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EVALUATION OF THE EFFECTS OF DETONATION IN A SPHERICAL BOMB

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DISCLAIMER

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ABSTRACT

Presented here is an analysis of the time-dependent pressure forces and impulse loadings on the walls of the hemispherical dome of a nuclear reactor pressure vessel arising from a centrally ignited hydrogen-oxygen detonation. Investigated in this context are the effects of richness of the detonable gas mixture as well as those due to the inclusion of water vapor. In the analysis the gas mixture was treated as a perfect gas, and the partial differential equations governing the gasdynamic flow were integrated using the CLOUD CODE--a finite-difference technique set in Lagrangian coordinates and incorporating the smoothing action of artificial viscosity. The most interesting results pertain to the ringing of pressure pulses at the walls. Their frequency is quite uniform, and their pressure peaks, at levels significantly higher than that of combustion at constant volume, decay at a negligible rate.

BACKGROUND

At approximately 4:00 A.M., March 28, 1979, the Three Mile Island Nuclear Plant - Unit 2 in Harrisburg, Pennsylvania, while operating at approximately 97% of full power, experienced a loss of feed water (NSAC-1, 1979; NUREG-0560, 1979). Unlike previous incidents (NUREG-75/104 [WASH-1400], 1975), a series of events took place that resulted in the formation of a potentially explosive gas bubble within the reactor pressure vessel. While field monitors recorded releases of radioactive gases, Nuclear Regulatory Commission, General Public Utility, and Industry Advisory Group personnel struggled to gain control over the growing gas bubble. Estimates of the bubble's size were as large as 2000 cubic feet at a pressure of 68.03 atms. and a temperature of at least 422°K. Chemical analysis indicated the gas bubble's composition to be a rich mixture of hydrogen, oxygen, and water vapor.

Questions as to the explosibility and flammability of the gas bubble arose. The immediate and primary concern was to assess the vulnerability of the reactor pressure vessel to the most serious of possible future events--accidental explosion of the gas bubble. Failure of the vessel to contain the explosion could have lead to the venting and subsequent dispersion of highly toxic radioactive material into the atmosphere. A potentially serious threat to the public existed.

The assessment of the potential damage resulting from confined and unconfined gas explosions has been extensively analyzed and documented.†

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†See Strehlow (1973), Haverdings et al. (1976), Oppenheim et al. (1977), and Nicholls et al. (1978).

Presented here is the analysis of the time-dependent pressure forces and impulse loadings on the walls of the hemispherical dome of a reactor pressure vessel arising from a centrally ignited gas detonation. Investigated in this connection were the effects of richness of the hydrogen-oxygen gas mixture as well as those due to inclusion of water vapor.

ANALYSIS

It was assumed that initial conditions at the instant the gas bubble is consumed are given by the self-similar solution of a Chapman-Jouguet detonation front headed by a blast wave. The evaluation of such an event was described in an earlier paper (Oppenheim et al., 1972). The analysis was performed using a numerical technique, the CLOUD CODE (Cohen et al., 1975), developed and modified by the authors (Oppenheim et al., 1977). This technique is set in Lagrangian coordinates and incorporates the smoothing action of artificial viscosity.†

Since the accuracy of the wave interaction processes were of particular interest, especially those occurring between the blast wave front and reactor wall, special attention had to be paid to the spatial resolution of the gas bubble. Over 400 grid points were used for this purpose.

RESULTS

For the same thermodynamic properties of the reacting medium, we analyzed the following three cases:

(1) Constant volume combustion (EV)

(2) Chapman-Jouguet detonation (CJ)

(3) Chapman-Jouguet detonation including the von Neumann spike (VN)

The medium was considered as one consisting of two components, unburned

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†See von Neumann and Richtmyer (1950), Wilkins (1969), and Oppenheim et al. (1977).

Fig. 3. Velocity distribution of SF_3^+ compared with three RRKM predicted velocity distributions. The vertical axis plots the number density of fragments normalized to the observed angular distribution.

— — — 5 excess photons

— – — 8 excess photons

———— 12 excess photons

case (2). Solutions for mixtures II - IV exhibit the same properties.

Peak static pressures and ringing frequencies are presented in Table II. Listed there, respectively, are: final pressures corresponding to constant volume combustion, EV; pressure behind the reflected Chapman-Jouguet detonation in the computed case of spherical geometry, CJRS; then for comparison, the equivalent pressure in the planar case, CJRP; computed pressure behind the reflected von Neumann shock front in the spherical case, VNRS; and, finally, pressure of the equilibrium Chapman-Jouguet state, CJ.

CONCLUSIONS

The conclusions of our analysis are as follows:

1. Maximum peak pressure is attained by the initial reflection of the detonation front from the wall of the reactor vessel. Its value can be estimated within about 15% accuracy by calculating the pressure due to planar reflection of the detonation front.
2. Pressure peaks of the ensuing ringing process are much weaker than that of the first peak, but they are nonetheless quite significant.
3. Impulse loadings are essentially the same as those attained by constant volume combustion.
4. Increasing the richness of the gas bubble mixture and introducing water vapor lessens the potential danger due to the detonation.

5. The ringing frequency is virtually independent of the initial composition of the mixture, ranging from 1300 to 1600 cps for the various cases we analyzed.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Figure 1. Static wall pressure and impulse loading histories [— —— Chapman-Jouguet detonation; — — — constant volume combustion; r_c(meter) - radius of hemispherical gas bubble].

Figure 2. Static wall pressure and impulse loading histories [—— —— Chapman-Jouguet detonation including von Neumann spike; —— —— —— constant volume combustion; r_c (meter) - radius of hemispherical gas bubble].

TABLE CAPTIONS

TABLE I. Chemical and gasdynamic states of the gas bubble.

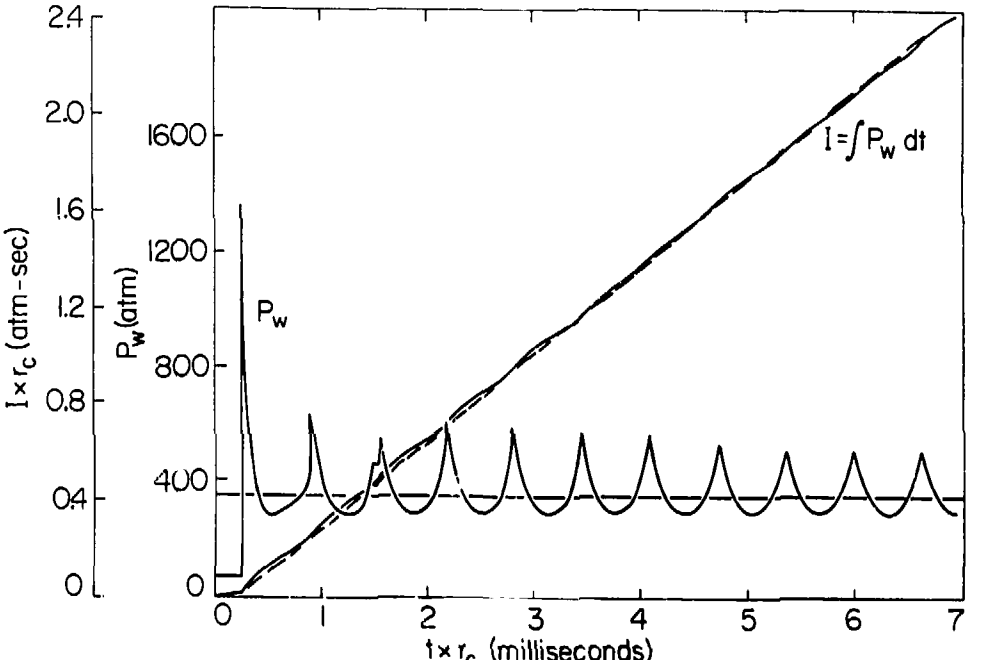
TABLE II. Summary of peak static pressures and ringing frequencies.

TABLE 1. Chemical and gasdynamic states of the gas bubble

Mixture	I	II	III	IV
UNBURNED GAS				
H_2 (mole)	0.90000	0.95000	0.90000	0.95000
O_2 (mole)	0.10000	0.05000	0.10000	0.05000
H_2O (mole)	0.	0.	0.07180	0.07180
ϕ (fuel/air)	4.5000	9.5000	3.5754	5.9476
P_u (atm)	68.030	68.030	68.030	68.030
T_u (°K)	422.22	422.22	422.22	422.22
H_u (cal/gm)	172.38	245.56	-509.39	-668.43
M_u (g/gm-mole)	5.014	3.515	5.885	4.886
C_{P_u} (cal/gm/°K)	1.3965	1.9091	1.2039	1.5763
γ_u	1.3962	1.3973	1.3899	1.3909
a_u (m/sec)	968.7	1191.3	910.5	1043.2
BURNED GAS				
(1) Constant Volume Combustion				
H (mole frctn)	0.00084	--	0.00036	0.83196
H_2 (mole frctn)	0.77704	0.89474	0.72001	0.16813
H_2O (mole frctn)	0.22208	0.10526	0.27961	--
OH (mole frctn)	0.00005	--	0.00007	--
P (atm)	350.22	231.35	328.64	[illegible]
T (°K)	2425	1518.	2257	1421
U (cal/gm)	5.04	6.87	-551.95	-855.44
H (cal/gm)	870.3	822.3	39.1	-254.5
S (cal/gm/°K)	7.2287	9.3182	6.3038	7.5169
M (gm/gm-mole)	5.569	3.700	6.490	4.706
C_p (cal/gm/°K)	1.7387	2.1926	1.4894	1.7466
γ	1.2612	1.3244	1.2602	1.3188
a (m/sec)	2136.8	2125.7	1908.9	1621.0
(2) Chapman-Jouguet Detonation				
H (mole frctn)	0.00190	0.00001	0.00046	--
H_2 (mole frctn)	0.77611	0.89473	0.71958	0.83186
H_2O (mole frctn)	0.22186	0.10526	0.27948	0.16813
OH (mole frctn)	0.00014	--	0.00007	--
M_n (Mach no.)	3.9024	3.1329	3.7734	3.0254
w_n (m/sec)	3658.3	3700.9	3435.6	3156.1
P (atm)	672.66	432.75	628.32	454.72
T (°K)	2697.	1722.	2510.	1611
H (cal/gm)	1349.0	1275.1	420.4	77.3
S (cal/gm/°K)	7.1832	9.2617	6.2656	7.4789
M (gm/gm-mole)	5.566	3.700	6.488	4.706
C_p (cal/gm/°K)	1.8133	2.2517	1.5419	1.7939
	1.2509	1.3133	1.2508	1.3079
a (m/sec)	2245.0	2254.[illegible]	2005.7	1929.1

TABLE II. Summary of peak static pressures and ringing frequencies.

	I	II	III	IV
Mixture				
$H_2/O_2/H_2O$	0.90/0.10/0.0	0.95/0.05/0.0	0.90/0.10/0.0718	0.95/0.05/0.0718
ϕ	4.500	9.500	3.5754	5.9476
M_n	3.9024	3.1329	3.7734	3.0254
Peak pressure (atm)				
EV	350.7	231.4	328.8	217.8
CJRS	1370.2	840.5	1269.9	776.0
CJRP	1569.9	957.1	1456.8	887.0
VNRS	5007.0	2663.5	4452.2	2344.8
CJ	672.9	432.8	628.3	404.7
Ringing frequency (cps)				
CJ	1557.5	1546.3	1388.8	1319.9
VN	1587.6	1583.9	1414.4	1355.7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2.0
1.6
1.2
0.8
0.4
0
I × r_c (atm-sec)
1600
1200
800
400
0
P_w (atm)
P_w
I = ∫ P_w dt
0
1
2
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4
5
6
7
t × r_c (milliseconds)

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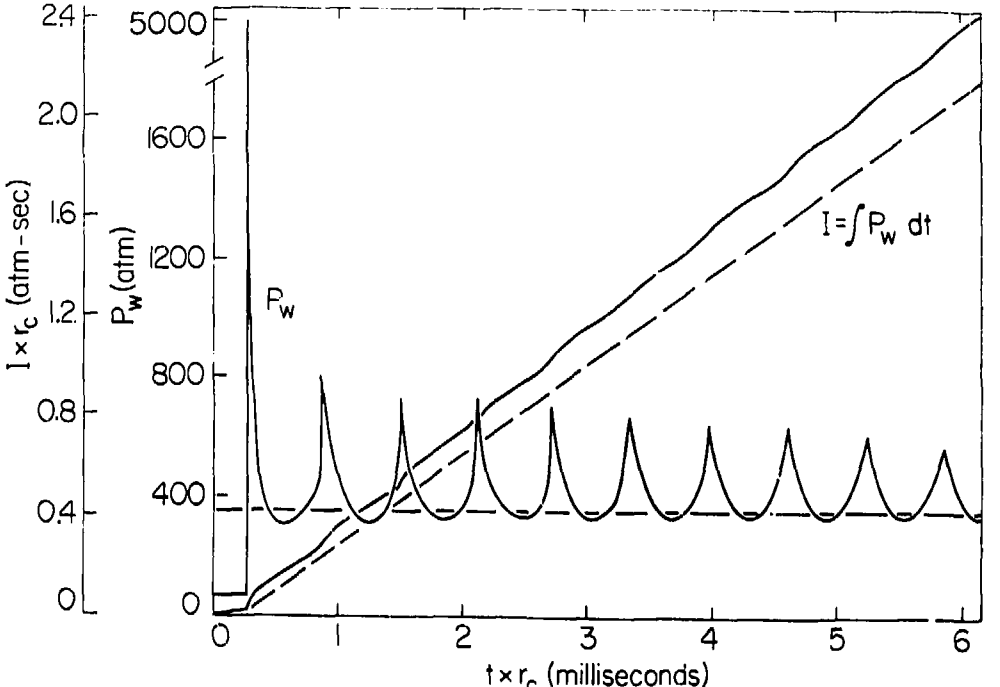
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2.0
1.6
1.2
0.8
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I × r_c (atm-sec)
5000
1600
1200
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400
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P_w (atm)
P_w
I = ∫ P_w dt
0
1
2
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t × r_c (milliseconds)

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