Post Earthquake Hydrogen Combustion Effects in the BL 13 NPDγ Experiment

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1 Introduction

The purpose of this calculation is to evaluate the peak pressure from a worst case, earthquake-initiated H_2 –air combustion event in the Beam Line 13 (BL 13) instrument enclosure. The basic scenario is a severe (PC-3 level) earthquake, occurring when with maximum hydrogen inventory is present in the cryostat of the NPDγ neutron beam target. The BL-13 enclosure is designed for PC-3 earthquakes but the NPDγ target, although robust, is not seismically qualified to PC-3 level. Therefore, it is assumed that it is possible for the experiment cryostat vacuum and hydrogen boundaries to fail during the seismic event, releasing hydrogen into the instrument enclosure. Penttila (Reference 1) has bounded the H_2 vaporization rate at 1.8 g H2/s, or 635 seconds to vaporize the entire 1.2 kg inventory of liquid H_2. In order to bound the pressure pulse after a combustion event, it is assumed that the ignition occurs at the worst possible time, after a flammable mixture of hydrogen and air has built up in the enclosure. Since hydrogen is extremely buoyant, it would flow along the ceiling and out of the enclosure through the enclosure entrance, a PPS-controlled chain link gate, as well as up through the ceiling in the slots formed between adjacent ceiling shielding T-beams.

The sections below show how the buoyant flows are developed in the spreadsheet used to perform the calculations reported here. The results of calculations to determine the maximum accumulation of flammable H2-air mixture in the enclosure are presented. Finally, the maximum pressure increase that could be expected from ignition of the maximum accumulation of H2-air is derived assuming that the combustion takes place in a closed, adiabatic volume.

2.1 Buoyant Flow along Ceiling

This section explains the approach used to determine post-seismic-event flow of buoyant H_2-air mixture parallel to the ceiling toward the open-mesh wire gate at the enclosure entrance. This is depicted in the schematic illustration below (see Reference 2 for a scaled drawing of the BL 13 instrument enclosure). The flow calculations below include only the flow along and parallel to the ceiling. The next section addresses the buoyant flow up through the enclosure roof in the slots formed between the adjacent ceiling T-beams.

As reported in Reference 1, the time required for the release of the 1.2 kg H_2 cryogenic inventory of the experiment is conservatively bounded (on the low side) as 635 s, with corresponding 1.8 g H_2/s release rate. It is assumed that sufficient heating to boil the hydrogen and heat it to 50 K takes place inside the experiment apparatus. The cold hydrogen released at 50 K is extremely buoyant. The resulting plume of H_2 entrains air as it rises to the ceiling. A spreadsheet (see Appendix A) was set up to calculate the buoyant ceiling flow out of the enclosure as a function of the thickness and hydrogen concentration of the hydrogen-rich layer at the ceiling. The spreadsheet executes a simple Bernoulli approach to determine the ceiling flow given the buoyant driving force and the flow losses.

The driving head for the buoyant ceiling flow is approximated as half of the total density head difference for the layer. For the purposes of illustrating the method, numbers pertaining to a 10%H_2 – 90% air ceiling layer are used, including the 0.62 m thickness determined in the spreadsheet for the 1.8 g H_2/s

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release rate. A temperature of 20 C (293 K) is used in the following example for simplicity in illustrating the method, whereas the spreadsheet uses adiabatic mixing temperatures.

$\Delta P = \Delta z*g*(rho_air - rho_10\%H2) = (0.64/2) * 9.8* (1.2 - 1.09) = 0.493\ kg/ms^2 = 0.345\ Pa$

Where,

Δz = the half thickness of the H_2-rich ceiling layer = 0.32 m
g = 9.8 m/s
rho_air = 1.2 kg/m^3 at 293 k and 1 atmosphere (no H_2)
rho_10%H2 = 1.09 kg/m^3 (air with 10% H_2 by volume)
rho_H2 = 0.09 kg/m^3 at 293 K and 1 atmosphere (100% H_2)

The flow is found by matching the driving head with the pressure drop in the channel.

$\Delta P = (fL/D)*rho_10\%H2* V^2/2$

We will solve for V by equating the driving pressure difference with the pressure losses, but first we'll need to know the total loss coefficient, K=fL/D. From previous calculations, we know that the flow is turbulent, with Reynolds number of ~19,000. The relative roughness of the flow path along the steel plates that line the ceiling is taken at 0.002. This is very conservative since it would mean that the average absolute roughness would be >1 mm for a 0.84 m hydraulic diameter (applicable to 10% H_2 as if flows through the doorway). From Reference 3 (on page A-24) we see that the friction factor is about 0.03. After tabulating the losses, we can sum them to get the total flow resistance coefficient.

The losses are tabulated as follows, using correlations from Reference 3. Referring to the schematic diagram below, as the H_2–air mixture flows toward the open doorway, the flow contracts, makes a 90 degree turn and then expands into open space above the door. The losses are tabulated as follows.

- 1 constriction, K=0.5
- 1 exit, K=1
- channel length itself, K=fL/D_h = 0.03*10/0.84 = 0.36
- One 90˚ bend @ 60 L/D, K = 0.03 * 60/0.84 = 2.1
- K, total of above = 4

Now we can solve for the flow velocity.

$V^2 = 2*\Delta P/ (21*rho_10\%H2) = 2 * 0.345 / (4*1.09) = 0.16$

V = 0.4 m/s

Total bulk (volumetric) flow is as follows:

B= V * (layer depth in doorway) * (width of doorway)

B = V * (0.64 m) * (1.22 m) = 0.31 m^3/s

The hydrogen density of the 10% mixture is 8.9 g H_2/m^3, so the mass rate of flow is:

W_H2 = 0.31 m^3/s * 8.9 g/m^3 = 2.8 g H_2/s.

This is >150% of the 1.8 g/s post-seismic-event hydrogen release rate. Therefore, the mixture layer would actually be thinner than assumed since the buoyant escape flow would be greater than the source flow from the leaking cryostat. In the spreadsheet and in the hydrogen inventory calculations reported below in a later section, the inflow and outflow rates are balanced.

Now we check the assumed Reynolds number to see if it is ~19000.

Re = (rho_10%H2) (V) (D_h)/mu_10%H2 =20,000.

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Where,

Rho_10%H2 = 1.09 kg/m3

V=.4 m/s

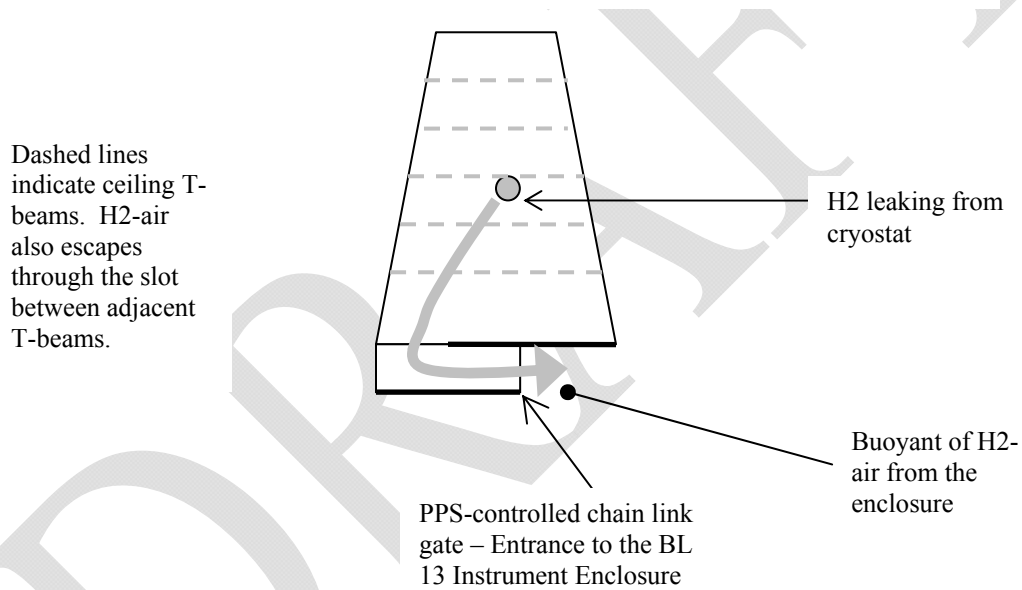
D_h= 0.84

mu_10%air = 0.1*mu_H2 + 0.9*mu_air

= viscosity of 10% H2 / 90% air mixture (at 293 K) = 18.2E-6 kg/ms

This Reynolds number is close to the assumed Re of 19000. Thus, the flow velocity of 0.4 m/s is consistent with the assumed Reynolds number and we need not iterate.

Schematic of BL 13 Instrument Enclosure Illustrating Buoyant Ceiling Flow of H2-air mixture (looking down on enclosure)



2.2. Buoyant Flow through Ceiling through Slots between Adjacent T-beams

In addition to the flow along the ceiling and out the enclosure entrance, buoyant flow would also occur through the slots formed between adjacent T-beams. This section explains the approach used to determine slot flows in the spreadsheet. The slot geometry is shown schematically, as follows:

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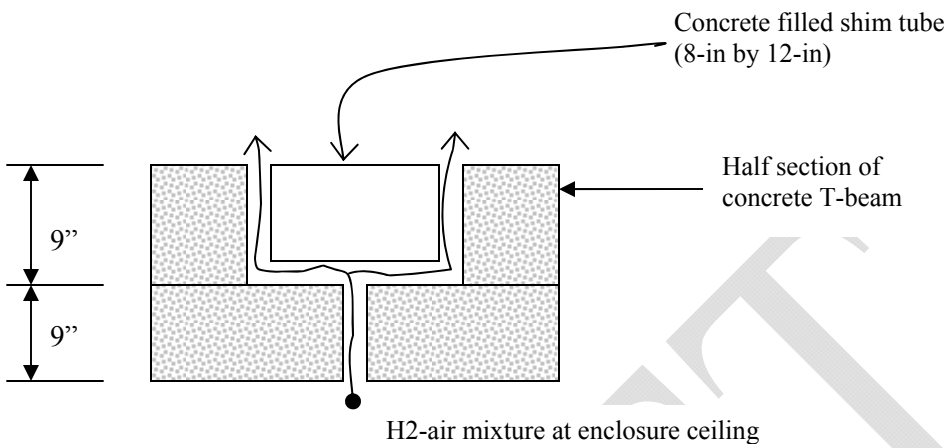
Partial Cross-section of BL 13 Enclosure Ceiling



Flow in the slots formed between the adjacent T-beam shielding blocks and the concrete filled shim tube is calculated using the simple Bernoulli approach explained above for the ceiling flow. As shown in the sketch above, the flow enters the slot (~1-in nominal, or 0.75-in with allowance for conservatism) between two T-beams for a 9 inch upward flow, then splits. Each (left and right) branch flows in a 6 in long by 0.75 in wide horizontal path that is 50% blocked by the shim devices, then turns upward for a vertical 9 in length by 0.5 in width run to the top of the T-beam. Flow velocity in the bottom vertical section is equal to the flow velocity in each horizontal branch because each horizontal branch is 50% blocked by the shims. Velocity in the final vertical branch is actually lower because total channel flow area of the two parallel 0.5 in width vertical channels is 33% higher than the flow area on the bottom vertical section which is 0.75 in width. For convenience, the flow is modeled as one 0.75 in wide channel of length 24 inches (0.61 m). The enclosure T-beam shielding blocks are shown on the drawing identified in Reference 4.

The driving force for buoyant flow is the difference between the ambient air density of 1.2 kg/m^3 and the density of the 10% H_2 –90% air mixture, 1.09 kg/m^3, at the assumed 293 K temperature.

$$\Delta P = \Delta z*g*(rho_air - rho_10\%H2) = .475 * 9.8* (1.2 - 1.09) = 0.493\ kg/ms^2 = 0.492\ Pa$$

where,

Δz = 18/39.37 m = 0.457 m
g = 9.8 m/s
rho_air = 1.2 kg/m^3 at 293 k and 1 atmosphere
rho_10%H2 = 1.09 kg/m^3

The flow is found by matching the driving head with the pressure drop in the channel.

$$\Delta P = (fL/D)*rho_10\%H2* V^2/2$$

Before we can solve for V, the upward velocity in the slots, we need to know the total loss coefficient, K=fL/D. From previous calculations, we know that the flow is laminar, with Reynolds number of ~500. From Reference 3, we find that the friction factor is given by the following expression:

$$f = 64/Re = 0.13$$

The hydraulic diameter of the channel is 4 times the flow area divided by the wetted perimeter. For a thin slot this is approximately equal to twice the width.

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D_h= 2*0.75/39.37 = 0.0381 m

The losses are tabulated as follows, using correlations from Reference 3:

- 1 entrance+1 constriction, K=1
- 1 exit, K=1
- channel length itself, K=fL/D_h = 0.13*0.61/0.0381 = 2.08
- two 90˚ bends @ 60 L/D each, K = 120 *0.13 = 15.6
- K, total of above = 19.7

Now we can solve for the flow velocity.

V^2 = 2*ΔP/ (21*rho_10%H2) = 2 * 0.492 / (19.7*1.09) = 0.0458

V = 0.214 m/s

Total bulk (volumetric) flow is as follows:

B= V * (slot width) * (total slot length)

B = V * (0.75/39.37) * (70.75/3.28) = 0.0876 m^3/s

The hydrogen density of the 10% mixture is 8.9 g H_2/m^3, so the mass rate of flow is:

W_H2 = 0.0876 m3/s * 8.9 g/m3 = 0.78 g H_2/s.

The slot flow is significant but as calculated above, is only about 43% of total flow of 10%H_2 mixture (1.8 g H_2/s). However, combined with what would be flowing out the open doorway of the enclosure this would be more than sufficient to vent the escaping H_2 and prevent a significant inventory from accumulating inside the enclosure. If we had assumed a richer mixture, such as 18% H_2, the slots would have been able to vent the entire flow.

Now we check the assumed Reynolds number to see if it is ~500.

Re = (rho_10%H2) (V) (D_h)/mu_10%H2 =488

Where,

Rho_10%H2 = 1.09 kg/m3
V=.21 m/s
D_h= 0.0381
mu_10%air = 0.1*mu_H2 + 0.9*mu_air
= viscosity of 10% H2 / 90% air mixture (at 293 K) = 18.2E-6 kg/ms

We see that this Reynolds number is very close to the assumed Re of 500. Thus, the flow velocity of 0.21 m/s is consistent with the assumed Reynolds number

3 Finding the Maximum Hydrogen inside the Enclosure

The H2 leaking from the seismically failed NPDγ experiment would be extremely buoyant even at the 50 K temperature it has leaving the vacuum boundary failure point (outermost boundary failure). The buoyant plume that forms above the failure point would entrain air as it flows toward the ceiling. The mixture of air and hydrogen that hits the ceiling would have an unknown composition. Rather than trying to predict the plume concentration, the approach was to bound the effect of plume entrainment by defining the worst possible combination of related parameters. To find the worst case for accumulation of hydrogen in the enclosure, the following two inputs were defined as inputs in the spreadsheet model: (1) hydrogen concentration by volume in air of the buoyant ceiling layer, and; (2) the thickness of the ceiling layer. Results (and intuition) show that increasing the hydrogen concentration and the thickness of the

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ceiling layer both tend to maximize the rate of outflow from the enclosure. However, for each assumed hydrogen concentration, only one layer thickness will have outflow equal to the accident inflow [i.e., the bounding 1.8 g H_2/s (for 635 s) inflow from the failed experiment]. The table below shows that the maximum hydrogen inventory inside the enclosure occurs for three hydrogen concentrations: 8.4%, 10%, and 18%. Higher concentrations than 18% are not reported because the buoyant escape becomes so dominant that buildup of escaped H2 inside the enclosure is very small. Lower concentrations than 8.4% are not reported because rapid, efficient combustion is not achievable at lower concentrations. For example, downward flame propagation does not occur below 9% H_2 and the ignition energy below 9% is increased by more than an order of magnitude to values characteristic of methane (Reference 5).

Table 3-1 Hydrogen Mass in Enclosure as a Function of Hydrogen Concentration

H2 concentration in ceiling layer (vol. %)	Layer thickness (m)	Mass of H2 in Ceiling Layer (kg H_2)	H2 concentration averaged over the entire enclosure volume (vol %)
18	0.22	0.14	0.97
10	.64	0.22	1.56
8.4	.8	0.24	1.64

The calculations summarized above show that the worst case accumulation of rapidly combustible mixture of hydrogen and air inside the enclosure would occur for the lowest concentration of 8.4%. Thus, this concentration is used in the next section to estimate the bounding pressure buildup potential.

4 Maximum Pressure from Combustion of Escaped Hydrogen

To maximize the potential pressure increase due to combustion, the following assumptions are made:

- No venting of combustion products occurs from the enclosure
- Hydrogen in the enclosure undergoes complete combustion and
- The combustion is adiabatic.

The theoretical maximum pressure multiplication under these circumstances is reported by Edeskuty (Reference 5, Figure 8.8). Values from Edeskuty's curve are repeated below in Table 4-1. The result for a 1.77% H2—air mixture are a pressure ration of 1.62. This is the worst case for the BL 13 instrument enclosure with post-earthquake hydrogen leakage from the failed NPDγ experiment. Since the BL-13 has an always-open entranceway, it is actually a vented enclosure instead of a sealed one. If the sudden ignition of the worst case configuration were to occur, the pressure spike would tend toward the listed 1.62 atmospheres but the venting would reduce the peak and limit it to a very short duration.

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Table 4-1 Theoretical maximum pressure multiplication resulting from the confined combustion of hydrogen—air mixtures

Hydrogen Concentration (vol. %)	Maximum Pressure Ratio (Final pressure ÷ initial pressure)
60%	5.8
28% (stoichiometric)	8 (this is the peak of the curve)
18%	6.3
10%	4.3
8.4%	3.7
1.64% (worst case for BL 13 enclosure-averaged H_2 accumulation)	1.6 (bounding pressure ratio for BL 13 post-seismic H_2 combustion)

5 Effects of Maximum Hydrogen Burn

The maximum hydrogen burn would not be able to send a pressure wave down the neutron beam tubes (i.e., inward, toward the mercury target) because the peak pressure is not able to cause sudden failure of any of the several beam windows between the BL-13 instrument enclosure and the mercury target. If earthquake movement caused failure of neutron beam tube or beam windows, a potentially flammable H2—air mixture could not be drawn into the beam tube because the H2—air mixture, if any, would be located at the top of the enclosure whereas the neutron beam tube is located about midway between floor and ceiling. The rapid combustion of hydrogen could cause flammables inside the BL 13 enclosure to catch fire, but post-earthquake fire has already been assumed in SNS accident analyses. The very brief 1.6 atm pressure pulse could cause some movement of the shielding T-beams in the enclosure ceiling, depending on how these are held in place. None of these effects would be able to threaten confinement of the target mercury inside the core vessel or target service bay.

6 References

1. Penttila (Reference ____) Hydrogen escape rate.
2. J. H. Luttrell and J. L Atwood, *Beam Line 13 Fundamental Neutron PhysicsGeneral Notes and Layout Plan,* Bldg 8700/FL 1/SH.1, FUND13-52-S8U-8713-A001 Rev. 0, Issued for Construction December 2007.
3. Flow of Fluids through Valves, Fittings, and Pipe, Crane Technical Paper No. 410, Crance Co., New York, 1991.
4. J. H. Luttrell and J. L. Atwood, *Beam Line 13 Fundamental Neutron Physics Roof Plan & Sections*, Bldg 8700/FL 1/SH.1, FUND13-52-S8U-8713-A002 Rev. 0, Issued for Construction December 2007.
5. J. J. Edeskuty and W. F. Stewart, *Safety in the Handling of Cryogenic Fluids*, Copyright 1996, Plenum Press, New York.

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APPENDIX A
SPREADSHEET CALCULATIONS
EARTHQUAKE INITIATED H2 RELEASE

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Parametric Study of H2 Release from Cryostat inside BL 13 Enclosure

NOTE: Calculated cryostat boil-off time = 635 s (see blue-bold lines below)

Rho_air0=	**1.2**	**kg/m^3**	**Air density @ T_air0**
T_air0=	293	K	
T_H0=	**50**	**K**	Temperature of H2 when it has escaped from the NPDGamma experiment
Rho_H0=	**0.491748**	**kg/m^3**	**Pure H2 density @ T_H0**
Cp_H=	13.1	kJ/kgK	
Cp_air=	1	kJ/kgK	

Flow out the Enclosure Door

Nv= 4.00 Velocity heads of loss for flow from the experiment, around the corner, and out the open doorway.
Losses include a contraction (K=0.5), an exit (K=1.0), 8.5 m of travel, and a 90-degree corner (equiv L/D=60).
For Nv computation, D_hydraulic is taken as ~0.84 m; Friction factor as 0.03 <Ref. Crane's Technical Paper No. 410)
This loss coefficient derivation is "tuned" to the situation when H2 conc=10% and thickness is about .64 m. Should be more conservative for thicker layer at lower concentration because the Reynolds number would be higher, making friction factor lower

rho_H2=	**0.0893**	**kg/m^3**	**Pure H2 density @ 273 K**
g=	9.8	m/s^2	Gravitational acceleration
W_dr=	1.22	m	Width of doorway
A_flr=	42	m^2	Area of enclosure (floor, ceiling)
H_ceiling=	3.81	m	Height of ceiling
Enclsr vol=	160.02	m^3	Enclosure volume

Concentration (vol. %) of 1.2 kg of H2, if uniformly mixed & at 273 K = 8.40 %

Flow out the Ceiling Slots

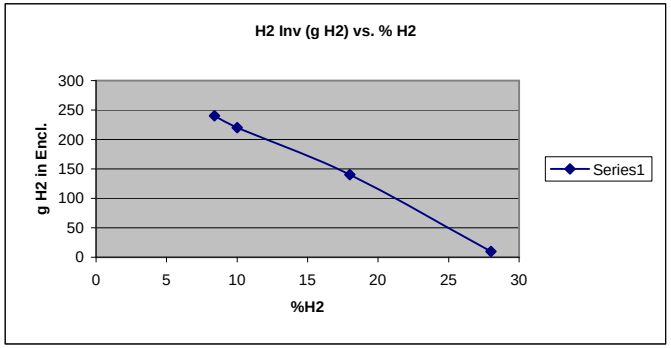
A_slots=	0.41	m^2	
D_hyd=	0.04	m	
K_slots=	19.00	FL/D value for contractions, expansions, and two 90 degree turns	
dZ=	0.46		
mu_air=	1.60E-05	kg/ms (250 K)	mu_H2= 7.80E-06 kg/ms (250 K)

Friction factor= 0.13 Laminar Flow relationship inside slots (Ref. Crane's, page A-24)
Overall Kslots= 19.96 K of 2 from contraction/exp and the balance from L/D =136=(2*60+16) for travel in slot with two 90 degree corners

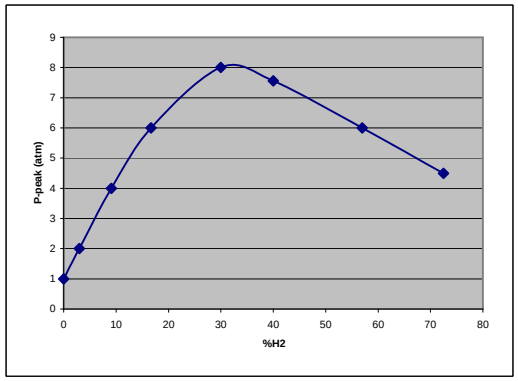
Bernoulli Model Cases: losses=Nv velocity heads in open ceiling channel											**T-slots**	**Rho_mxtr in slots**	**V-slots**	**B-mixtr**	**Rnolds# in slots**	**Rnolds# along ceiling**
Thickness of layer (m)	**H2 Conc.** (vol fract)	H2:air Ratio	**T-mixtr** (K)	**Rho_mxtr** (kg/m^3)	**V-mixtr** (m/s)	**B-mixtr** (m^3/s)	**W-H2** (g/s)	**Mass of H2 in ceiling layer** (kg)	**Time to flow 1.2 kg H2** (s)	**Overall Enclosure H2 Conc (Vol.% H2)**	(K)	(kg/m^3)	(m/s)			
0.001	**0.28**	**0.03**	**229.8**	**1.13**	**0.01**	**0.07**	**2.09E+00**	**0.00**	**574.9**	**0.01**	229.8	1.13	0.17	0.07	533.3	
0.03	0.28	0.03	**229.8**	1.13	0.07	0.07	2.23E+00	0.04	539.3	0.22	229.8	1.13	0.17	0.07	549.9	
0.1	0.28	0.03	**229.8**	1.13	0.12	0.09	2.75E+00	0.13	436.8	0.73	229.8	1.13	0.19	0.08	588.1	
0.1	0.18	0.02	**264.8**	1.11	0.14	0.08	1.30E+00	0.07	922.5	0.47	253	1.16	0.15	0.06	444.4	2307.341
0.2	0.18	0.02	**264.8**	1.11	0.20	0.12	1.85E+00	0.14	647.6	0.94	253	1.16	0.16	0.07	482.7	6526.146
0.205	**0.18**	**0.02**	**264.8**	**1.11**	**0.21**	**0.12**	**1.89E+00**	**0.14**	**635.8**	**0.97**	**253**	**1.16**	**0.16**	**0.07**	**484.5**	6772.4
0.3	0.18	0.02	**264.8**	1.11	0.25	0.16	2.60E+00	0.20	461.1	1.42	253	1.16	0.17	0.07	518.1	11989.3
0.4	0.18	0.02	**264.8**	1.11	0.29	0.22	3.47E+00	0.27	345.8	1.89	253	1.16	0.18	0.07	551.2	18458.73
0.5	0.18	0.02	**264.8**	1.11	0.32	0.28	4.44E+00	0.34	270.2	2.36	253	1.16	0.19	0.08	582.5	25796.86
0.1	0.10	0.01	**273.8**	1.16	0.09	0.05	4.81E-01	0.04	2493.4	0.26	270.8	1.18	0.10	0.04	309.8	1341.561
0.2	0.10	0.01	**273.8**	1.16	0.12	0.08	6.84E-01	0.08	1754.7	0.52	270.8	1.18	0.11	0.05	336.4	3794.508
0.3	0.10	0.01	**273.8**	1.16	0.15	0.10	9.37E-01	0.11	1280.1	0.79	270.8	1.18	0.12	0.05	361.1	6970.956

0.4	0.10	0.01	**273.8**	1.16	0.17	0.14	1.23E+00	0.15	975.5	1.05	270.8	1.18	0.13	0.05	384.2	10732.49
0.5	0.10	0.01	**273.8**	1.16	0.19	0.17	1.56E+00	0.19	770.9	1.31	270.8	1.18	0.14	0.06	406.0	14999.11
0.594	**0.10**	**0.01**	**273.8**	**1.16**	**0.21**	**0.21**	**1.89E+00**	**0.22**	**634.5**	**1.56**	**270.8**	**1.18**	**0.14**	**0.06**	**425.5**	19421.83
0.6	0.10	0.01	**273.8**	1.16	0.21	0.21	1.91E+00	0.23	627.2	1.57	270.8	1.18	0.14	0.06	426.7	19716.84
0.7	0.10	0.01	**273.8**	1.16	0.23	0.26	2.30E+00	0.26	522.2	1.84	270.8	1.18	0.15	0.06	446.4	24846.06
0.8	0.10	0.01	**273.8**	1.16	0.24	0.30	2.71E+00	0.30	443.1	2.10	270.8	1.18	0.16	0.06	465.3	30356.06
0.1	0.084	0.006	**274.4**	1.18	0.06	0.07	5.50E-01	0.03	2182.6	0.22	282	1.15	0.16	0.07		
0.2	0.084	0.006	**274.4**	1.18	0.09	0.09	6.95E-01	0.06	1727.0	0.44	282	1.15	0.17	0.07		
0.3	0.084	0.006	**274.4**	1.18	0.11	0.12	8.70E-01	0.09	1380.0	0.66	282	1.15	0.19	0.08		
0.4	0.084	0.006	**274.4**	1.18	0.13	0.14	1.07E+00	0.13	1125.0	0.88	282	1.15	0.20	0.08		
0.5	0.084	0.006	**274.4**	1.18	0.14	0.17	1.28E+00	0.16	935.1	1.10	282	1.15	0.21	0.09		
0.6	0.084	0.006	**274.4**	1.18	0.15	0.20	1.52E+00	0.19	790.8	1.32	282	1.15	0.22	0.09		
0.7	0.084	0.006	**274.4**	1.18	0.17	0.24	1.77E+00	0.22	678.9	1.54	282	1.15	0.23	0.09		
0.746	**0.084**	**0.006**	**274.4**	**1.18**	**0.17**	**0.25**	**1.89E+00**	**0.24**	**635.7**	**1.64**	**282**	**1.15**	**0.23**	**0.10**		
0.8	0.084	0.006	**274.4**	1.18	0.18	0.27	2.03E+00	0.25	590.3	1.76	282	1.15	0.24	0.10		
0.9	0.084	0.006	**274.4**	1.18	0.19	0.31	2.31E+00	0.28	519.1	1.98	282	1.15	0.25	0.10		
1	0.084	0.006	**274.4**	1.18	0.20	0.35	2.60E+00	0.32	460.8	2.20	282	1.15	0.26	0.11		

%H2	Inventory (g H2)
28	10
18	140
10	220
8.4	240



%H2	P-peak (atm)
0	1
3	2
9.1	4
16.7	6
30	8
40	7.56
57	6
72.5	4.5



MAXIMUM PRESSURE PULSE FROM COMBUSTION EVENT

If we read Figure 8.8 of Edeskuty carefully for the maximum pressure multiplication ratio for a 1.64 volume % H2-air mixture, we find that the pressure ratio is ~1.6. This compares to about 3.7 for an 8.4% mixture.

Description	H2 Concentration from Flow-Temp (vol%)	Pressure Ratio (Pfinal/P_initial)
Concentration with outflow thru open door and slots	1.64	1.6
Concentration with no H2 outflow (air flows out needed to maintain initial pressure=1 atm)	8.4	3.7

The 1.64% case represents a case from the Flow-Temp spreadsheet in which there is a H2-rich layer of H2-air mixture at the higher 8.4% H2-air concentration that averages to 1.64% considering the cell volume that does not have any H2. The actual pressure rise should be smaller because the smaller because of complete combustion is not possible and because the instrument enclosure has a wide open doorway that should take some of the top off the pressure spike, even if rapid conbustion does occur in the hydrogen rich layer.