can be as much as four times lower than that in an "equivalent" spherical blast wave. This difference also results in a significant decrease in the calculated reflected impulse.

3.0 Estimating the Pressure-Time Curve

This part of the study will calculate a conservative pressure-time history which will be assumed to result from a local hydrogen detonation. In this context, the importance of distinguishing between detonation waves and blast waves, and plane or spherical wave propagation will be demonstrated.

The basic characteristics which differentiate detonation waves from blast waves were given in Section 2.b. Section 2.c further established that the pressure and impulse resulting from wave reflection are the primary concern in this study. A full appreciation of the differences between detonation and blast waves is gained when determining the respective characteristics, including reflection from a structure, in each calculation.

3.1 Reported Pressures for Hydrogen Detonations

Table 1 provides a compilation of peak pressure in the incident detonation wave for various mixtures of hydrogen and oxygen or air. The incident pressure in the detonation wave is the pressure after which the chemical reaction is complete. Among the references noted in Table 1, there was generally good agreement on the incident pressure.

Only a few investigators reported measurements of the reflected pressure in hydrogen-oxygen/air detonations. None of the experiments evaluated measured both the incident and reflected pressures in the same test. This was usually due to limitations in the experimental apparatus. Table 2 compiles data obtained on reflected pressure. Additional data is provided in Figure 1.

As can be seen from Table 2 and Figure 1, there is a substantial difference between measured and calculated reflected pressures, and there is also a range of reported values among the various investigators. Some insight can be gained from a closer look at these experiments, and examination of the nature of detonation waves in greater detail.

Gordon (Ref. 2) provides an excellent description of a detonation wave. A detonation wave is characterized as a constant speed shock wave followed by a reaction zone of finite width. In the very front of the detonation wave, the combustible gas is compressed, without reaction, much the same as in a blast wave. The chemical reaction is initiated by the high pressure and temperature existing in the compressed gas. As the reaction continues to completion, the temperature of the gas rises considerably, while, conversely, the pressure drops. For instance, Gordon examined the detonation wave for a 20% hydrogen-air mixture. At the very front of the wave, when there has been no reaction, he reported a pressure of about 24 atm, and a temperature of approximately 1350°K. At the tail end of the

wave, when the reaction is near 100% complete, the pressure has dropped to approximately 13 atm and the temperature has increased to 2425°K. This latter state point is the Chapman-Jouget (C-J) point. Behind the detonation wave, the reaction product gases expand rapidly, resulting in a precipitous drop in pressure, temperature, and mass velocity.

The significance of the chemical reaction and the resulting expansion of the gaseous reaction products is manifested when calculating the reflection pressure. Gordon estimated the reflection pressure which would result for detonation waves where the chemical reaction went to various stages of completion. Table 3 summarizes his calculations. In a detonation wave with no chemical reaction (α=0, in which case, it is no longer a detonation wave, but a blast wave), the reflected pressure would be 153 atm. When the reaction goes to 100% completion, the reflected pressure is only 31 atm. In the experiment, Gordon actually measured 44 atm, indicating the reaction had gone to about 90% completion.

Results similar to Gordon's were reported by Sokolik (Ref. 3) for experiments carried out by Kogarko. In this case, Kogarko measured the reflection pressure and the detonation wave velocity. Then, for comparison, he made calculations of the reflection pressure for the following three cases:

a. For a detonation wave (DW) with 100% completion of reaction;

b. For a shock wave with an incident pressure equal to the detonation wave incident pressure (SWp);

c. For a shock wave with a velocity equal to the detonation wave velocity (SWv).

Table 4 gives the results of the experiments. Kogarko's results, like Gordon's, show that the pressures generated during wave reflection are much smaller for detonation waves than for "equivalent" blast waves. His results also point out that, in 3 out of 4 cases, the equal pressure shock wave model (SWp) provides the closest approximation of the reflection pressure resulting from a detonation wave.

The basic conclusion to be drawn from the preceding discussion is that detonation waves are profoundly different than blast waves. Calculations of reflected pressures for detonation waves must consider the nature of the wave, since detonation wave reflected pressure is much less than would be calculated for "equivalent" blast waves.

3.2 Spherical Detonation Waves versus Plane Detonation Waves

The pressures reported in the preceding section were from experiments which generated plane detonation waves. Another type of wave propagation, spherical, is also possible (cylindrical is the third type, but it has properties similar to spherical). When calculating the effects from any shock wave, it may be important to distinguish between plane or spherical propagation.

The relative significance between plane and spherical propagation is best shown by a TNT blast example. This can be done by assuming a detonation of a one kilogram charge of TNT located 2 feet from a wall. Using the TNT blast characteristic curves in Reference 1, the impulse imparted to the wall can be determined for both type propagations. In each case, the impulse due to the incident wave is the same, about 1.5 atm-msec. For a plane wave, the reflected impulse would be, at most, twice the incident impulse, or about 3.0 atm-msec. However, if the wave were spherical, the impulse from the reflected wave would be about 17 atm-msec, almost six times higher than the plane wave case. Closer to the charge, the difference between the spherical and plane reflected impulse increases (to a maximum of about 32 times), while at distances farther away, the difference disappears. In this example, the spherical and plane reflected impulse are equal at about 10 feet.

The type of propagation is also important for detonation waves. The differences, however, between the spherical and plane detonation waves are not as great as in the blast wave case. A plane detonation wave, in a shock tube, will be self-sustaining once initiated. In contrast, Sokolik found that a spherical detonation will experience continuous attenuation as it propagates. Spherical detonations are characterized by abrupt drops in density, pressure, and mass flow velocity just behind the reaction wave front . This velocity decreases to zero over a distance equal to half the radius of the sphere enveloped by the detonation front. Thus, 1/8 of the total volume is filled with reaction product gases at rest. This characteristic tends to decrease the magnitude of the difference in impulses between the two types of detonation waves (as compared to plane and spherical blast waves). Also, as with the blast wave, at large distances from the center the characteristics of the spherical detonation wave tend to resemble those of a plane detonation wave.

The critical question is whether a hydrogen detonation should be assumed to be a spherical or a plane wave. The most conservative approach would be to use spherical wave propagation; however, it may not be possible to generate a spherical detonation. Sokolik (Ref. 3) summarized the events necessary to form a spherical detonation via spark ignition:

"1. the propagation away from the spark of the primary flame front leaves part of the chemical energy unliberated; the higher the flame velocity, the greater is this energy. This may be related to a retardation of the reaction in the flame when the compressions and rarefaction waves reflected from the wall pass through it;
2. a compression wave reflected from the envelope is focused at the center of the charge, causing at this point an explosive liberation of the remaining energy and the production of a spherical shock wave; this type of ignition is analogous to the explosion of a powerful detonator;
3. finally, propagation of the shock wave, related to the liberation of the energy remaining behind the primary flame front, represents the final stage of spherical detonation."

Therefore, without a powerful detonator to initiate detonation, spherical detonation will be difficult to generate and impossible without an enclosure. It is highly improbable that these conditions will exist in a Mark III containment.

Both plane and spherical propagations will be examined.

3.3 The Pressure-Time Curve

A significant part of this study is the selection of the pressure-time history to be assumed for the postulated hydrogen detonation. It must be emphasized here that this selection process is extremely judgemental, and, in some cases, arbitrary assumptions are necessary to define the detonations. Theoretical calculations done for this study have been supported and modified with experimental evidence to ensure a conservative evaluation. For example, shock tube data has been assumed applicable to the containment despite significant environmental and geometrical differences. Blast wave correlations have been used to calculate detonation wave parameters despite the differences already noted. All of these are significant assumptions; however, the final conclusion is that the pressure-time curves selected are very conservative.

The data presented in Section 3.1 will form the basis for the pressure-time curve. Two concentrations of hydrogen will be assumed, 20% and 67%, only because this represents the upper and lower bounds of the data available (see Table 2).

As mentioned in Section 3.1, there is reasonably good agreement on the incident pressure in the detonation wave. For a 20% hydrogen-air mixture, the incident pressure (P_1) is approximately 13 atm, and for 67% hydrogen plus oxygen (assumed to be the same as air), P_1=19 atm.

The reflected pressure (P_2) is more difficult to calculate. Some values are given in Table 2. Also, in Reference 5, a methodology for calculating the impact pressure developed in hydrogen-oxygen detonations is given. A conservative application of this technique yielded a ratio of P_2/P_1 equal to 2.90. This agrees closely with the ratio calculated in Table 3 (α=.90) of 2.94. If ratios are taken of the measured values reported in Tables 1 and 2, the value of P_2/P_1 lies between about 2.9 and 3.5. Therefore, it was conservatively assumed that the peak reflected pressure is 3.5 times the incident pressure. This yields values of P_2 equal to 45.5 atm and 66.5 atm for the 20% and 67% hydrogen mixtures, respectively.

Having obtained an estimate of the peak pressure, the next important parameter to determine is the time duration of the pressure pulse. The shape of the curve is also very important. Unfortunately, very little data was found on these parameters for hydrogen detonations. Therefore, to determine these parameters, TNT blast wave characteristic curves were used. These curves are available in Reference 1 (Figures 25, 26, 27). The degree of conservatism introduced by this model is discussed in Section 5.0.

The resulting pressure curves are shown in Figure 2 with significant parameters summarized in Table 5. For each hydrogen mixture concentration, two curves are shown; one is the pressure pulse assuming spherical propagation, the other assumes plane propagation. The significance of the type of propagation is discussed in Section 3.2.

The worst case curve in Figure 2 is curve 1. As expected, it is the 67% hydrogen mixture assuming spherical propagation. The maximum impulse is 21 atm-msec. By comparison, the impulse generated assuming plane propagation is less than half the spherical case, only 9 atm-msec.

4.0 Containment Structural Analysis

The load of the local detonation is a short-duration pressure impulse load. It can be expressed as a pure impulse, denoted by:

i = impulse = 21 atm-msec = .31 psi-sec. (See Table 5)

For an idealized bilinear behavior system, the required resistance of a structure can be obtained by:

$$R_m = \frac{i\,\omega}{\sqrt{2\mu - 1}} \qquad \text{(EQ. 5.16 of Ref. 7)}$$

where R_m = required yield resistance in terms of uniform pressure, psi.

ω = angular natural frequency of structure, rad/sec.

μ = ductility ratio.

In the case of elastic response (μ=1), EQ. 5.16 of Ref. 7 is reduced to a static equivalent pressure of:

$$R_{El} = i\,\omega$$

Using the above formulations, the dynamic responses of the containment wall, equipment hatch and upper personnel lock are summarized in Table 6. From Table 6, it can be observed that the structural components have adequate capacities to resist the postulated hydrogen detonation. Although the equipment hatch and the panels of the personnel lock exceed their elastic limit, the ductility ratio is well within the acceptable value for the short duration loading (Refs. 8, 9). In addition, the dynamic increase factor (DIF) for the material yield strength and the actual material yield strength have not been utilized in the analyses.

Based on the ductility ratio of 3 for the containment wall structure (Ref. 8) and 10 for steel structures (Ref. 9), the limiting pressure impulse for the containment is estimated to be .375 psi-sec., or 26 atm-msec.

5.0 Conclusions/Major Conservatisms

This report demonstrates that the Grand Gulf containment is able to withstand the postulated local detonations of hydrogen under a wide variety of conditions. This is true even under the very conservative assumptions established in this report. It is emphasized that the pressure profiles established in Section 3.0 and shown in Figure 2 are hypothetical; there is no real set of circumstances which could generate pressures this severe. The major conservatisms incorporated into this study are listed below.

- Data and observations obtained from shock tube experiments were assumed applicable to the Mark III containment geometry and environment.

- The worst case pressure pulse assumes a 67% hydrogen mixture. This curve is actually based on experiments for a $2H_2 + O_2$ mixture. If the mixture were 67% hydrogen + air, detonation may not occur, since the upper detonation limit for hydrogen in air is approximately 65%.

- In calculating the peak reflected pressure, the maximum ratio of reflected pressure/incident pressure was used (3.5). The ratio is actually closer to 3.0.

- The worst case pressure pulse assumes spherical wave propagation. Spherical propagation yields much more conservative (greater) impulses than plane propagation; furthermore, spherical detonations are much harder to obtain.

- The impulse due to the reflected detonation wave is overestimated by the blast wave curves. The blast curves do not incorporate the fact that the gases behind a detonation wave experience a severe deceleration, eventually coming to rest; thereby reducing the impulse.

- The impulses given in Table 5 consider only the positive phase of wave reflection. There is a negative phase, for both incident and reflected waves. In actuality, the resultant impulse should be used, which would be less than that given.

- When the containment wall response due to a pressure pulse loading is determined, the peak impulse (from Table 5) is applied over the entire wall surface. Realistically, this peak impulse would only be seen in the wall area located at right angles to the wave propagation. For surface areas not at right angles, the impulse is less.

- The effect of varying the initial hydrogen mixture pressure and temperature was not considered. Initial conditions are usually 1 atm and 291°K (with some variations in temperature used among the investigators). The primary effect of changes in the initial conditions is to modify the detonation limits, which would have no impact on the results of this study.

6.0 References

1. Granström, S.A.;" Loading Characteristics of Air Blasts from Detonation Charges," Acta Polytechnical, No. 196, 1956.

2. Gordon, W.E.; "Third Symposium on Combustion and Flame and Explosion Phenomena," p. 579, Baltimore, 1949.

3. Sokolik, A.S.; "Self-Ignition, Flame and Detonation in Gases," Translated 1963, NASA TTF-125, OTS63-11179.

4. Lewis, B. and G. Von Elbe; "Combustion, Flames and Explosions of Gases," 2nd Edition, 1961.

5. Moyle, M.P. and Churchill, S. W.; "Impact Pressures Developed in Hydrogen - Oxygen Detonations," Symposium on Shock Waves in Process Equipment Annual Meeting; Chicago, Ill., 1957.

6. "Probability of Containment Failure Due to Steam Explosions Following a Postulated Core Meltdown in an LWR"; Sandia National Labs, NUREG/CR-2214; June, 1981.

7. Biggs, John M., "Introduction to Structural Dynamics," McGraw-Hill Book Co., 1964.

8. ACI 349-80, Code Requirements for Nuclear Safety Related Concrete Structure, Appendix C.

9. Nuclear Regulatory Commission, Standard Review Plan, Section 3.5.3, Appendix A, July 1981.

Table 1

Incident Pressures in Hydrogen Detonation Experiments

Mixture Composition	Incident Pressure (atm)		Reference
	Measured	Calculated	
$2H_2 + O_2$	20.4	18	3
		18.05	4
	18.3	19.0	2
		18.06	3
$(2H_2 + O_2) + 5O_2$		14.13	4
	15.0		3
	16.0	14.1	2
		13.8	3
$(2H_2 + O_2) + 1N_2$		17.37	4
$(2H_2 + O_2) + 5N_2$		14.39	4
$(2H_2 + O_2) + 5Ar$		16.3	4
$(2H_2 + O_2) + 5He$		16.3	4
$(2H_2 + O_2) + 2H_2$		17.25	4
		17.31	3
20% H_2 - Air		13	3

Table 2

Reflected Pressure in Hydrogen Detonation Experiments

Mixture Composition	Reflected Pressure (Atm)		Reference
	Measured	Calculated	
$2H_2 + O_2$	67.3	--	3
	40.4*	46.7	2
25% H_2 - Air	44.8	34.4	2
20% H_2 - Air	44.2	31.0	2

*In the $2H_2 + O_2$ mixture, Gordon stated that the measured reflection pressure of 40.4 atm is smaller than expected because of limitations in time resolution of the instrumentation.

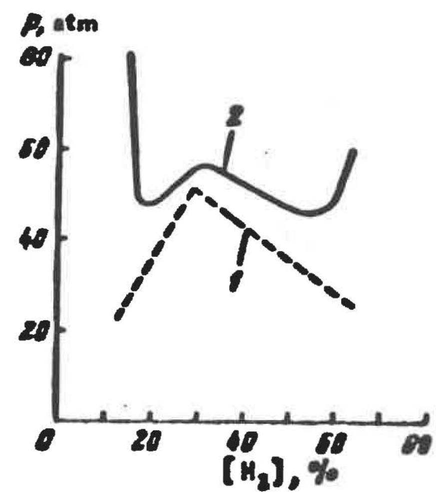

Figure 1

Pressure accompanying detonation-wave reflection in hydrogen-air mixtures:

1) calculated; 2) measured (according to Kogarko and Zel'dovick, Ref. 3).

Table 3

Theoretical Pressures Before and After Reflection

For Different Degrees of Reaction (α) in 20 Percent H_2- Air(Ref. 2)

α	P(before) (atm)	P(after) (atm)	P(after)/ P(before)
0.0	23.7	152.9	6.46
0.9	16.1	47.4	2.94
1.0	13.0	31.0	2.38

Table 4

Results of Kogarko's Experiments - Ref. 3

Mixture Composition	Velocity of detonation wave (DW), m/sec	Reflection Pressure (atm)			
		Measured	DW	SWp	SWv
$2H_2 + O_2$	2820	67.3	46.5	99.7	237
$C_3H_8 + 5O_2$	2530	195.5	106.5	200.3	400.7
$CH_4 + 2O_2$	2322	168.4	68.2	203.2	464.5
$CH_4 + 2O_2 + 2N_2$	2030	149.0	54.2	103.6	207.1

Table 5

Summary of Pressure Pulse Characteristics

Curve No.	Type of Propagation	Peak Pressure (atm)	Positive Impulse (atm-msec)
1	spherical	66.5	21
2	plane	66.5	9
3	spherical	45.5	18
4	plane	45.5	8

Table 6

Structural Responses Due to Local Hydrogen Detonation

	Angular Natural Frequency (rad/sec)	Equivalent Resistance $R_m = i\omega$ (psi)	Yield Capacity (psi)	Ductility Ratio μ
Containment Wall	160	40	56	<1
Equipment Hatch	1054	327	207	1.7
Personnel Lock				
Bulkhead Panel	228	71	55	1.4
Door Panel	526	163	125	1.4

Figure 2

Pressure - Time Curves

For Local Hydrogen Detonations