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LLNL-TR-651668

Gas Gun Safety Calculations

P. Chiao

March 13, 2014

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

4.0 Design Calculations

Gun Component Failure

The following table lists the components of the gun that were evaluated for structural integrity.

Item	Description	SF (ULT)	Calculation Location
Breech	Pressure from propellant on breech	6.5	App. A
Breech Plug	Pressure from propellant on threads	6.8	App. A
Breech Bolts	Reaction force acting on Breech/Flange bolts	8.5	App. A
Flange Threads	Reaction force acting on Flange/Pump Tube connection	16.2	App. A
Pump Tube	Reaction force acting on Pump Tube thread	5.5	App. A
Launch Tube	Pressure acting on Launch Tube	6	App. A
Misfire Condition for Breech*	Pressure remains within the breech due to a stuck piston and does not vent	2.25	App. A
AR Section	Stresses induced from extruding the piston during firing operations	Plastically deformed – regular inspection, max deformation criteria defined	App. A

* This has never happened in over 30 years of operation.

The calculations show that catastrophic failure is unlikely.

Fragmentation

The primary containment of fragmentation for personnel safety from catastrophic failure of components is more robust in the B191 Gun Bay than in B341. B341 relied on six inches of concrete and a steel rollup door to contain fragments. The B191 Gun Bay has 0.75 inch reinforced steel blast doors and six inch concrete walls with seven inch concrete "Tilt-up" walls.

Fragmentation resulting from firing the gun remains unchanged. Listed below is the minimum required thickness for typical shots. Operational procedures require that these values be met. Additional shielding is evaluated on a case by case basis for each experiment.

The following table summarizes the protection requirements and the protection provided. For reference, a comparison between B191 and B341 can be seen in this table as well.

Shielding	Description	Required Protection	Protection in B191	Protection in B341	Calculation Location
Doors	Doors containing fragments from a ruptured breech	0.55" Steel	0.75" Steel Blast Doors	Steel rollup door	App. A
Concrete Spall	Walls containing fragments from a ruptured breech	6" concrete (Borderline spall)	6" Concrete with 7" concrete tilt up walls	6" concrete	App. A
Projectile Barrier	Required min. thickness to stop the maximum speed projectile	2" steel	2" Steel	2" Steel	App. C
Fragment Shielding	Required thickness to keep fragments with the TCA/catch tank	0.54" steel	0.75" Tank Walls	0.75" Tank Walls	App.C

Shielding in B191 meets the protection required and is equal to or better than B341. Therefore, there is no threat to personnel. There is a risk to programmatic equipment if there is a catastrophic component failure or if the tank shielding fails.

Hydrogen

Hydrogen is an essential driving gas in maximizing the performance of the gun. However, with the use of this gas species comes a risk of unintended combustion. In 1977, there was a major incident involving this gun in B341. At the time, there was no nitrogen inerting process following a shot. The contents, including hydrogen, were vented to the atmosphere. The remains of the shot target had an electrical lead that was still energized which initiated the hydrogen/air mixture. The combustion of the hydrogen caused the door to eject off the hinge and impact the building wall. There was significant damage to the facility wall. However, because all operations were unmanned, there were no personnel injured in the incident.

This incident has directly led to the inerting process currently in place today. After 2 seconds, all power is cut off inside of the catch tank, eliminating an ignition source. Immediately after that, the tank is slightly pressurized from a vacuum state with pure nitrogen gas. This is followed by a nitrogen purge for a minimum of 10 minutes. After this process is complete, the air-fuel mixture inside the tank is no longer combustible. For added safety, the volume of the catch tank is pumped down again to under 2 psia and then vented to air.

The following table lists the safety parameters associated with safely operating the gun with Hydrogen.

Hydrogen Safety	Description	Calculated Result	Mitigation	Calculation Location
Minimum Purge Time	Purge time required to lower the hydrogen content in TCA to under 4% for venting	10 min	NA	App. B
Hydrogen Energy	Energetic output if all of the Hydrogen is detonated in the high bay	4.4 kg TNT	B191 Gun Bay rated to 10 kg TNT	App. B
Hydrogen Leaks	Potential "off-normal" scenarios involving hydrogen leaking into areas with air	Same or better in all instances		App. C
Catch Tank Overpressure	Hydrogen detonating within the catch tank	10 psi	10 psi[1]	App. D

All hydrogen operations are performed remotely and therefore pose no threat to personnel. There is a small risk to equipment if the layers of safety systems fail and the Catch Tank door opens as a relief.

High Explosives

The TCA and catch tank were rated to 50 grams of PBX9404 in B341. A new TCA was fabricated and will maintain the 50 gram rating. The locations of the port openings are identical to the previous TCA. Therefore, the dynamic loading on the TCA walls and ports are identical to the previous TCA. The original TCA was proof tested to further validate the calculations.

Enhanced estimates to the first mode frequency were made using Pro/Mechanica to further refine the effective loading parameters.

[1] Closure bolts strip and the pressure is relieved through the catch tank door at this value.

The following table lists the calculated stresses using the new first mode frequency of each plate compared to stresses measured in original qualification tests. Note that the calculated stresses are conservatively high because they assume a detonation in ambient pressure. However, all shots on this gun will be fired in a vacuum. The shock wave imparted on the chamber components will be significantly less in a vacuum due to the lack of compressible gas. The measured stress values were performed in a vacuum. Therefore the differences seen in the safety factors are due to this reason.

To ensure that all shots are fired in a vacuum, the control system will not give a permissive to fire unless the chamber is less than 150 mTorr.

HE Loading	Description	SF (Yield) by calcs (in air)	SF by measured stress (in vacuum)
Shell	Cylindrical shell of the TCA	18	5.4
Endplate	Endplate on the TCA	3.27	7
Big Door	Large 25” x 19” Door on a hinge	3.3	2.8
Small Side Port	Smaller access ports for diagnostics	4.15	4.5
Diagnostics Port	Larger access ports for diagnostics	6.1	NA
X-ray	X-ray window ports	1.29	190
Large Access Port	Door to access the target	1.9	13.3

All high explosive firing operations in HEAF are done remotely and therefore pose no risk to personnel.

Pressure

There are two systems that incorporate the use of high pressure systems: the hydrogen purge system, and the Pump Tube Gas Selection system. The hydrogen purge system uses a nitrogen skid to supply a constant flow of nitrogen to the catch tank and its auxiliary systems. Standard “K” type bottles of nitrogen gas flood the catch tank volume immediately after a hydrogen shot. All components in this system are commercial and have commercial ratings above the MAWP of the system.

There are three pressure “regions” in the Pump Tube Gas Selection system. The first region includes the gas selection panel. These components are connected to the Nitrogen Skid and standard “K” type bottles and have a MAWP of 2400 psig. The second region is the hardware connected after the regulator on the selection panel and have a MAWP of 400 psig. The third region includes the V31 Seal Valve and the Pump Tube Flexible Hose. These two components can be subjected to pressures of up to 15,000 psig due to standard gun firing operations.

Nitrogen Inerting System Components

Pressure Safety Component	Model Number	Description	MAWP (PSI)	Commercial Rating (PSI)
Nitrogen Skid		Nitrogen source for Nitrogen Purge System	2400	2400
S.S. Pressure Lines		Stainless steel lines for components	2200	3000
R1, R2, R3	Victor VTS-450E	Regulators to the Nitrogen Purge, Foreline Fill, and Scrubber Purge lines	2200	3000
V4, V5, V11	Swagelok SS-63EF8-33C-L2	Valves for Nitrogen Fast Fill and Emergency Fast Fill	2200	3000
Flowmeter	Teledyne Hastings HFM-I45	Nitrogen flow meters for slow purge lines	200	1500
Flowmeter	Teledyne Hastings HFM-I45	Nitrogen flow meters for scrubber purge line	15	1500
V6, V7	Swagelok 6LVV-DPHFR4-P1-CM2	Foreline and Scrubber Line supply valves	5	3000
V3, V8, V1, V2	Vacuum Research	Gate valves for the scrubber and vacuum pump	5	17.6
V251*	MKS	Bypass valve for high vacuum and vacuum side	10	Unknown (Vacuum Component
V17*	MDC	Manual vent valve	10	Unknown (Vacuum Component)
V13*	Swagelok 6LVV-DPHPFR4-P1-CM2	Catch Tank vacuum gauge isolation valve	10	3000
Catch Tank pressure transducer*	Dynisco PT270DN-150	Transducer measuring the Catch Tank pressure	10	250
V253, V254*	Swagelok 6LVV-DPHPFR4-P1-CM2	High Vacuum Isolation Valves	10	3000
V250, V252, V9, V12*	Vacuum Research	Gate valves for the high vacuum	10	17.6

*These components are vacuum components that could be exposed to pressure if one of the regulators (R1, R2, R3) **and** a pressure valve (V4, V6, V7) were to fail. There is no risk to personnel because the area is vacated during operations involving pressure. There is only risk to programmatic equipment.

Pump Tube Gas Transfer System

Pressure Safety Component	Model Number	Description	MAWP (PSI)	Commercial Rating (PSI)
V31	Autoclave 20SM9071-CH	Sealing valve for the pump tube	15,000	20,000
Pump Tube Supply Flex Hose	Spir-Star Hose ASSY-6/4, SST 3/8 ends	Flexible hose from the V31 to the pump tube	15,000	21,000
V29, V30, V32	Autoclave 20SM9071-CH	Valves for the gas fill line, vent line, and vacuum line	400	20,000
Fill Line pressure transducer	Dynisco 12-31-09307102	Transducers measuring the pump tube fill pressures	400	2500
Fill Line Flex Hose	Gates 10TH18NC	Fill line flex hose for driving gas	400	3000
Vacuum Line Flex Hose	Gates 10TH18NC	Vacuum Line hose	8	3000
Vent Line Flex Hose	Gates 10TH18NC	Vent Line hose	150	3000
V36, V37, V38, V39, V40	Swagelok SS-6UG-6C-M2	Hydrogen-rated Gas Selection Valves	2200	2500
V34, V35	Dragon 10M057	Manual Gas Selection Valves	2200	6000
Gas Selection Check Valves	Circle Seal	Check valves on Gas Selection Panel	2200	5000
R12	Atheson Model 3066	Regulator for Nitrogen supplied by outside skid	2200	6000
R10	Parker P/N 41600836 Model HPR800B5P10404	Gas supply regulator	400	4000
V33	Circle Seal A9559T_2PP	Manual Vacuum Vent Valve	8	2000

All components are commercial and rated above the system MAWP.

Seismic

The components of the gun have been seismically anchored. The hardware attached to the facility infrastructure is documented in the Project Management Engineering and Construction (PMEC) document EDD-STR-2009-0191-003 (Ref. 2). This includes hardware such as the Target Chamber Assembly, Catch Tank, and the I-beams that the gun barrels rest on.

Seismic calculations included in Appendix F cover the gun barrels and the barrel mounts.

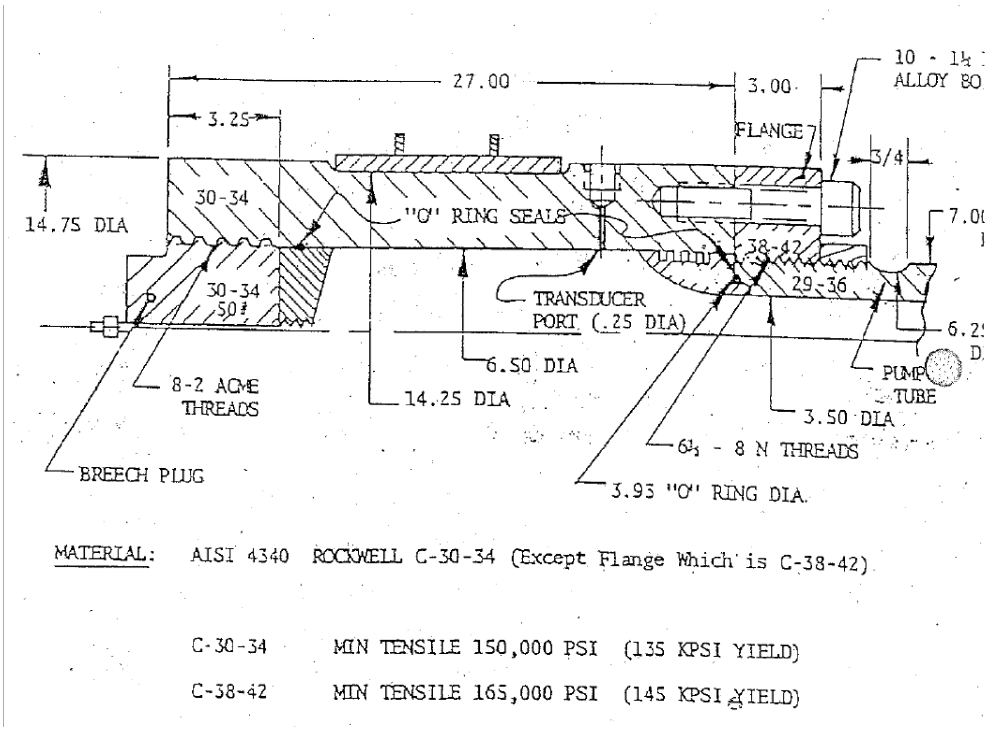
All components exceed the ME DSS guidance for seismic anchoring.

Appendix A.2

Per END76-908

Ultimate Strength AISI 4340: $S_{ult} := 150ksi$

Max Breech Pressure: $P_{breech_pressure} := 15ksi$



(1) Breech Cylinder: (Using Thick-Walled Cylinder Equation)

$r_{o_breech} := 7.12in$

$r_{i_breech} := 3.25in$

$$\sigma_{breech_long} := \frac{\pi \, r_{i_breech}^{2} \cdot P_{breech_pressure}}{\pi \cdot \left(r_{o_breech}^{2} - r_{i_breech}^{2}\right)} = 3.948 \times 10^{3} \, psi$$

$$\sigma_{breech_hoop} := P_{breech_pressure} \cdot \frac{\left(r_{o_breech}^{2} + r_{i_breech}^{2}\right)}{r_{o_breech}^{2} - r_{i_breech}^{2}} = 22.896 \cdot ksi$$

$$\sigma_{vm_breech} := \sqrt{\sigma_{breech_long}^{2} - \sigma_{breech_long} \cdot \sigma_{breech_hoop} + \sigma_{breech_hoop}^{2}}$$

$$\sigma_{vm_breech} = 21.2 \cdot ksi$$

$$SF_{breech} := \frac{S_{ult}}{\sigma_{vm_breech}} = 7.1$$

(2) Pump Tube: (Using Thick-Walled Cylinder Equation)

$$r_{o_pt} := 3.25in$$

$$r_{i_pt} := 1.75in$$

$$\sigma_{pt_hoop} := P_{breech_pressure} \cdot \frac{\left(r_{o_pt}^{2} + r_{i_pt}^{2}\right)}{r_{o_pt}^{2} - r_{i_pt}^{2}} = 27.25 \cdot ksi$$

$$\sigma_{pt_long} := \frac{\pi r_{i_pt}^{2} \cdot P_{breech_pressure}}{\pi \cdot \left(r_{o_pt}^{2} - r_{i_pt}^{2}\right)} = 6.125 \times 10^{3} psi$$

$$\sigma_{vm_pt} := \sqrt{\sigma_{pt_long}^{2} - \sigma_{pt_long} \cdot \sigma_{pt_hoop} + \sigma_{pt_hoop}^{2}}$$

$$\sigma_{vm_pt} = 24.8 \cdot ksi$$

$$SF_{pt} := \frac{S_{ult}}{\sigma_{vm_pt}} = 6.1$$

(3) Launch Tube (Thinnest walled):

$r_{o_LT} := 2.5in$

$r_{i_LT} := 1.25in$

$$\sigma_{LT_hoop} := 15ksi \cdot \frac{\left(r_{o_LT}^2 + r_{i_LT}^2\right)}{r_{o_LT}^2 - r_{i_LT}^2} = 25 \cdot ksi$$

$$\sigma_{LT_long} := \frac{\pi\, r_{i_LT}^2 \cdot P_{breech_pressure}}{\pi \cdot \left(r_{o_LT}^2 - r_{i_LT}^2\right)} = 5 \times 10^3\, psi$$

$$\sigma_{vm_LT} := \sqrt{\sigma_{LT_long}^2 - \sigma_{LT_long} \cdot \sigma_{LT_hoop} + \sigma_{LT_hoop}^2}$$

$\sigma_{vm_LT} = 22.9 \cdot ksi$

$$SF_{LT} := \frac{S_{ult}}{\sigma_{vm_LT}} = 6.5$$

MECHANICAL ENGINEERING SAFETY NOTE

END 76-908

TWO STAGE LIGHT GAS GUN
BUILDING 341 - ROOM 1200

AUGUST 1976

PREPARED BY R. L. Waldron
R. L. WALDRON
N.E.E.D.

REVIEWED BY D. S. Ravenscroft
D. S. RAVENSCROFT
N.E.E.D.

APPROVED BY T. Perlman 8-17-76
T. PERLMAN
R.E.D. LEADER

RLW:rrt

Distribution:

G. A. Broadman
D. S. Ravenscroft
R. L. Waldron
C. R. Henry, L-450
B. L. Hord, L-504
D. L. Montgomery, L-112
T. Perlman, L-141
B. J. Schumacher, L-141
R. G. Stone, L-123

INTRODUCTION

This Engineering Safety Note reviews the "Two-Stage Light Gas Gun" facility, being used in shock-wave research studies by H-Division. The gun was purchased from GM Defense Research Lab., (Goleta, California) in late 1971, at which time it was set up and operated in Building 243. Early in 1975 the gun was moved to the present location (Room 1200 of Building 341). Prior to the purchase, the Gun Powder Chamber (breech) had been fired approximately 1000 times at peak pressures ranging from a few thousand psi to 20,000 psi. To date, at LLL, there have been about 400 additional firings.

The Two-Stage Gun assembly is shown on drawing number AAA72-104286. The associated Impact Chamber and Catcher Tank are shown on drawings AAA74-110001 and AAA72-113778, respectively. The operational responsible person, as spelled out in OSP-341 Appendix F, is B. L. Hord (Technical Supervisor) or, in his absence, W. H. Stutler (Technician Supervisor).

POTENTIAL HAZARDS

The potential hazards of the Two-Stage Gun system stem from use of a solid propellent and hydrogen gas. For the purposes of this Safety Note the mass limits involved are 1350 grams of HPC-95 double base smokeless powder and 60 grams of H_2 gas (at 125 psia).

There are three general areas of concern:

PART I. Gun Powder Chamber (breech)

PART II. Accelerated Reservoir (AR)

PART III. Impact Chamber and Catch Tank

Each area is examined for structural integrity to insure reasonable protection of surrounding equipment and building. The nature and extent of energy release potential obviously prohibits manned area firing of the gun. More specifically, the unknown fatigue characteristics, the general high use factor, the very high stress levels produced in the Accelerated Reservoir and the possibility of a hydrogen explosion make it mandatory that proper shielding and barricading exist to protect personnel in the event of unplanned energy release.

Thus, in addition to the general structural integrity review, this safety note will look at ruptures, fragmentation and overpressures resulting from some very pessimistic potential failures, and then determine if any additional shielding or barricading, etc., is required to obtain the proper confidence in personnel protection.

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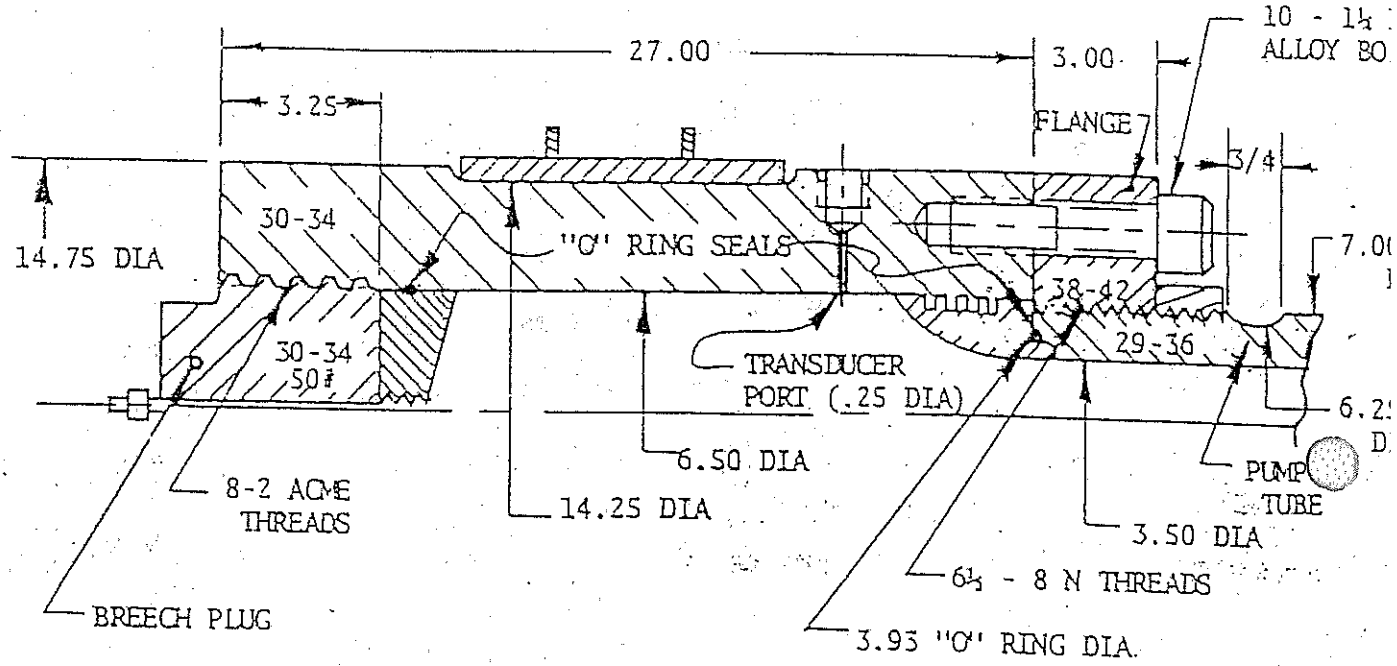
PART I. GUN POWDER CHAMBER (BREECH)



MATERIAL: AISI 4340 ROCKWELL C-30-34 (Except Flange Which is C-38-42)

C-30-34	MIN TENSILE 150,000 PSI	(135 KPSI YIELD)
C-38-42	MIN TENSILE 165,000 PSI	(145 KPSI YIELD)

NOTE: AT THE ABOVE HARDNESS LEVELS THE MATERIAL WILL HAVE AT LEAST 15% ELONGATION AND 40% REDUCTION IN AREA.

FAILURE PRESSURE ESTIMATES

(1) Basic Cylinder:

$$P_{rupture} = S_{ULT} \, Ln\left(\frac{r_o}{r_i}\right)$$ (REF. No. 1)

$$P_{rupture} = 150{,}000 \, Ln\left(\frac{7.12}{3.25}\right) = \boxed{117{,}600 \text{ PSI}}$$

$$P_{yield} = S_{YLD} \times \frac{\left(\frac{r_o}{r_i}\right)^2 - 1}{\sqrt{3}\left(\frac{r_o}{r_i}\right)^2} = 61{,}700 \text{ PSI}$$

(MAXIMUM DISTORTION ENERGY THEORY)

(2) Breech Plug:

ACME Thread 8-2

$$\text{SHEAR AREA/INCH OF THREAD} = \pi K_n\left[0.5 + \frac{1}{p} \text{TAN } 14\tfrac{1}{2}° \left(E_s - K_n\right)\right]$$

Where: K_n = MAX. MINOR DIA. OF INTERNAL THREAD = 7.525"

p = PITCH = 0.5

E_s = MIN. PITCH DIA. OF EXTERNAL THREAD = 7.710"

(REF. No. 2)

$$\text{SHEAR AREA/INCH} = \pi \cdot 7.525\left[0.5 + 2 \text{ TAN } 14\tfrac{1}{2}°(7.710 - 7.525)\right]$$

$$= 14.08 \text{ IN}^2/\text{IN}$$

$$\text{SHEAR AREA} = 3.25 \times 14.08 = 45.76 \text{ IN}^2$$

$$\text{SHEAR ULT} \geq \frac{150{,}000}{2} = 75{,}000 \text{ PSI}$$

$$P_{rupture} = \frac{\text{SHEAR ULT} \times \text{AREA}}{\pi r^2} = \frac{75{,}000 \times 45.7}{\pi (3.25)^2}$$

$$P_{rupture} = \boxed{103{,}300 \text{ PSI}}$$

(3) Bolts:

10 - 1¼" Socket Head Cap Screws UNC

Per FF-S-86D (160,000 PSI Ult. Tensile)

Ult. strength is 153,500 LBS per bolt.

(REF. No. 3)

$$P_{rupture} = \frac{10 \times 153{,}500}{\pi r^2} = \boxed{127{,}200 \text{ PSI}}$$

r = 1.96" (SEAL RADIUS OF "O" RING)

RECOMMENDED DRY TORQUE: 1600 FT-LBS

(REF. No. 3)

(4) Flange Threads (Shear):

6½ - 8N - 2A

Assume 65% of thread area is effective.

$$\text{SHEAR AREA} = 3.00 \times .65 \times \pi \times d = 39.01 \text{ IN}^2$$

$$d = 6.375''$$

$$\text{SHEAR ULT.} \geq \frac{150{,}000}{2} = 75{,}000$$

$$P_{rupture} = \frac{75{,}000 \times 39.01}{\pi r^2} = \boxed{242{,}400 \text{ PSI}}$$

$r = 1.96''$ (SEAL RADIUS OF "O" RING)

(5) Pump Tube (Thread Relief Area):

$$P_{rupture} = S_{ULT} \, Ln\left(\frac{r_o}{r_i}\right) \qquad \text{(REF. No. 1)}$$

$$P_{rupture} = 150{,}000 \, Ln\left(\frac{3.12}{1.75}\right) = \boxed{86{,}700 \text{ PSI}}$$

FACTORS OF SAFETY

The maximum breech pressure recorded to date at the Lab is 15,000 psi using the 1350 gram limit of HPC-95. Thus with 15,000 as the normal maximum working pressure the minimum factor of safety from the above is $\boxed{5.8}$ based on ultimate strength.

Assuming that all the heat of explosion of the propellent is converted into gas pressure within the breech volume (piston not allowed to move) the peak pressure would be as follows:

$$E = \frac{P_B V}{(\gamma - 1)} \quad \text{(ENERGY EQUATION OF STATE, ADIABATIC APPROXIMATION)}$$

$$P_B = (\gamma - 1)\frac{E}{V} = (\gamma - 1)\frac{E_S \times W}{V_B} \quad \text{(PSI)}$$

Where: $\gamma = 1.4$ (CONSERVATIVE)

$$E_S = 1150 \text{ CAL/GM} \times .738 \frac{\text{FT LBS}}{\text{JOULE}} \times 4.186 \frac{\text{JOULES}}{\text{CAL}}$$

$$\times 12 \frac{\text{IN}}{\text{FT}} = 42.63 \times 10^3 \frac{\text{IN LBS}}{\text{GM}}$$

$$W = 1350 \text{ GMS (MAX LIMIT)}$$

$$E = 4.79 \times 10^6 \text{ FT LBS (OR)} \frac{4.79 \times 10^6}{1.55 \times 10^6} = \boxed{3.1 \text{ LBS of TNT EQUIVALENT}}$$

$$V_B = \text{VOLUME OF BREECH} = 600 \text{ IN}^3$$

$$P_B = (0.4)\left(\frac{42.63 \times 10^3 \times 1350}{600}\right) = 38{,}400 \text{ PSI*}$$

Which is still well above a safety factor of $\boxed{2}$.

DISCUSSION

Although fragmentation is possible, it is very unlikely with ductile pressure vessels which most often open up and slowly relieve the pressure without fragments. This fact in consideration of the safety factors involved and the very low probability of a stuck piston effectively eliminates the breech fragmentation problem in regard to personnel safety.

According to the above calculation the pump tube thread relief is the most highly stressed region and under increasing loads it is in this region that one would expect failure to occur. A conservative estimate of the consequences is given below:

Assumptions:

1. Burst Pressure = 20,000 PSI Initial
2. Linear decay of burst pressure to zero in four inches of breech travel.

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*NOTE: This pressure is considerably greater than that estimated by using Ref. No. 6 and the HPC-95 specifications.

3. No restraining force applied by breech mounting or the aluminum roll-up door.

4. Initial velocity of breech is such as to allow it to exit the aluminum roll-up door.

$$\text{KINETIC ENERGY OF BREECH} = \int F ds = P_A A S$$

$$P_A = \frac{20,000}{2} \; ; \; A = \frac{\pi}{4}(3.5)^2 \text{ IN}^2 \; ; \; S = \frac{4}{12} \text{ FT}$$

$$\text{K.E.} = \frac{20,000}{2} \times \frac{\pi}{4}(3.5)^2 \times \frac{4}{12} = 32,000 \text{ FT LBS}$$

$$\text{VELOCITY } (v_H) = \sqrt{\frac{2g \text{ K.E.}}{W}} = \sqrt{\frac{2 \times 32.2 \times 32,000}{1300}} = \underline{40 \text{ FT/SEC}}$$

Where W = WEIGHT OF BREECH = 1300 LBS

Time for breech to hit ground (assuming velocity is initially horizontal):

$$t = \frac{\sqrt{2gh}}{g} = \frac{\sqrt{2 \times 32.2 \times 3}}{32.2} = \underline{0.43 \text{ SECONDS}}$$

Distance For Breech To Hit Ground:

$$d = vt = 40 \times 0.43 = \underline{17 \text{ FEET}}$$

Impact Angle:

$$\alpha = TAN^{-1}\left(\frac{v_V}{v_H}\right) = TAN^{-1}\left(\frac{14}{40}\right) = \underline{19°}$$

Where $v_V = \sqrt{2gh} = 14$ FT/SEC

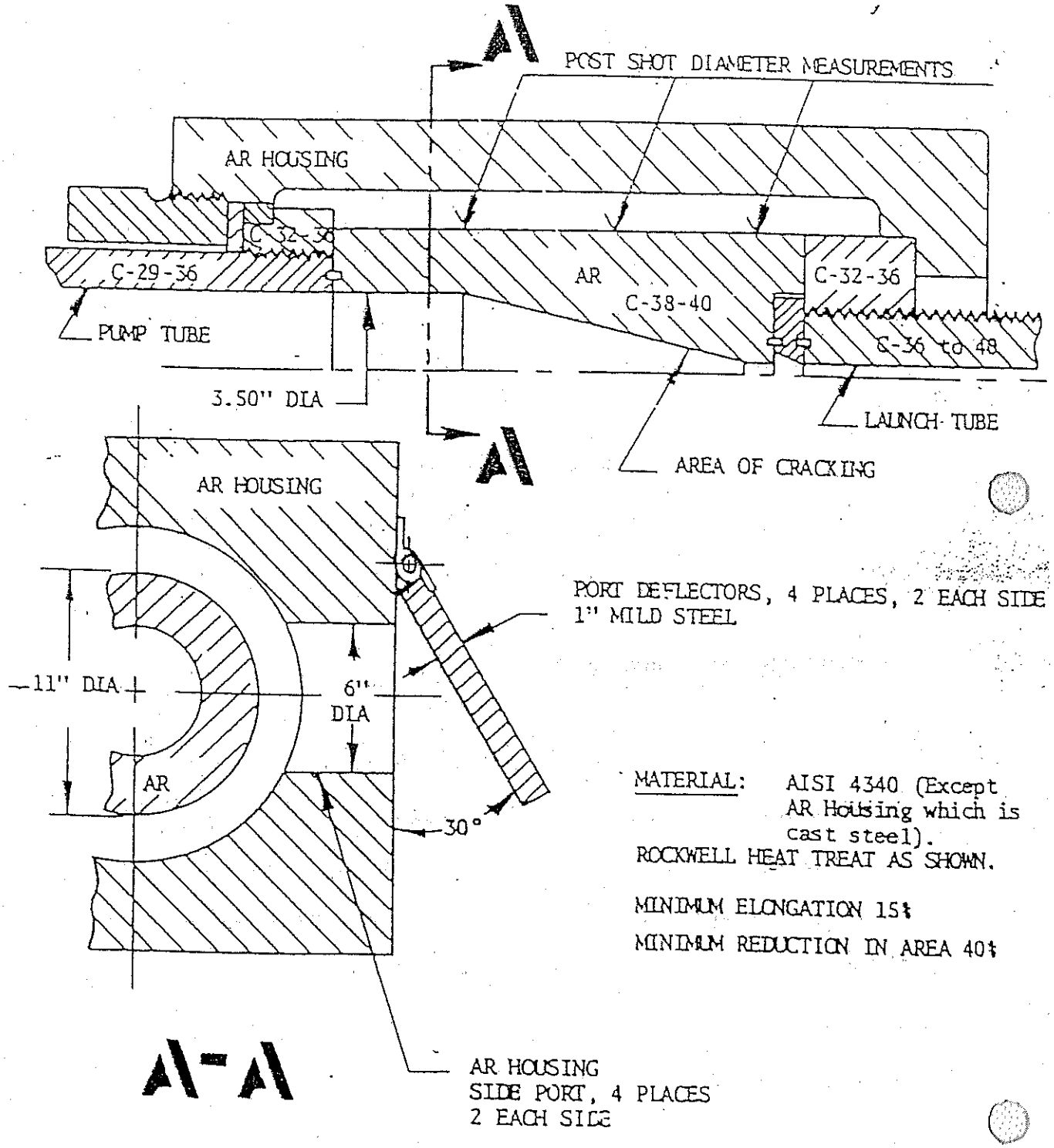
The time interval between breech rupture, release of hydrogen and subsequent possible detonation of the hydrogen is certainly great enough to negate any compounding effect of propellent and hydrogen. Note, hydrogen detonation is considered in PART II - ACCELERATED RESERVOIR.

Shock pressure impulse was not considered. The possibility of instantaneous release of the propellent energy, in a manner normally associated with high order detonation, is highly improbable.

CONCLUSIONS FOR POWDER CHAMBER

The conclusion from above is that no additional shielding or barricading is required in the "Gun Powder Chamber" area. It is recommended, however, that the North equipment door remain minimal strength (aluminum roll-up); also that the area around this door be roped off for gun firings.

PART II. ACCELERATED RESERVOIR (AR)



The stress levels produced in the AR are well above yield for the high level shots. Years of experience at GM Defense Research Lab. has shown that once an AR has expanded in diameter about 5/32 of an inch, a subsequent high level shot has a high probability of rupture. The procedure at LLL is to take three post shot diameter measurements along the length of the AR, and once a total expansion of 1/8 inch has occurred, the AR is replaced. On occasion the AR will be replaced prior to this due to cracking and/or erosion of the ID close to the launch tube.

GM has had several AR ruptures. With one exception, all ruptures were without fragmentation. However, one rupture did send a few fragments through the AR housing ports.

In view of the stress levels involved (150,000 PSI +) in the AR, the probability of rupture with fragmentation and release of hydrogen to the room atmosphere is high enough to warrant study.

FRAGMENTATION

One assumption is to use the Gurney Equation and to say that all of the energy (3.1 LBS TNT) is released in the form of high explosive detonation.

$$v = (2E^{-})^{\frac{1}{2}} \left[\frac{W/W_c}{1 + W/2W_c} \right]^{\frac{1}{2}}$$ (Gurney Equation) REF. No: 4 (EQUATION 4-10)

Where: v = THE INITIAL FRAGMENT VELOCITY (FT/SEC)

$(2E^{-})^{\frac{1}{2}}$ = GURNEY ENERGY CONSTANT = 6940 FOR TNT

W_c = WEIGHT OF CYLINDRICAL CASE ≅ 600 LBS

W = WEIGHT OF EXPLOSIVE ≅ 3 LBS

$$v = 6940 \times \left[\frac{3/600}{1 + 3/1200} \right]^{\frac{1}{2}} = \boxed{490 \text{ FT/SEC}}$$

MAXIMUM FRAGMENT WEIGHT W_f

$$W_f = \left\{ M_a \, \mathrm{Ln} \left[\frac{8W_c}{M_a^2} \right] \right\}^2 \text{(OZ)}$$ REF. No. 4 (EQUATION 4-14)

Where: M_a (FRAGMENT DISTIPARAMETER) $= Bt_c^{5/6} \, d_i^{1/3} \left[1 + \frac{t_c}{d_i} \right]$

REF. No. 4 (EQUATION 4-13)

And t_c = THICKNESS OF CASE ≅ 4.3 INCHES (IN AREA OF HISTORICAL FAILURE)

d_i ≅ 2.4 INCHES = INSIDE CASE DIAMETER (IN AREA OF HISTORICAL FAILURE)

B = CONSTANT = 0.30 (FOR STEEL AND TNT)

$$M_a = 0.30 \, (4.3)^{5/6} \cdot (2.4)^{1/3} \left[1 + \frac{4.3}{2.4} \right] = 3.78$$

$$W_f = \left\{ 3.78 \, \mathrm{Ln} \left[\frac{8 \times 600}{(3.78)^2} \right] \right\}^2 = \boxed{483 \text{ OZ OR } 30.2 \text{ LBS}}$$

TOTAL FRAGMENT ENERGY

The kinetic energy of all the case fragments based on W_c = 600 LBS and v_o = 490 FT/SEC is:

$$K.E. = \frac{1}{2} mV^2$$

$$= \frac{1}{2} \left(\frac{600}{32.2}\right) (490)^2$$

$$K.E. = 2.24 \times 10^6 \text{ FT-LBS}$$

Comparing this to the energy available in 3.1 LBS of TNT (4.79×10^6 FT-LBS), we have a ratio of

$$R = \frac{2.24}{4.79} = 0.47 = 47\%$$

For comparison purposes, a single stage gun will have approximately 30% of the thermochemical energy transformed into kinetic energy of translation of the projectile.

REQUIRED SHIELDING THICKNESS

$$T^* = K \frac{w}{A} \text{LOG} \left(1 + \frac{V^2}{215{,}000}\right) \text{ INCHES}$$

REF. No. 5 (PETRY EQUATION)

Where: K = MATERIAL CONSTANT = 2.1 (IN^3/LB) FOR MILD STEEL

w = FRAGMENT WEIGHT (LBS) ≅ 30 LBS

A = CROSS-SECTIONAL AREA = 12.5 IN^2

(Estimated on bases of a cylinder two times it's diameter in length) DIAMETER = 4 INCHES and LENGTH = 8 INCHES.

$$T^* = 2.1 \times \frac{30}{12.5} \text{LOG} \left(1 + \frac{(490)^2}{215{,}000}\right) = \boxed{1.64 \text{ INCHES FOR DESIGN}}$$

Thus, the estimated penetration would be $\boxed{0.55 \text{ INCHES}}$ of steel.

CONCRETE WALL SPALL CHECK

The above extrapolation of the Gurney and Petry formulas to the AR situation may not be strictly valid. A different set of conditions are

---

*NOTE: This thickness is a design thickness which is three times the estimated penetration thickness in mild steel of infinite thickness. On this basis, one might assume that the above fragment would penetrate the 1" steel plate. However, to assume that the residual velocity would be sufficient to subsequently spall the concrete wall seems unreasonable. Particularly when one considers the probability of the largest fragment exiting one of the four ports unimpeded. (Note fragment assumed dimensions.)

looked at below to determine the possibility of spalling the concrete wall. The following assumptions are made:

1. The deflection plate (see page 12) is left in an up position (a finite possibility).

2. A 7½ pound fragment is propelled through the side port unimpeded. This 7½ pounds represents a slug with approximately 1/3 the area of the port opening with a length that is approximately the average wall thickness of the AR (3").

3. The fragment energy is about 1/3 that achieved by the test sample under a normal full load shot, which is approximately 25 gms accelerated to 20,000 FT/SEC or $.34 \times 10^6$ FT LBS. Thus, the assumed fragment energy is 0.11×10^6 FT LBS or approximately 2½% of the total heat of detonation of the propellent.

4. The equations and data presented in Chapter 8 of REF. No. 4 are valid.

W_f = FRAGMENT WEIGHT = 7.5 x 16 = 120 OZ

v_s = STRIKING VELOCITY $= \sqrt{\frac{2g}{W} \cdot E_f} = \sqrt{\frac{2 \times 32.2}{7.5} \times .11 \times 10^6}$

= 970 FT/SEC

X_f = MAXIMUM PENETRATION IN INCHES IN CONCRETE*

*Data based on armor piercing projectiles with hemispherical-cylinderical contour and L/d ratio of 1.

$$X_f = 0.162 \times 10^{-5} \times W_f^{0.4} \times v_s^{1.8} = 2.6 \text{ INCHES}$$

EQUATION 8-1

The calculation of coefficients C_1 and $\frac{W_f^{1/3}}{X_f}$ for comparison with Graph 8-4 (REF. No. 4) follows:

$$C_1 = \left[\frac{T_c + 0.348\ (W_f)^{1/3}}{X_f} - 1\right] \left[\frac{C_s}{v_s}\right]^{1/3}$$

Where: T_c = WALL THICKNESS = 6 INCHES

C_s = DILATATIONAL VELOCITY (FT/SEC)

$$C_s = 5.16\ (E_c)^{1/2}$$

EQUATION 8-2

E_c = MODULUS OF ELASTICITY FOR CONCRETE

$$E_c = W^{1.5}\ 33\sqrt{f'_c} \text{ PSI}$$

EQUATION 5-17

W = 145 LBS/FT^3 (DENSITY)
f'_c = 4000 PSI (COMPRESSIVE STRENGTH)
} ASSUMED AS AVERAGE

$$E_c = 3.64 \times 10^6 \text{ PSI}$$

$$C_s = 5.16(3.64 \times 10^6)^{1/2} = 9{,}840 \text{ FT/SEC}$$

$$C_1 = \left[\frac{6 + 0.348(120)^{1/3}}{2.6} - 1\right] \times \left[\frac{9{,}840}{970}\right]^{1/3} = \underline{4.26}$$

$$\frac{W_f^{1/3}}{X_f} = \frac{(120)^{1/3}}{2.6} = \underline{1.90}$$

Plotting these on Graph 8-4 shows that it is on the $\boxed{\text{border line}}$ of a $\boxed{\text{spall condition}}$. NOTE: Similar calculations using the Gurney velocity of 490 FT/SEC and maximum fragment weight of 30 LBS also indicates a border line spall condition.

HYDROGEN DETONATION

Assuming that all 60 grams of hydrogen is released, mixed with air and detonated, the energy is equal to:

Heat of combusion is 68,300 CAL/MOLE (H_2O Liquid)

$$\text{TOTAL HEAT } \frac{60}{2} \times 68{,}300 = \underline{2.05 \times 10^6 \text{ CAL}}$$

$$\text{OR } 2.05 \times 10^6 \times .737 \frac{\text{FT LBS}}{\text{JOULE}} \times 4.186 \frac{\text{JOULES}}{\text{CAL}} = \underline{6.3 \times 10^6 \text{ FT LBS}}$$

$$\text{OR } \frac{6.3 \times 10^6}{1.55 \times 10^6} = \boxed{\text{4 LBS TNT EQUIVALENT}}$$

THE STATIC OVER-PRESSURE (ASSUMING NO VENTING)

$$\Delta P = 4000 \frac{hW}{V} = \text{PSI} \left(\begin{array}{l}\text{ADIABATIC PRESSURE INCREASE} \\ \text{DUE TO HEAT INPUT}\end{array}\right)$$

Where: h = HEAT COMBUSTION = 34.15 k CAL/GRAM

W = WEIGHT IN LBS = $\frac{60}{454}$ LBS

V = ROOM VOLUME = 40,000 FT^3 (20' x 20' x 100')

$$\Delta P = 4000 \frac{34.15 \times 60}{40{,}000 \times 454} = \boxed{0.45 \text{ PSI OR } 65 \text{ LBS/FT}^2}$$

THE SHOCK PRESSURE - TIME ESTIMATE

In order to calculate a peak pressure and impulse, information presented in REF. No. 4 is used with the following assumptions:

1. The roof is considered frangible as well as the roll-up equipment door.

2. Detonation is centered within the room volume.

From Figure 4-15 N = 3 (20' WIDE, 20' HIGH & 100' LONG),

$$\frac{h}{H} = \frac{1}{2}; \frac{\ell}{L} = \frac{1}{2}; \frac{L}{H} = 5; \frac{L}{R_a} = 10, \text{ and } Z_a = \frac{R_a}{(W)^{1/3}}$$

$$= \frac{10}{(4)^{1/3}} = 6.3$$

From Chart 4-51 (ASSUME $\frac{L}{H} = 6$) the scaled unit blast impulse

$$\bar{i}_b = 12 \text{ PSI - ms/LB}^{1/3})$$

$$\bar{i}_b = 12 \times (4)^{1/3} = \boxed{19 \text{ PSI-ms}}$$

an estimate of the time duration is given by

$$t_o = \text{DURATION OF LOAD (ms)} = \left(t_A\right)_F - \left(t_A\right)_A + 1.5 \left(t_o\right)_F$$

EQUATION 4-1

$$t_o = W^{1/3}\left[\left(\frac{t_A}{W^{1/3}}\right)_F - \left(\frac{t_A}{W^{1/3}}\right)_A + 1.5\left(\frac{t_o}{W^{1/3}}\right)_F\right]$$

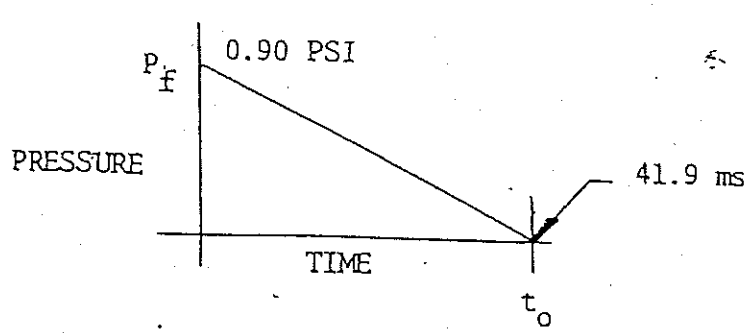
From Figure 4-5 $Z_F = \frac{R_F}{W^{1/3}} = 31.4$, $Z_A = \frac{R_A}{W^{1/3}} = 6.3$:

$$t_o = 1.59\left[24 - 2.3 + 1.5\ (3.1)\right] = \boxed{41.9 \text{ ms}}$$

From Equation 4-2

$$P_f = \frac{2\bar{i}_b}{t_o} = \frac{2 \times 19}{41.9} \cong \boxed{0.90 \text{ PSI OR } 130 \text{ LBS/FT}^2}$$

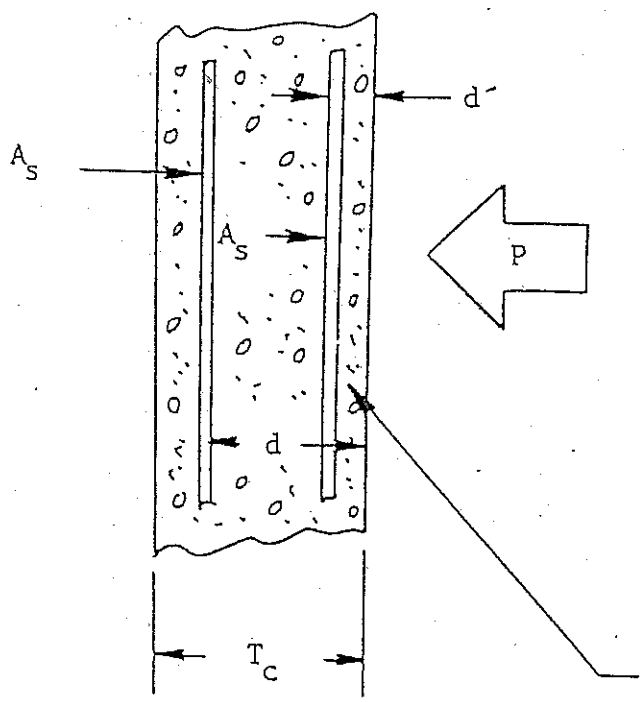
EQUATION 4-2



CALCULATION OF WALL STRENGTH (REF. No. 4)

For the pressure time relationship given above and the wall dimensions below, the problem is assumed to be in the intermediate pressure design region. Which means that time t_o is between 1/3 and 10 times the dynamic response (t_m) of the wall (note, this will be verified). Assumptions:

1. Type I concrete cross-section and less than 2° support rotation.
2. Concrete section as shown:



T_c = 6 INCHES

d' = 3/4 INCH

d = 5¼ INCHES

#5 @ 12 INCH CENTERS EACH WAY, EACH FACE.

$\therefore A_s = \frac{\pi}{4}(D)^2 = 0.31\ IN^2/FT$

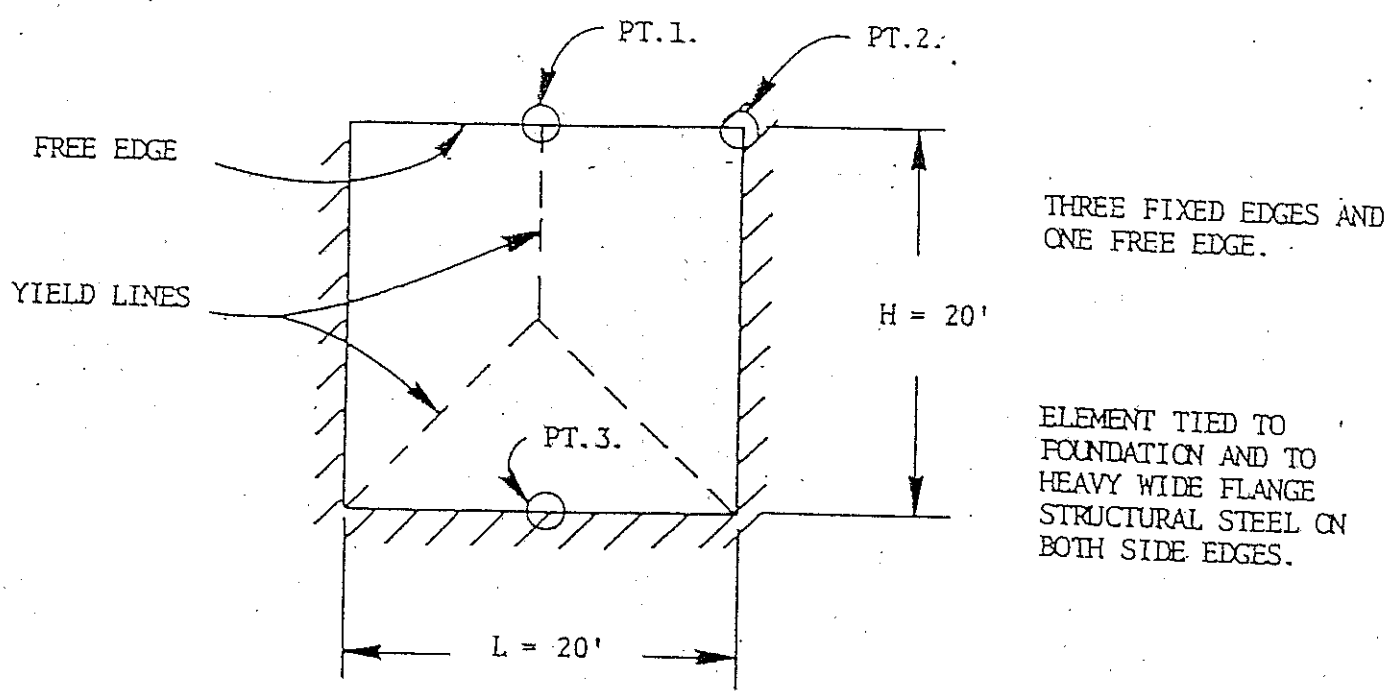
FOR WIDTH (b) = 12 INCHES

3. Neglecting dynamic strength increase the strengths are:

f_s = STEEL YIELD = 60,000 PSI (AVERAGE)

f'_c = 4000 (AVERAGE) FOR CONCRETE

4. Two way element with yield line locations as shown:



<u>ULTIMATE MOMENTS</u> (CONSIDERING TENSION REINFORCEMENT ONLY, CONSERVATIVE)

$$M_u = \frac{A_s}{b} f_s \left(d - \frac{a}{2}\right) \qquad \text{EQUATION 5-1}$$

Where: $a = \dfrac{A_s f_s}{0.85\, f'_c b} = \dfrac{0.31(60{,}000)}{0.85(4000)(12)} = 0.456$ IN

Horizontal Direction Moment:

Negative and positive moments are equal.

$$\therefore M_{HN} = M_{HP} = \frac{0.31}{12}(60{,}000)\left(5.25 - \frac{0.456}{2}\right) = \boxed{7784 \text{ IN LBS/INCH}}$$

Vertical direction moment are assumed equal to horizontal (actual reinforcement dimensions unknown).

$$\therefore M_{VN} = M_{VP} = \boxed{7784 \text{ IN LBS/INCH}}$$

ULTIMATE RESISTANCE

From Figure 5-10

$$\frac{L}{H}\left(\frac{M_{VN} + M_{VP}}{M_{HN} + M_{HP}}\right)^{1/2} = \frac{20'}{20'}\left(\frac{7784 + 7784}{7784 + 7784}\right)^{1/2} = 1.0$$

$$\frac{y}{H} = 0.64 \; ; \; y = 240 \times 0.64 = 154$$

From Table 5-6

$$r_u(\text{ULTIMATE RESISTANCE}) = \frac{5(M_{VN} + M_{VP})}{y^2}$$

$$r_u = \frac{5(7784 + 7784)}{(154)^2} = \boxed{3.3 \text{ PSI}}$$

ELASTIC RESISTANCE

$\frac{H}{L} = 1.0$ From Figure 5-14

$\beta_1 = .045 \quad \beta_2 = .087 \quad \beta_2 = .052 \quad \gamma_1 = .0035 \quad \nu = \frac{1}{6}$

$M = \beta r H^2$; least resistance at point 2.

$$\therefore r_e(\text{ELASTIC}) = \frac{M}{\beta_2 H^2} = \frac{7784}{.087 \times (20 \times 12)^2} = \boxed{1.5 \text{ PSI}}$$

VERIFYING INTERMEDIATE PRESSURE DESIGN ASSUMPTION

Calculation of the response time t_m (time for wall to reach maximum deflection).

Moment of Inertia:

EQUATIONS 5-20, 21 & 22

$$I_a = \frac{I_g + I_c}{2}$$

$$I_g = \frac{bT_c^3}{12} = \frac{(1)(6)^3}{12} = 18 \text{ IN}^4$$

$I_c = Fbd^3 = .0275(1)(5.25)^3 = 3.98 \text{ IN}^4$ (F from Figure 5-5, n = 8)

$$I_a = \frac{18 + 3.98}{2} = \boxed{11.0 \text{ IN}^4}$$

Stiffness:

Table 5-11 (one way elements, fixed-simple supports).

$$K_e = \frac{185E_cI_a}{bL^4} = \frac{185(3.64 \times 10^6)(11.0)}{(1)(12 \times 20)^4} = \boxed{2.2\ \text{LBS/IN}^3}$$

Deflection:

$$X_e = \frac{r_e}{K_e} = \frac{1.5}{2.2} = \boxed{.68\ \text{INCHES}}$$

Effective Mass of Element:

$$m_e = K_{LM} \cdot \frac{wT_c}{g} = (.73)\ \frac{(150)\left(\frac{6}{12}\right)10^6}{32.2(1728)} = \boxed{984\ \text{LB-ms}^2/\text{IN}^3}$$

From Table 6-1

$$K_{LM} = 0.65 - 0.16\left(\frac{L}{2H} - 1\right) = 0.73$$

Natural Period of Vibration: EQUATION 6-15

$$T_N = 2\pi\sqrt{\frac{m_e}{K_e}} = 2\pi\sqrt{\frac{984}{2.2}} = \boxed{133\ \text{ms}}$$

Response Chart Parameters (Figure 6-7):

PEAK PRESSURE (P_f)	B	= .90 PSI
PEAK RESISTANCE	r_e	= 1.5 PSI
DURATION (t_o)	T	= 41.9 ms
PERIOD VIBRATION	T_N	= 133 ms

$$\frac{B}{r_e} = 0.60 \; ; \; \frac{T}{T_N} = 0.32$$

From Figure 6-7: $\frac{t_m}{T_N} = 0.30$ (ROUGH EXTRAPOLATION, $\frac{X_m}{X_E} < 1$)

$$t_m = 0.30 \times 133 = \boxed{40 \text{ ms}}$$

$$\frac{t_m}{t_o} = \frac{40}{41.9} = \boxed{0.95}$$

Therefore the assumption of intermediate pressure region was correct.

$$3 > \frac{t_m}{t_o} > 0.1$$

DISCUSSION

According to the Gurney Equation and maximum fragment weight calculation there is no hazard, even if the deflection plate is in the up position. Calculations show a border line spall condition for both assumed fragments (7½ LBS at 970 FT/SEC and 30 LBS at 490 FT/SEC). In reality however there is no problem when one considers the conservative approach taken.

A basic assumption that there is a complete "detonation" of the hydrogen in air is considered to be very conservative. The most probable situation is that it will simply dissipate in the air, the next probable is that it will burn rather than detonate, next that a portion will detonate and finally that all will detonate.

Complete "burning" of the hydrogen would blow out the aluminum roll-up door and probably lift the roof (65 LBS/FT^2) in order to vent. Complete "detonation" of the hydrogen would assuredly lift the roof. No structural damage of the walls should be expected on the basis of the assumptions and calculations above, since the peak pressure was less than 2/3 the elastic limit pressure. Dynamic response calculations were not necessary, but were done to verify the intermediate pressure design region and to show that using the peak pressure as a static design load is conservative.

CONCLUSIONS FOR ACCELERATED RESERVOIR

The conclusion from above is that no additional shielding or barricading is required for the AR. Although the probability of complete hydrogen detonation is extremely low, it is recommended that the area 20 feet from each of the three exterior walls be roped off for firing, as a protection against debris from roof and/or equipment door.

END 76-908
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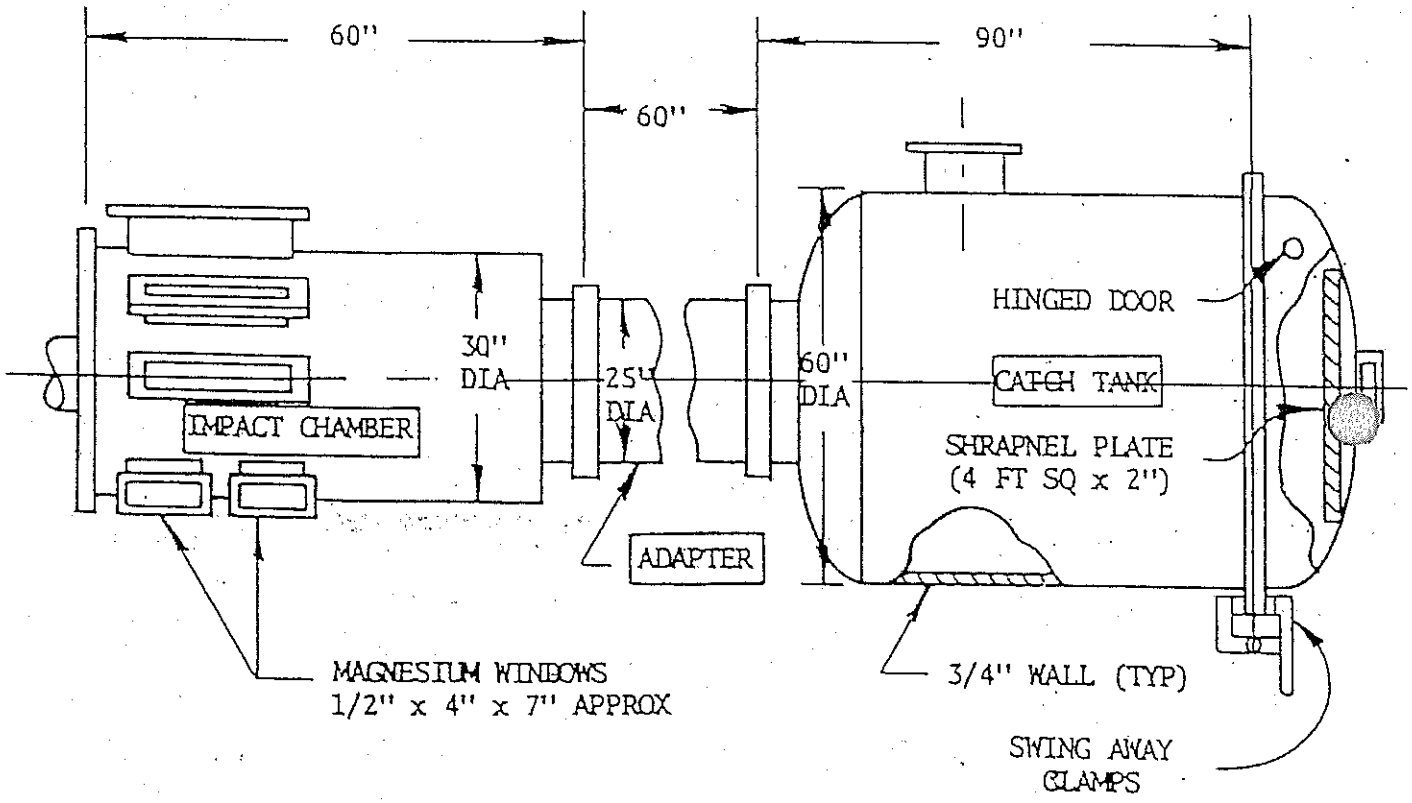
PART III. IMPACT CHAMBER AND CATCH TANK



WEIGHT OF HINGED DOOR AND SHRAPNEL PLATE
IS APPROXIMATELY 3300 LBS.

CHAMBER, ADAPTER AND TANK VOLUME = 179 FT^3

EQUILIBRIUM PRESSURE FOR 60 GMS OF HYDROGEN
IS APPROXIMATELY 2 PSIA.

SHRAPNEL FROM SAMPLE IMPACT

All ports are covered with steel plates with the exception of two flash radiography ports which are 1/2 inch magnesium. Occasionally in the past a few small holes have been found in these plates. It is unrealistic, however, to conceive of a situation where a particle could penetrate the magnesium with enough energy left to subsequently penetrate or spall the concrete wall. The ports are oriented at an angle of 45 degrees down toward the floor and the exterior side wall. The only valid consideration here is the remote possibility of damage to equipment.

HYDROGEN EXPLOSION

Although a nitrogen purge procedure is being adopted (REF. ENR 76-16), a finite possibility will still exist that a hydrogen-air explosion can occur within the tank system.

Basic Assumptions:

1. Tank pressure is 14.7 PSIA just prior to explosion.

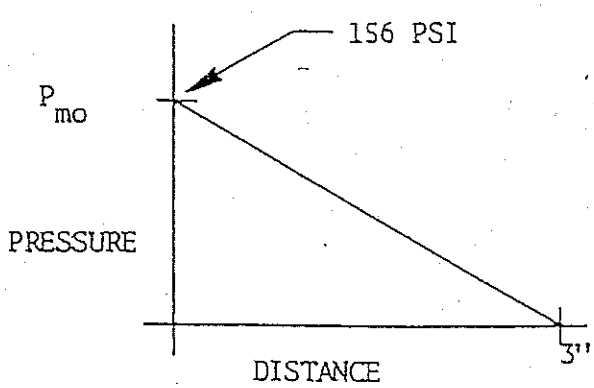
2. All 60 grams of hydrogen are consumed, which is approximately 4 LBS of TNT equivalent.

NOTE: Burning of the hydrogen would give approximately 100 PSI increase in tank pressure assuming $\Delta P = 4000 \frac{hW}{V}$ (see page 19).

The peak mean overpressure from REF. No. 4:

$$P_{mo} = 2410\left(\frac{W}{V}\right)^{0.72} = 2410\left(\frac{4}{179}\right)^{0.72} = \boxed{156\ \text{PSI}} \quad \text{(From Figure 4-65)}$$

This is an experimentally fitted curve for partially vented explosions. Use of this data assumes blow out of the catch chamber door to provide the venting. This is reasonable provided that only swing away clamps (Destaco type) are used to hold the door closed. Velocity is estimated below assuming this pressure accelerates the door and shrapnel plate over a distance of three inches as shown:



From F = ma :

$$a = \frac{P_{mo}Ag}{2W} \quad \text{(AVERAGE)}$$

$$a = \frac{156(\pi 30^2)32.2}{2(3300)} = 2152\ \frac{\text{FT}}{\text{SEC}^2}$$

$$v = \sqrt{2as} = \sqrt{2(2152)\frac{3}{12}} = \boxed{33\ \text{FT/SEC}}$$

TIME $\cong$ 15 ms

In order to stop the door and plate with minimal damage to the wall the following is suggested:

Approximately three feet of Hexcel material with a crush strength of 5 LBS/IN^2 faced with 1/2 inch thick aluminum plate. The assumption here is that the plate will effectively double the crushing area. Under these conditions the average crush dimension is:

$$\text{STOPPING FORCE} = 2\left(\overline{30}^2\right) \times 5 = 28{,}270 \text{ LBS}$$

$$\text{DECELERATION} = a_d = \frac{Fg}{W} = \frac{28{,}270 \times 32.2}{3300} = 276 \text{ FT/SEC}^2$$

$$\text{STOPPING (CRUSH) DISTANCE} = \frac{v^2}{2a_d} = \frac{(33)^2}{2 \times 276} = \boxed{2.0 \text{ FT}}$$

$$\text{TIME} \cong 120 \text{ ms}$$

CONCLUSIONS FOR IMPACT CHAMBER AND CATCH TANK

No additional shielding or barricading required for impact chamber area.

Catch tank door flange should be held only by swing-away type clamps or bolts of strength sufficient to obtain the initial vacuum seal and also to allow a positive pressure of 10 PSIG. This provides a predictable failure mode.

Energy absorbing material should be placed on the south wall in line with system axis to prevent serious structural damage. The system suggested above would limit the wall loading to 5 PSI which should be satisfactory.

REFERENCES

1. Faupel, J. H., Trans. A.S.M.E., 75 (1953) p. 352.

2. Machinery's Handbook.

3. Engineering Standard Reference 286B.

4. Structures to Resist the Effects of Accidental Explosions, Departments of the Army, the Navy and the Air Force, June 1969, (TM 5-1300/NAVFAC P-397/AMF 88-22).

5. M.E. Safety Manual.

6. A.M.C.P. 706-150, "Interior Ballistic of Guns".

Appendix B. Hydrogen Flammability/Inerting

B.1 Introduction

The following calculations replace the pertinent calculations expressed in END80-912 and END80-912 Addendum A. Changes to the calculations in END80-912 and END80-912 Addendum A were due to the increased volume of the new Target Chamber Assembly (AAA08-505250-OB) and the relocation of the gas gun into a larger high bay . Background on the inerting process and system hardware can be found in the historical safety notes.

Appendix B.2 Revised Calculations

Gas Gun Data

1. TCA volume: $V_{tca} \equiv 77212in^3$
2. Transition volume: $V_{trans} \equiv 5252in^3$
3. Catch Tank Volume: $V_{catch} \equiv 251673in^3$
4. Tank Total Volume: $V_{tank} \equiv V_{trans} + V_{catch} + V_{tca} = 193.366 \cdot ft^3$
5. Launch tube Volume: $V_{launch} \equiv 2.54ft^3$
6. Pump tube Volume: $V_{pump} \equiv 2.54ft^3$
7. Total Contained Volume: $V_{contained} \equiv V_{tank} + V_{launch} = 195.906 \cdot ft^3$
8. Initial H2 fill (350 psi fill pressure): $P_{h2_init} \equiv 350psi$
9. Catch tank vacuum before shot (gas species air): $P_{pre_shot} \equiv .020torr$
10. Ideal Gas Law:

$$P_{stp} := 1atm$$
$$T_{stp} := 293K$$
$$R := 0.082 \frac{l \cdot atm}{mol \cdot K}$$

The pressure in the catch tank after the shot will be:

$$P_{post_shot} := \frac{P_{h2_init} \cdot V_{pump}}{V_{contained}} = 4.538\,psi$$

Volumetric calculation of hydrogen, in catch tank, at STP:

$$V_{h2_stp} \equiv V_{pump} \cdot \frac{P_{h2_init}}{1atm} = 60.493 \cdot ft^3$$

The number of moles of H2:

$$n_{h2} := P_{stp} \cdot \frac{V_{h2_stp}}{R \cdot T_{stp}} = 71.296\,mol$$

$$mm_{h2} := 2.016 \frac{gm}{mol}$$

$$m_{h2} := mm_{h2} \cdot n_{h2} = 143.734 \cdot gm$$

Required Volume of nitrogen needed to bring catch tank to 15.7 psia:

$$P_{15.7} := 15.7psi$$

$$n_{n2} := 1mol$$ (Guess)

Given

$$P_{15.7} \cdot V_{contained} = \left(n_{h2} + n_{n2}\right) \cdot R \cdot T_{stp}$$

$$n_{n2} := Find\left(n_{n2}\right) = 175.372\,mol$$

$$V_{n2_stp} := \frac{n_{n2} \cdot R \cdot T_{stp}}{P_{stp}} = 148.798 \cdot ft^3$$ N2 at STP

Calculation of the minimum purge time required:

$$\frac{d}{dt} V_{h2} = -\left(\frac{V_{h2}}{V_{catchtank}}\right)\left(\frac{d}{dt} V_{n2}\right)$$

Can be integrated to:

$$V_{n2} = -V_{contained} \cdot \ln\left(V_{h2}\right) + C$$ (See END 80-912 Addendum A for derivation)

Following the fast-fill process, the scrubber system is turned on. The pressure in the tank drops back down to atmospheric pressure.

$$V_{h2_purge} := V_{h2_stp} \cdot \frac{14.7psi}{15.7psi} = 56.64 \cdot ft^3$$

The slow-fill process in initiated immediately after.

Initial Condition (New nitrogen into the tank): $V_{n2}(0) = 0$

Therefore, the integration constant can be found:

$$C := V_{contained} \cdot \ln\left(\frac{V_{h2_purge}}{ft^3}\right) = 790.817 \cdot ft^3$$

To inert the tank, the hydrogen level must be brought to below 4% by volume (per LLNL ES&H Manual Section 18.4) .

$$V_{h2_inert} := 4\% \cdot V_{contained} = 7.836 \cdot ft^3$$

The amount of nitrogen required to flow into the catch tank is found to be:

$$V_{n2_inert} := -V_{contained} \cdot \left(\ln\left(\frac{V_{h2_inert}}{ft^3}\right)\right) + C = 387.493 \cdot ft^3$$

The slow-fill process introduces nitrogen at a rate of: $FR_{n2} := 40 \frac{ft^3}{min}$

Therefore the time required:

$$t_{purge} := \frac{V_{n2_inert}}{FR_{n2}} = 9.687 \cdot min$$

$$t := 0, .5 .. 10$$

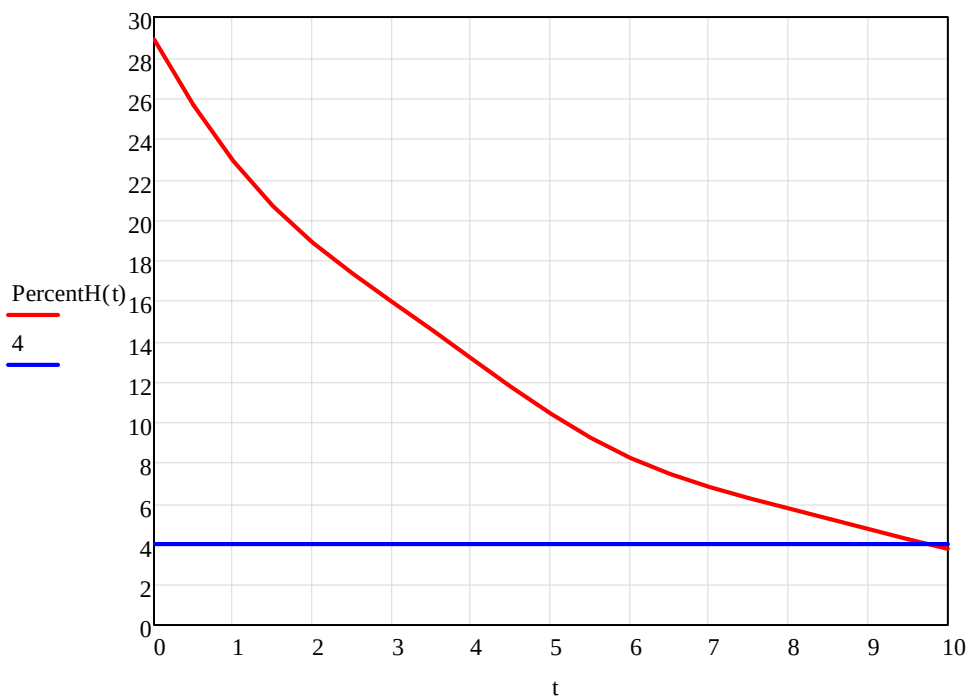
$$FR := \frac{FR_{n2}}{\frac{ft^3}{min}}$$

$$N(t) := (t + .15 \cdot \sin(.4 \cdot \pi t)) \cdot FR$$

$$V_{h2_dyn}(t) := \exp\left(\frac{\frac{C}{ft^3} - N(t)}{\frac{V_{contained}}{ft^3}}\right)$$

$$PercentH(t) := \frac{V_{h2_dyn}(t) \cdot 100}{\frac{V_{contained}}{ft^3}}$$

t =	$V_{h2_dyn}(t)$ =	PercentH(t) =	N(t) =
0	56.64	28.912	0
0.5	50.23	25.64	23.527
1	44.854	22.895	45.706
1.5	40.501	20.673	65.706
2	36.979	18.876	83.527
2.5	33.997	17.354	100
3	31.255	15.954	116.473
3.5	28.537	14.567	134.294
4	25.768	13.153	154.294
4.5	23.01	11.745	176.473
5	20.406	10.416	200
5.5	18.097	9.237	223.527
6	16.16	8.249	245.706
6.5	14.591	7.448	265.706
...	...	...	...



To ensure that the chamber has been inerted with sufficient nitrogen, the total purge time will be set for 10 minutes or greater.

Conservatively assuming that there was no mixing of the nitrogen and the hydrogen, and that the hydrogen content was unaffected by the nitrogen purge operation, then the hydrogen concentration in the tube would be

$$H_{2_concentration} := \frac{V_{h2_stp}}{V_{contained}} = 30.878 \cdot \%$$

In order to obtain complete inerting (reduce the hydrogen concentration to below 4% - see diagram in App."B" from U.S. Bureau of mines bulletin #503) the additional dilution can be obtained by re-evactuating the catch tank. This would require pumping the catch tank down to:

$$H_{2_limit} := 4\%$$

$$P_{pumpdown} := 1psi$$ (Guess)

Given

$$\frac{H_{2_limit}}{H_{2_concentration}} = \frac{P_{pumpdown}}{1atm}$$

$$P_{pumpdown} := \mathrm{Find}\left(P_{pumpdown}\right) = 1.904\,psi$$

Therefore the catch tank will be pumped to below 1.9 psia.

Residual O2 in Catcher before shot

Prior to the shot, the catch tank vacuum is 20 micron

$$V_{o2_residual} := \frac{P_{pre_shot}}{760torr} \cdot V_{contained} \cdot 21\% = 1.083 \times 10^{-3} \cdot ft^3$$ of O2

For flammibility, 5% O2 is required

$$V_{o2_limit} := 5\% \cdot V_{contained} = 9.795 \cdot ft^3$$

The contribution of the residual O2 to the flammable limit is:

$$\frac{V_{o2_residual}}{V_{o2_limit}} = 0.011 \cdot \%$$ This is neglible.

Energy content of maximum amount of hydrogen used

$$m_{h2} = 143.734 \cdot gm$$

$$E_{h2} := 34.15 \cdot 10^{3} \frac{kcal}{gm} \cdot m_{h2} = 4.908 \times 10^{6} \cdot kcal$$

$$TNT_{equiv} := E_{h2} \cdot 3.085 \frac{ft \cdot lb}{kcal} \cdot \frac{1 lb}{1550000 ft \cdot lb} = 9.769 lb$$

$$TNT_{equiv} = 4.431 \times 10^{3} \cdot gm$$

AAN81-100307-00

END 80-912

MECHANICAL ENGINEERING SAFETY NOTE

Two Stage Light Gas Gun
September 03, 1980

Addendum A

Raising Maximum Pump Tube Hydrogen Pressure From 200 Psi To 350 Psi
September 20, 1994

Prepared by: _____
Bruce Cunningham, Engineer
C-Group

Reviewed by: _____
Mark Accatino, Pressure Engineer
New Technologies Engineering Division

Reviewed by: _____
Chuck Borzileri, Pressure Safety Manager
Hazards Control

Approved by: _____
Gus Carlson, Division Leader
New Technologies Engineering Division

Distribution:

M.	Accatino	L-373
C.	Borzileri	L-384
G.	Carlson	L-113
J.	Crawford	L-374
B.	Cunningham	L-321
	EIC	L-118
D.	Erskine	L-299
N.	Hinsey	L-400
N.	Holmes	L-299
B.	Morgan	L-374
B.	Nellis	L-299
K.	Snyder	L-374

Introduction

The following calculations and discussion are in response to a memo written by Jim Crawford and dated July 19, 1994, expressing a desire to raise the maximum pump tube hydrogen pressure in 341's Two Stage Light Gas Gun from 200 psi to 350 psi. Raising the pressure would have the positive result of lowering peak pressure in the pump tube (see END 71-2 Figure 3), reducing gun wear, and also lowering the risk of lead contamination.

The hydrogen delivery system for the Two Stage Gas Gun has been inspected and approved for operation at 375 psig MAWP. For documentation see Pressure Test/Inspection Record PE 0033 dated 9/19/94, and drawing PLM 78-341-002DE.

During a normal test firing, the following sequence of events occurs. Prior to firing a shot the pump tube is charged with nitrogen and checked for leaks. The charge pressure for this test is the pressure that used in the upcoming shot. The pump tube is then emptied and refilled with hydrogen. A propellant charge is used to drive a piston down the pump tube and compress the hydrogen. A petal valve, just ahead of the conical accelerator reservoir, bursts at a predetermined pressure and the compressed gas is allowed to flow into the launch tube. The gas accelerates a projectile into the evacuated target holder and catch tank. At this stage the shot is complete and all electrical connections to the tank are disconnected within two seconds of firing. Immediately following the shot, nitrogen is rapidly dumped into the tank until pressure within it reaches approximately 15.7 psia. Then a ventilating scrub valve is opened and additional nitrogen is pumped in at the rate of 70 ft3/minute. The nitrogen-hydrogen mix is ventilated to the atmosphere through a stack pipe on the roof. Purging continues until the hydrogen concentration falls below 4%. Finally, the tank is pumped down to a pressure well below atmospheric to insure that potentially hazardous hydrogen concentrations do not remain within the launch tube. Throughout the pre-test and experimental sequence, the area in which the gun resides is unmanned, and operations are conducted remotely.

This set of notes contains two main parts. In Part I, calculations are performed to predict the new gas pressures and volumes associated with operation at the higher proposed pump tube pressure. Part II contains calculations and discussion relating to potential hazards associated with gun operation and the (increased) hydrogen volume. Part II is patterned closely after engineering note END 80-912. Where calculated results differ from those in END 80-912, due to the change in pump tube pressure, those numbers are marked by an asterisk. These differences, as well as those in Part I, are summarized in a listing at the end of the memo.

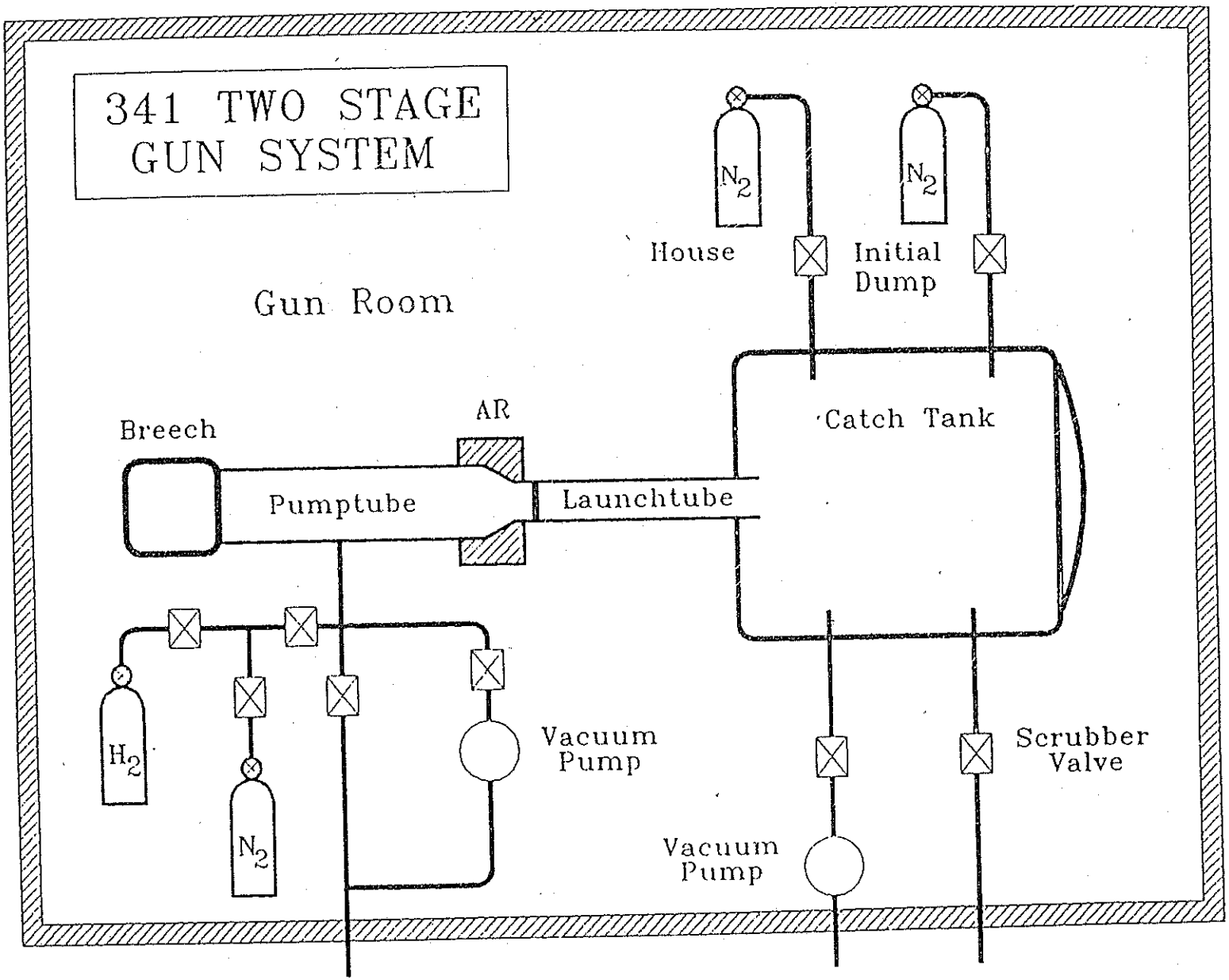

341 TWO STAGE
GUN SYSTEM
Gun Room
House
Initial
Dump
N_2
N_2
Catch Tank
AR
Breech
Pumptube
Launchtube
H_2
N_2
Vacuum
Pump
Vacuum
Pump
Scrubber
Valve

Figure 1

Part I

Operations

Calculations to determine the quantity of hydrogen and the pressure in the launch tube and catch tank following the shot, assuming the pump tube was initially charged with hydrogen gas to a pressure of 350 psia.

Upon firing, the combined volume of the catch tank and launch tube will contain...

(72 liters) x (350 psia/14.7 psia /atm) = 1714 liter-atm

(1714 liter-atm)(.03523 ft3/liter) = 60.38 ft3 of hydrogen at STP

The number of moles is....

N = PV/RT

= (1714 liter-atm)/(.082 liter-atm/mole deg K)(293 K)

= 71.34 moles

At 2.016 grams/mole this is equivalent to:

143.82 grams of hydrogen

The hydrogen, initially occupying a volume of 72 liters at 350 psia, will expand into a volume of 5152 liters. The pressure in the tank and launch tube will be.....

P2 = P1V1/V2

P2 = (350 psia)(72 liters)/(5152)

= 4.89 psia

Note: This calculation assumes that the compression and subsequent expansion of hydrogen takes place at constant temperature. There will probably, in fact, be a short term net increase in the temperature of the hydrogen (see ENR76-16) and so the pressure in the tank, immediately following the shot, will be somewhat higher than calculated

Calculations to determine the initial nitrogen volume necessary to bring the catch tank up to 15.7 psia. Assumes the pump tube was charged to 350 psia with hydrogen gas prior to firing.

Volume of Pump Tube = 72 liters (2.5 ft3)
Volume of Catch Tank = 5152 liters (181.5 ft3)

Expressing pressure in atmospheres:

$P1*V1 + P2*V2 = P*V$

$P2*V2 = P*V - P1*V1$

$P2*V2 = (15.7/14.7)*(5152) - (350/14.7)*(72)$

$P2*V2 = 3788$ liter-atmospheres

$= 133.5$ ft3 of nitrogen at STP

Derivation of the equation to determine the hydrogen content in the catch tank and lauch tube as a function of time.

During the purge, at any given time the rate of change of the amount of hydrogen in the catch tank and launch tube will be equal to the volume of hydrogen at STP, divided by the total volume of the pump tube and catch tank, multiplied by the flow rate of nitrogen.

$dH/dt = -(H/V)(dN/dt)$

rearranging....

$dN = -Vdh/H$

integrating....

$N = -V(\ln H) + C$

To evaluate the constant C we use initial conditions. Initially N = 0. Assuming the scrubber valve has been opened, pressure in the tank has dropped from 15.7 psia to 14.7 psia. H, the amount of hydrogen, is initially.....

H = (60.38 ft3)(14.7 psia/15.7 psia)

H = 56.53 ft3

substituting

$0 = -181.5(\ln(56.53)) + C$

$C = +732.37$

Our equation becomes....

$N = -181.5(\ln H) + 732.37$

The hydrogen content will be 4% of the volume when....

H = (.04)V

H = (.04)(181.5 ft3)

H = 7.26 ft3

The volume of nitrogen necessary to reduce the hydrogen content to this level is....

$N = -181.5(\ln(7.26)) + 732.37$

N = 373 ft3

Assuming a nitrogen flow rate of 70 ft3/minute, the purge time to achieve a 4% hydrogen level is....

t = N/F, where F is the nitrogen flow rate

t = (373 ft3)/(70 ft3/min.)

t = 5.33 min.

Solving the general equation for H...

lnH = (732.37 - N)/181.5

Taking the inverse...

H = e^((732.37-N)/181.5)

Substituting for N...

H = e^((732.37 - 70t)/181.5)

Calculations for the nitrogen flushing operation, assuming an initial pump tube charge of hydrogen at 350 psia.

$t := 0, .5 .. 10$

$N(t) := 70 \cdot t$

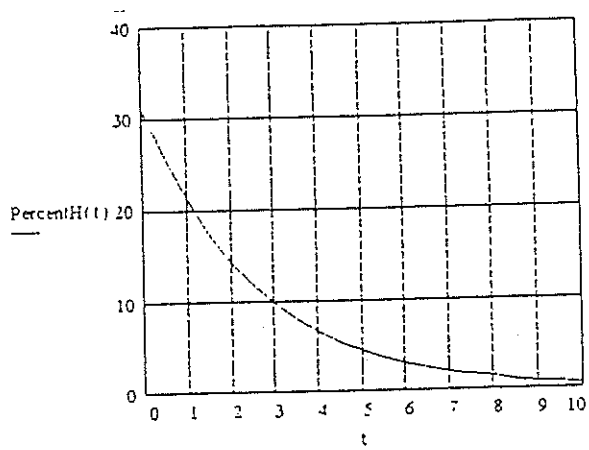
$H(t) := e^{\left(\frac{732.37 - 70 \cdot t}{181.5}\right)}$

$PercentH(t) := \frac{H(t) \cdot 100}{181.5}$

Note: These calculations determine the nitrogen flow in ft3, the catch tank hydrogen content in ft3 at STP, and the corresponding percent of hydrogen in the catch tank, assuming a nitrogen flow rate of 70 cfm.

t	N(t)	H(t)	PercentH(t)
0	0	56.548	31.156
0.5	35	46.631	25.692
1	70	38.452	21.186
1.5	105	31.708	17.47
2	140	26.147	14.406
2.5	175	21.561	11.88
3	210	17.78	9.796
3.5	245	14.662	8.078
4	280	12.09	6.661
4.5	315	9.97	5.493
5	350	8.221	4.53
5.5	385	6.779	3.735
6	420	5.59	3.08
6.5	455	4.61	2.54
7	490	3.801	2.094
7.5	525	3.135	1.727
8	560	2.585	1.424
8.5	595	2.132	1.174
9	630	1.758	0.968
9.5	665	1.449	0.799
10	700	1.195	0.659

Catch Tank Hydrogen Content
As A Function Of Nitrogen Flow



Time (minutes)

The threshhold mark of 4% hydrogen occurs when H(t)=181.5*.04=7.26 ft3. Substituting and solving for t yields t=5.33 min.

Calculation to determine the pump down pressure following the nitrogen purge.

If the hydrogen in the pump tube, following the shot, were to be unaffected by the nitrogen purge operation, then the hydrogen concentration in the tube would be...

(60.5 ft3/181.5 ft3)(100) = 33.3 %

To eliminate the danger by pumping down and thereby reduce the hydrogen concentration in the tube to 4 %, the pump down pressure should be...

.04 = .333(Pump down pressure)/14.7

Pump down pressure = 1.77 psia

Part II

Hazards Assessment

A Case by Case Examination of Possible Leakage Scenarios and Associated Potential Hazards

PRESHOT FAILURES

Case I - Leakage from the pump tube into the breech

During a shot, the maximum allowable pressure drop in the pump tube is 10 psi, otherwise the shot is scrubbed and the pump tube is evacuated. If a major leak into the breech did occur then the equilibrium pressure arrived at would be...

$$P1V1 + P2V2 = P3(V1 + V2)$$

$$P3 = (P1V1 + P2V2)/(V1+V2)$$

$$P3 = ((14.7\ \text{psia})(11\ \text{liters}) + (350\ \text{psia})(72\ \text{liters}))/(83\ \text{liters})$$

$$P3 = 305.5\ \text{psia}\ *$$

Thus a 44.5 psi drop would occur and the shot would be scrubbed. In addition, the hydrogen content in the breech would be ..

$$\%\ \text{hydrogen} = ((305.5\ \text{psi} - 14.7\ \text{psi})/(305.5\ \text{psi}))*100$$

$$\%\ \text{hydrogen} = 95.1\ \%\ *$$

This mixture is too hydrogen rich to support combustion (see figure 2).

Leakage just short of that necessary to cause a 10 psi drop in pressure in the pump tube would introduce (10/14.7)(72) = 48.98 liter-atm or 4.11 grams of hydrogen into the breech. This would be ignited upon firing the shot and would have little effect.

Case II - Leakage of hydrogen from the pump tube to the breech and into the gun room.

As discussed in Case I, the amount of hydrogen lost which would result in a 10 psi pressure drop in the pump tube would be 4.11 grams. Assuming it all found its way through the breech and into the room and was subsequently ignited before it disbursed (worst case), the static over-pressure would be...

$$O.P. = 4000\ HW/V$$

where

H = heat of combustion in kcal/gram

W = weight of combustible in lbs

V = volume of enclosure in ft^3

O.P. = (4000)(34.15 kcal/gram)(4.11/454 lb)/(50000 ft^3)

O.P. = .0247 psi = 3.557 lb/ft^2

This is not a sufficiently high pressure to cause damage.

Case III - Leakage from the pump tube directly into the gun room.

Again, the maximum pressure drop allowed in the pump tube is 10 psi. Consequently, the maximum amount of hydrogen available to burn would be 4.11 grams. Over-pressure in the gun room, in the worst case scenario, is estimated to be .0247 psi (see Case II).

Case IV - Leakage from the pump tube past the petal valve into the launch tube/catch tank.

Once Again, the maximum pressure drop before shut down of the experiment is 10 psi. For this to occur, leakage would have to be sufficient to cause the projectile to move down the launch tube. To incur a 10 psi pressure drop, the hydrogen would have to expand into a volume equal to...

V2 = P1V1/P2

V2 = (350 psia)(72 liters)/(340 psia)

V2 = 74.12 liters

This would require the projectile to move down the launch tube a distance sufficient to displace 74.12 - 72.00 liters = 2.12 liters. This is equivalent to a distance of approximately 3.5 feet in a 2 inch barrel or 13.7 feet in a 1 inch barrel. Shot results could be affected but no safety hazard would occur. In the event leakage was sufficient to cause the projectile to be forced into the catch tank there would be no hazard because insufficient oxygen would be present in the evacuated tank to support combustion.

Case V - Leakage of hydrogen into the catch tank accompanied by leakage of air into the catch tank with ignition.

This very low probability occurrence would require a substantial leak in the petal valve and as well as a much greater than 10 psi drop in the pump tube (the projectile would have to move down the launch tube and drop into the tank). In addition, a loss of vacuum in the catch tank would also have to occur

simultaneously (which would cause the interlock to trip and shut down the experiment). If all the hydrogen in the pump tube were to somehow be emptied into the tank there would be more hydrogen than necessary to form a stoichiometric mixture. The volume of hydrogen and air for the largest possible stoichiometric mixture are found by solving the two equations...

$$\text{Vol. } H_2 + \text{Vol. Air} = 181.5 \text{ ft}^3$$

$$\text{Vol. Air } (.205)/\text{Vol. } H_2 = 1/2$$

$$\text{Vol. } H_2 = 52.8 \text{ ft}^3$$

$$\text{Vol. Air} = 128.7 \text{ ft}^3$$

Calculating the TNT equivalent.

$$52.8 \text{ ft}^3 \text{ of hydrogen} = 62.4 \text{ moles}$$

$$= 125.8 \text{ grams}$$

The TNT equivalent is estimated to be...

TNT equiv. = (energy available from Hydrogen)/(energy/lb TNT)

$$\text{energy available from hydrogen} = (34.15 \text{ kcal/g})(125.8 \text{ g})$$

$$= 4296 \text{ kcal}$$

$$= 13.25 \times 10^6 \text{ ft lbs}$$

$$\text{So TNT equiv.} = 13.25 \times 10^6/(1.55 \times 10^6/\text{lb TNT}) = 8.55 \text{ lbs}$$

For detonations, the peak overpressure can be estimated from an empirical equation.....

$$P_{mo} = 2410(W/V)^{0.72}$$

$$P_{mo} = (2410)(8.55/181.5)^{0.72}$$

$$P_{mo} = 267 \text{ psi}$$

7 The catch tank door (30 inch radius) is equipped with swing away clamps to allow for ventilation in the event of an explosion. It weighs 3300 pounds with shrapnel plate attached. Assuming pressure is applied (average 267/2 = 133.5 psi) over a distance of 3 inches, the plate will experience an average acceleration of...

$$a = F/m$$

$$a = (133.5 \text{ psi})(\text{pi})(30 \text{ in.})^2(32.2 \text{ ft/sec}^2)/(3300 \text{ lb})$$

$$a = 3683 \text{ ft/sec}^2$$

The door/shield would reach a velocity of....

v = sqrt(2as)

v = sqrt((2)(3683)(3/12))

v = 42.9 ft/sec *

Case VI - Leakage from the catch tank into the gun room via the launch tube.

Assume worst case where a large leak allows the hydrogen at 350 psia to flow into the tank. Since the tank is evacuated, then the pressure in the tank would be....

P2 = P1V1/V2

P2 = (350 psia)(72 liters)/(72 + 5069 liters)

P2 = 4.90 psia *

This is substantially below atmospheric so there would be no tendency for the contents of the tank to flow out into the room. Following the rapid Nitrogen dump into the tank, the pressure will be at 15.7 psia. The hydrogen content will now be...

% Hydrogen = (4.9 psia)(100)/(15.7 psia)

= 31.2 % *

As soon as the Nitrogen purge begins, tank pressure would drop back down to atmospheric and there would be little tendency for leakage to occur. After a 6 minute purge of nitrogen the hydrogen content would be below 4%.

Case VII - Venting the pump tube to the atmosphere.

In the event of a shot abort hydrogen would be vented from the pump tube directly to the roof and is released 4 feet above the roof surface. The amount of hydrogen is....

N = PV/RT

N = (350/14.7 atm)(72 liters)/(293 deg K)(.082 l-1tm/m deg K)

= 71.35 moles

= 143.8 grams *

Case VIII - Venting the catch tank to the atmosphere.

This situation would arise in the event a shot was scrubbed and all the hydrogen had somehow passed from the pump tube to the catch tank. In dealing with this situation, procedures would be the same as after a normal firing. There would be a rapid nitrogen dump to the tank followed by a purge of house nitrogen. See calculations on the initial dump and purge for details.

Case IX - Leakage from the pump tube to the gun room and then to the atmosphere.

As in case VII the maximum loss to the atmosphere would be 143.8 grams. It would be rapidly dispersed.

Case X - Leakage from Gun room into the catch tank.

This would produce a loss of vacuum in the tank which would cause the interlock to prevent firing the shot. The shot would then be scrubbed by venting the hydrogen in the pump tube to the atmosphere.

Case XI - Leakage from the atmosphere into the catch tank.

The leak would occur through the valving. Events would proceed as described in Case X.

POST SHOT FAILURES

Case XII - Leakage from the pump tube into the breech followed by propellant ignition.

A small amount of hydrogen (maximum 4.11 grams, based on the limit of 10 psi drop in the pump tube) burning in the breech would have very little effect on the launch.

Case XIII - Leakage from the pump tube into the breech and out into the gun room as the piston is being driven down the pump tube.

Hydrogen leaking, in the very brief time this could occur, would mix with propellant gasses. Hydrogen Concentrations would be very small.

Case XIV - Leakage from the seals in the AR.

Piston-compressed hydrogen is under pressure for a very brief period of time before it is vented into the catch tank. A significant pre-existing leak would be picked up in the nitrogen pressure test prior to the shot. Leakage past the various rings would be audible and most likely very limited. Significant leakage

would require a major failure in the AR seal system.

Case XV - Leakage from the gun room into the catch tank.

This situation could occur if a portion of the projectile or target perforated the catch tank wall or x-ray windows. The nitrogen dump into the catch tank occurs immediately after the shot is fired. Assuming an average flow rate of nitrogen into the tank of 200 ft3/min then the time to bring the 181.5 ft3 volume up to 15.7 psia is....

$$\text{Fill Time} = (181.5 - 60.5\ ft^3)(15.7/14.7)/(200\ ft^3/min)$$

$$= .65 \text{ minutes}$$

$$= 39 \text{ seconds } *$$

An expression for the percentage of oxygen as a function of time in seconds, and air leakage flow rate is...

$$\%\ \text{Oxygen} = (.205(l.f.)t/60)/(60.5 + 200t/60 + (l.f.)t/60)(100)$$

where l.f.=leak flow rate

The volume to be filled, in cubic feet at STP, is $181.5(15.7/14.7) = 194.4\ ft^3$. A second expression in l.f. and t is...

$$(l.f.)t/60 + 60.5 + 200(t)/60 = 194.4$$

Setting % Oxygen equal to the threshold below which combustion will not be supported - 5% - and solving simultaneously yields a fill time of 32.4 seconds and an average leak flow rate of 111.9 ft^3/min.

The hole size necessary to allow this flow rate can be estimated from the following equation (REF. 2)...

$$\text{air flow (lb/sec)} = \frac{.53(C_D)(\text{pressure outside tank})(\text{hole area})}{(\text{sqrt Temperature in deg R})}$$

where CD is an empirically derived coefficient

The density of air at STP = .075 lb/ft^3

the air flow rate of 111.9 ft^3/min = .140 lb/sec

However, the flow rate will diminish to zero as the tank pressure reaches atmospheric, so the initial rate must be .140 x 2

=.280 lb/sec to achieve the same total flow as a steady flow of 111.9 ft3/min.

$$\text{hole area (in}^2) = (.280)(\text{sqrt}(528))/((.53)(.61)(14.7)$$

$$= 1.35 \text{ in}^2$$

Therefore, the hole in the tank would need to be larger than 1.25 inches in diameter for this to occur. This analysis assumes mixing. See engineering note END 80-912 for analysis where cases are examined assuming mixing does not occur and there is localized burning.

Case XVI - Leakage from the catch tank into the gun room.

If the pressure in the catch tank were raised to 15.7 psia as a result of the initial nitrogen dump, and then leakage from the catch tank occurred, it would continue until pressure in the catch tank dropped to atmospheric. This necessitates the purge process being delayed a sufficient time for equilibrium to be reached. The amount of hydrogen (mixed with other gasses) released into the gun room would be....

$$\text{amount of } H_2 \text{ released} = (181.5)(60.5/181.5)(1/14.7)$$

$$= 4.11 \text{ ft}^3$$

$$= (4.11/.03523))/24 = 4.89 \text{ moles } *$$

Case XVII - Venting the pump tube in the case of a misfire.

Should a misfire occur, evacuation of the pumptube would be necessary. This was covered under Case VII.

Case XVIII - Hydrogen flow from the pump tube to the catch tank and then to atmosphere.

This describes the normal operation scenario. See calculations on hydrogen quantity and pressure in the catch tank, the initial nitrogen dump, and the nitrogen purge.

Case XIX - Leakage through the vacuum pump or scrubber valve.

Since the lines leading from these devices to exhaust are previously back filled with nitrogen, leaks from these devices would initially force additional nitrogen into the tank (about 50 ft^3 for the scrubber line and 14 ft^3 for the vacuum pump line - see END 80-912). If leakage occurred, then in order for the 5% percent oxygen threshold to be achieved, the total air flow would need to be....

$$.05 = (\text{air leakage})(.205)/(181.5)$$

$$\text{air leakage} = 44\ ft^3$$

Case XX - Leakage of burned propellant gasses from the breech into the pump tube.

This probably does occur. However, there is insufficient oxygen to support combustion.

Case XXI - Hydrogen flow from the pump tube to the catch tank.

This occurs as the normal consequence of any experiment. See case XVIII.

Case XXII - Ignition/detonation of the hydrogen in the tank (worst case scenarios).

Assumption 1 - Assume complete combustion of all 60.5 ft^3 of hydrogen within the (unvented) gun room. Note that detonation of unconfined hydrogen-air mixtures will not occur unless initiated by at least 2 grams of high explosives (REF. 3).

$$\text{Static overpressure}=4000(\text{heat of combustion}H_2)(\text{weight}H_2)/(\text{roomvol.})$$

$$=4000(34.2\ kcal/gm)(143.8\ grams/454)/(50000\ ft^3)$$

$$=.87\ psi$$

$$=125\ lb/ft^2\ *$$

This is several times that necessary to raise the roof and blow out the roll-up door, if closed. It would not be sufficient to cause damage to the walls (see END 76-908 which estimates the maximum elastic resistance pressure for the wall to be 1.5 psi).

Assumption 2 - Assume Detonation inside the tank.

There is an insufficient volume in the tank to allow a stoichiometric mixture of all the hydrogen. The largest stoichiometric mixture possible at STP is found by solving the two equations...

$$\text{Vol. } H_2 + \text{Vol. Air} = 181.5\ ft^3$$

$$\text{Vol. Air } (.205)/\text{Vol. } H_2 = 1/2$$

$$\text{Vol. } H_2 = 52.8\ ft^3$$

$$\text{Vol. Air} = 128.7\ ft^3$$

Calculating the TNT equivalent.

$52.8\ ft^3$ of hydrogen = 62.4 moles

= 125.8 grams

The energy content is....

(125.8 grams)(34.15 K Cal/gram) = 4296 K Cal

(4296 K Cal)(3.085 ft lbs/Cal) = 13,253,000 ft lbs

Its TNT equivalency is...

(13,253,000 ft lbs)/(1,550,000 ft lbs/lb TNT equiv.)=8.550lbs/TNT

Based on TM 5-1300 (REF. 4) and 8.55 lbs of TNT, an estimate of the overpressure on the end wall (see END 80-912) is...

$h/H=.5,\ l/L=.5,\ L/H=5,\ L/Ra=8,\ Za=Ra/W^{1/3}$

Use L/H = 6 in chart 4-51

From chart 4-51 $i_b = 15$ psi-ms/$lb^{1/3}$

$i_b = (15)(8.55^{1/3}) = 30.65$ psi-ms

$Z_F = 50/W^{1/3} = 24.5,\ Z_A = 12.5/W^{1/3} = 6.11$

From equation 4-1 and figure 4-5

$t_o = 2.04[\ 17 - 2.2 + 1.5(3.3)\ ] = 40.3$ ms

From equation 4-2

$P_f = 2*i_b/t_o = 2(30.65)/40.3 = 1.52$ psi

This is approximately equal to the elastic limit calculated for the end wall. However, as discussed in END 80-912, the assumption of detonation is an extremely conservative one.

Finally, the KO code model which is used in END 80-912 makes the very conservative assumption that the vent door in the tank opens, not at its rated 15 psi over atmospheric, but at 100 psi. The conclusions from this analysis apply regardless of the amount of hydrogen in the tank.

Stresses In The Pump Tube Due To Static Pressure Loading

The pump tube is essentially a long, thick-walled tube which is internally pressurized. It has a 7.0 inch outer diameter with a bore diameter of 3.5 inches (see drawing number SK-01740). Timoshenko (REF 1) gives the equations for maximum radial and hoop stresses...

$$S_r = ((a^2 * P) * (1-b^2/a^2))/(b^2 - a^2)$$

$$S_t = (P * (a^2 + b^2))/(b^2 - a^2)$$

Here P is the internal gage pressure and a and b are the inner and outer radii, respectively. Both peak stresses occur at the inner wall. For an internal pressure of 350 psig, the stresses are calculated to be ...

$$S_r = ((1.75^2 * 350) * (1 -3.5^2/1.75^2)/(3.5^2 - 1.75^2)$$

$$= - 350 \text{ psi}$$

(The peak radial stress is compressive, and is equal to the internal pressure.)

$$S_t = ((350 * (1.75^2 + 3.5^2))/(3.5^2 - 1.75^2)$$

$$= 583 \text{ psi}$$

Calculating the Von Mises stress condition...

$$S_{vm} = \text{sqrt}(.5 * ((S_1 - S_2)^2 + S_1^2 + (-S_2)^2))$$

$$S_{vm} = 816 \text{ psi}$$

This is less than one percent of the yield strength of the 4340 barrel steel (Y.S. = 130,000 psi).

Summary

I. The following significant operational changes will occur as a result of increasing the pump tube hydrogen charge pressure from 200 to 350 psia. Numbers are approximate.

1) The amount of working hydrogen in the system increases from 82 grams to 144 grams.

2) Pressure in the catch tank immediately following the shot increases from 2.8 psia to 4.9 psia.

3) The amount of nitrogen necessary to bring the tank pressure up to 15.7 psia decreases from 154 ft^3 to 133 ft^3.

4) The purge time necessary to achieve a 4% hydrogen content in the tank increases from just under 4 minutes to 5.33 minutes.

5) The final pump down pressure necessary to assure a 4% or lower hydrogen concentration in the launch tube drops to 1.77 psia.

II. The following changes in the case-by-case hazard assessment occur as a result of the increase in hydrogen working pressure.

1) (Case I, END 80-912) In the case of hydrogen leakage from the pump tube to the breech, equilibrium pressure increases from 175 psia to 306 psia. Hydrogen content would be 95% instead of 92 %.

2) (Case VI) If all the hydrogen were to leak from the pump tube into the catch tank then the pressure in the tank would be 4.9 psia instead of 2.8 psia. After the nitrogen dump the hydrogen content will be 31% instead of 18%.

3) (Case VII) In the event of experiment abort, the amount of hydrogen vented to the atmosphere would be 144 grams instead of 82 grams.

4) (Case XV) The time to bring the catch tank up to 15.7 psia with a 200 ft3/min. dump decreases from approximately 47 seconds to approximately 39 seconds.

5) (Case XVI) If catch tank leakage occurred after the nitrogen, dump but before the nitrogen purge, then the amount of hydrogen lost to the gun room would be 9.8 grams instead of 5.3 grams.

6) (Case XXII-A) Assuming all the hydrogen were to burn within the (unvented) gun room, the static pressure would be .87 psi (125 lb./ft2) instead of .49 psi (71 lb./ft2).

7) (Case XXII-B) The TNT equivalency for the largest stoichiometric mixture possible in the tank is 8.56 pounds instead of 5.59 pounds. Using methods of reference (2), the shock pressure is estimated to be 1.52 psi instead of 1.36 psi.

REFERENCES

1. Strength of Materials, Part II-Advanced Theory and Problems, S. Timoshenko, D. Van Nostrand & Company, 1956.

2. Mark's Standard Handbook for Mechanical Engineers, Ninth Edition, McGraw Hill, copyright 1987.

3. Experimental Investigation of Detonation in Unconfined Gaseous Hydrogen-Oxygen-Nitrogen Mixtures, Leon H.Cassutt, ARS Journal, 1960.

4. Structures To Resist The Effects of Accidental Explosions, Departments of the Army, Navy and Air Force, (TM 5-1300) copyright 1969.

19, July 1994

UP GRADING THE ENGINEERING SAFETY NOTE

ENR75-16

We need to raise the pump tube hydrogen pressure from 200 psi maximum operating pressure ~~to 350 psi~~ maximum operating pressure. This may require modifying ENR75-16. ?

Raising the pressure in the launch tube will do two things:

1: Prevent the piston from hitting the back of the tank. When the piston hits the back of the tank it deposits lead on the walls of the tank. This spreads lead into areas where it shouldn't be, it also creates mixed waste if we later shoot D-38.

2: Stop the piston at the acceleration reservoir. This is how the gun was designed to operate. Having the piston go beyond the AR causes excessive damage and wear on the gun.

There is a safety issues associated with increasing the hydrogen pressure.

1. Hydrogen in the gun tank after the shot.

There is a danger of getting a leak in the tank and having oxygen get into the tank and forming an explosive mixture with the hydrogen in the tank.

To prevent this we have two purges, the first is a fast purge with a bottle of nitrogen (currently 204 cubic feet) designed to quickly bring the tank to atmosphere and preclude any oxygen from leaking into the tank.

The second purge is after the scrubber valve is opened it is from of our house N2 system, it is designed to force the hydrogen from the tank to outside above the bldg.... After a predetermined length of purge time, we re-evacuate the tank and consider it safe.

We now shoot with 145 psi pump tube pressure which gives us 22 cubic feet of gas in the tank after the shot. The proposed 350 psi pump tube pressure will give us approximately, 60 cubic feet of gas in the tank after the shot. The catch tank volume is approximately 185 cubic feet.

We need to know how much nitrogen to put into the tank during the first purge to get to atmospheric pressure (1 psia) and how long to purge the tank during the second purge to get the hydrogen to below 4% of the tank volume.

Please go though the numbers and let me know how much nitrogen we need to get to atmosphere and the length of purge time required to achieve a safe (non-flammable) gas mixture. Please let me know what (if any) changes need to be made to the equipment and safety note.

JAMES CRAWFORD

TWO STAGE GUN

BLDG. 341 RM 1200

x29646

END 80-912

MECHANICAL ENGINEERING SAFETY NOTE

TWO STAGE LIGHT GAS GUN

BY

Bernard Monahan

September 03, 1980

APPROVED:

R. B. Carr
Division Leader
Nuclear Explosives Eng. Div.

J. Rego
Project Engineer
Nuclear Explosives Eng. Div.

B. G. Monahan
Device Engineer
Nuclear Explosives Eng. Div.

Distribution:

D. Bakker, L-374
M. Brooks, L-374
R. B. Carr, L-122
G. Devine, L-374
C. Henry, L-355
A. Mitchell, L-355
B. Monahan, L-122
W. Mumper, L-374
W. Nellis, L-355
J. Rego, L-122
B. Simecka, L-123
M. Van Thiel, L-355

MECHANICAL ENGINEERING SAFETY NOTE

TWO STAGE LIGHT GAS GUN

INTRODUCTION

"H" Division has been operating a "Two Stage Light Gas Gun" since 1971. This apparatus was purchased from G.M. Defense Research Laboratory, Goleta, California. In addition to the gun, we received numerous spare parts and a large supply of HP-95, gun powder. We have used this powder for all shots until 1980. Recently, we have noticed that other labs using the same model guns (all bought from G.M.), were reporting higher velocities then we have been able to acheive. This has led to inquiries to their experimenters and then a program to investigate the operation and the efficiency of their techniques. Our inquiries showed that other experimenters are using different gun powder which better matches to the piston's dynamic characteristic, namely its acceleration down the pump tube. These powders are slower burning and give a lower breech pressure, but a longer pressure pulse. This allows more powder to be used for achieving higher piston velocities and still maintaining low breech pressures.

The second change to the operating technique is to increase the H_2 pressure in the pump tube. We have been using 125 psi H_2 which best matches the piston weight and the HP 95 powder characteristics. The increase in the pressure allows the gas to be pressurized to higher pressures by the piston all the while causing the piston to decelerate. Thus the piston arrives at the tapered section of the accelerator resevoir (AR) at a slightly lower velocity than what we now have. This does two things: it increases the efficiency of the gun and decreases the internal pressure in the AR as the piston is extruded through the tapered section. The AR's are essentially large extrusion dies which receive high stresses due to the high rate of extrusion. They grow in diameter after repeated inpacts, so that they have a usable lifetime from 60 to 200 shots. Increasing their lifetime by increasing th H_2 pressure will decrease their cost and will achieve up to 15% higher velocities. This will be well received all the way around.

The purpose of this safety note is to show that increasing the H_2 pressure from 125 psia to 200 psia maximum pressure would not violate any of the LLL safety practices using the operating practices currently enforced and written in the "Operating Safety Procedures Building 341". This safety note addresses the hydrogen flammability hazard in detail. It covers the other hazards of safety note - END 76-908 which are affected by the change in the H_2 pressure.

035

EQUIPMENT AND OPERATION

The two stage gun consists of a breech which is loaded with gun powder, a pump tube which contains a piston which is located at the breech end and a tapered section called the accelerator reservoir (AR) located at the other end, behind the AR is a rupture diaphragm called a petal valve. The pump tube is filled with H_2 gas to a specified pressure. On the other side of the petal valve is the launch tube. The projectile to be fired is placed in the launch tube just behind the petal valve. At the other end of the launch tube is the evacuated target chamber and catch tank inside which are the diagnostics, the target, and the shrapnel catching plates.

In the operating sequence the powder is ignited. This increases the breech pressure forcing the piston to accelerate down the pump tube. When the piston compresses the H_2 gas to 14,000 psi the petal valve ruptures and the high pressure gas causes the projectile to accelerate down the launch tube. The piston advances into the tapered section and is extruded, further accelerating the gas. The projectile, the H_2 gas, and parts of the piston move down the launch tube and into the catch tank. The powder gas is then vented from the pump tube; and the catch tank is rapidly filled with nitrogen and then purged to the outside atmosphere, by flowing nitrogen through the catch tank.

The persons responsible for the operation of the equipment are William Nellis - Physicist, Group Leader; Douglas Bakker - Facility Supervisor.

HAZARDS

This safety note is concerned only with the hydrogen flammability hazard caused by changing the maximum pump tube pressure from 125 psia H_2 (51.3 gms) to 200 psia H_2 (82.0 gms). All the other hazards are covered in safety note END 76-908.

The hydrogen gas is kept in a hydrogen bottle manifold along the wall of the gun room. The manifold is double valved along with the two automatic remote control valves that are used for filling the pump tube. In the operating sequence all setups are made and the projectile, petal valves, AR and piston are assembled, the pump tube is evacuated and then filled with N_2 gas to the pressure to be used on the shot. The pump tube is leak checked by pressure stabilization and is then evacuated. This procedure follows Section 5, Pumptube Pressure Fill Preparation, and Section 6, Pump Tube Pressure Leak Check, of the Procedure Check List. The powder is loaded and the gun room evacuated. At this point the pump tube is filled to the desired H_2 pressure as part of the Section 9, Firing Sequence. This procedure (Section 9) is done remotely from the control room panel.

The analysis of the hydrogen hazard is concerned with the time period after fill and before firing which will be called Preshot, and with the time during and after firing until the hydrogen is completely purged from the tank called Post Shot. The sequence of operations in the post shot procedure minimize the chance that an air leak can produce a flammable mixture and then ignite. All electrical power to the catch tank is switched off automatically 2 seconds after firing. Immediately after firing the shot, the operator opens the fast purge valve #5. This empties a cylinder of nitrogen into the chamber which brings it to about one psi above atmospheric pressure.

The schematic view of the equipment is shown in Figure 1.

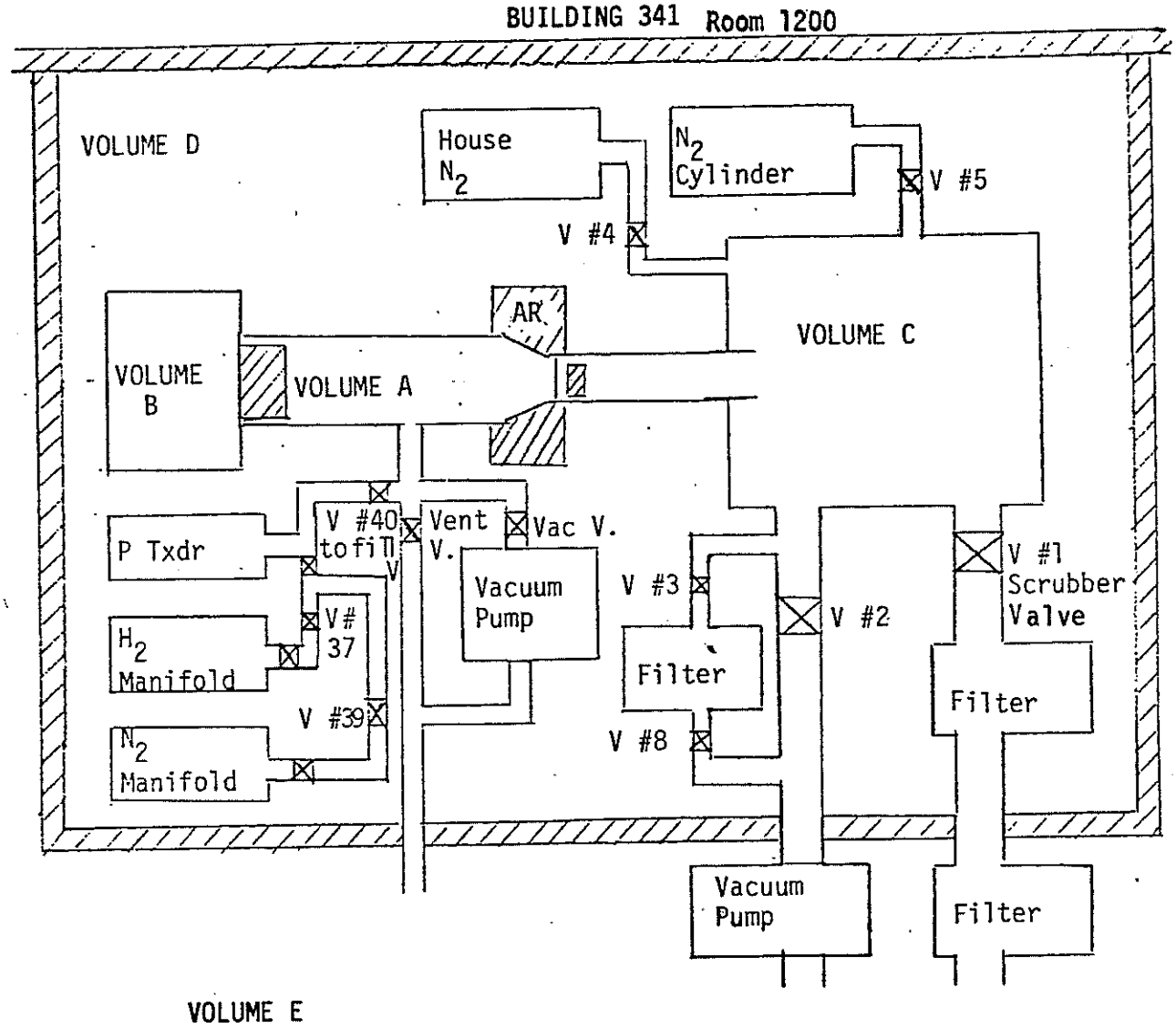


FIGURE 1

	SYSTEM	VOLUME	PRESSURE	GAS
A	Pumptube	72 liters	200 psia	H_2
B	Breech	11 liters	14.7 psia	Air
C	Catch Tank	5,069 liters	0.0 psia	Vacuum
D	Gun Room	1,132,000 liters	14.7 psia	Air
E	Enviornment	5 megaliters	14.7 psia	Air

There is an emergency backup cylinder which can be opened pneumatically if the first cylinder cannot be opened electrically. If this can't be done there is the "house" nitrogen system which can be used, although this will take longer. After this is done the scrubber valve #1 is opened and "house" nitrogen is flowed for four minutes at 70 cfm. This is verified by reading a flow gage on the remote TV monitor. After this is done the catch tank is pumped down to 4 psiq and then refilled with nitrogen. After this air is flushed through the tank for five minutes. Only after this, is reentry into the gun room permitted.

HAZARDS ANALYSIS

PRESHOT

To burn the hydrogen we must have it leak into volumes which contain oxygen or vice versa. Referring to figure 1, the possible leaks to be analyzed are:

Case I	A to B	Case VII	A to E
Case II	A to B to D	Case VIII	A to C to E
Case III	A to D	Case IX	A to D to E
Case IV	A to C	Case X	D to C
Case V	A to C with D to C	Case XI	E to C
Case VI	A to C to D		

The leaks not considered are:

B to D, D to B, D to E, E to D - trivial

B to A, D to A, E to A - flow against a pressure head

C to A, B, D, E. - no gas to escape

B to C - no connection

POSTSHOT (starting from powder ignition)

Case XII A to B

Case XIII A to B to D

Case XIV A to D

Case XV D to C

Case XVI C to D

Case XVII A to E

Case XVIII A to C to E

Case XIX E to C

Case XX B to A

Case XXI A to C is considered part of the firing process

Again, leaks not considered are:

B to D, D to B, D to E, E to D - trivial

C to B, D to A, E to A - flow against a pressure head

B to C - no connection

In addition to the leaking (CASES I thru XXI) it is essential that an ignition source be present and that the mixture be within the flammability limits.

FLAMMABILITY LIMITS

The published limits for flammability of H_2 in an air mixture at atmospheric pressure are*:

Lean flammability limit 4% volume H_2 96% volume air

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* Bolz, R.E. "Handbook of Tables for Applied Engineerng Science" 1st edition, page 311; 2nd edition, page 783 CRC Press (1970, 1973).

Rich flammability limit 75% volume H_2 25% volume air

The flammability limits for hydrogen and air with nitrogen dilution are given in Figure 2*. The detonation limits of these mixtures are included as Enclosures I.

LIMITS OF INDIVIDUAL GASES AND VAPORS

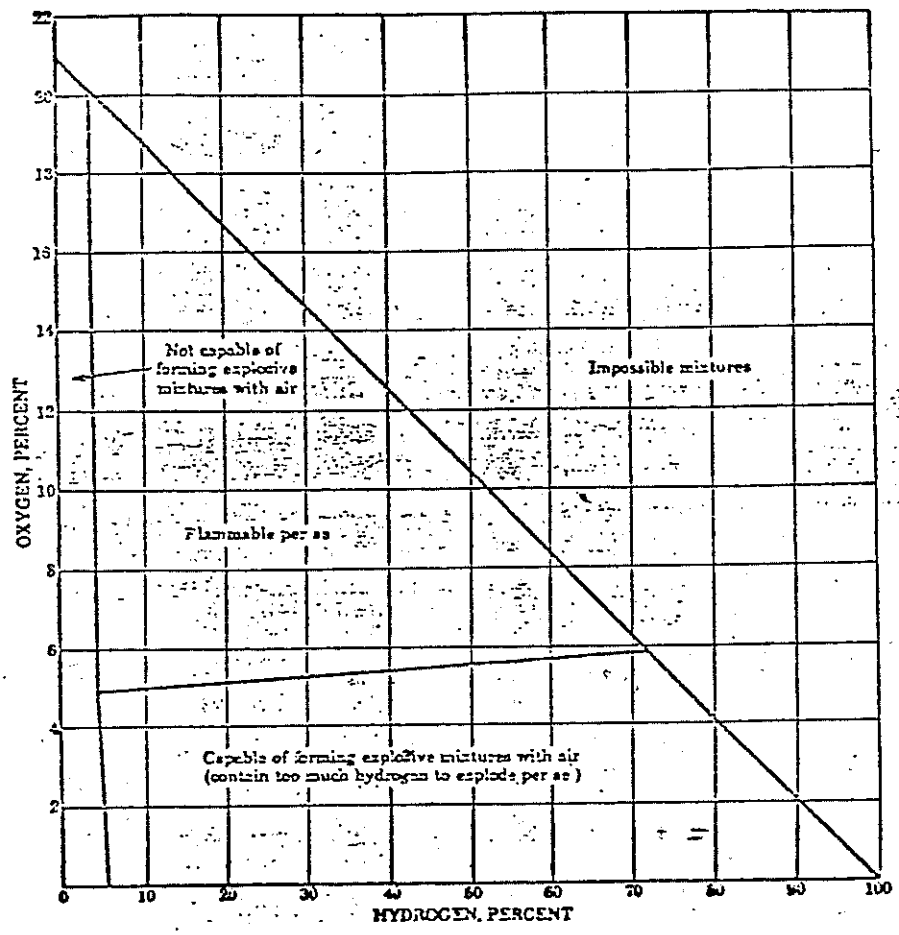

FIGURE 2 - Relation Between Composition and Flammability of Mixtures of Hydrogen, Oxygen, and Nitrogen at atmospheric pressure.

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* U.S. Bureau of Mines Bulletin #503.

Each case will be presented descriptively and the most hazardous cases will be analyzed in detail. It is the opinion of the author that the most hazardous case was Case XV; however this case has been given the full safety treatment and its accident potential has been considerably reduced. While its probability of occurrence is greatly reduced, the consequences of its occurrence rate it as having the highest potential for damage. Before cases are discussed the safety measures and the operational environmental considerations which are enforced will be described.

A CASE HISTORY AND THE OPERATIONAL ENVIORNMENT IT GENERATED

On April 26, 1976 an incident occurred where the hydrogen was ignited in the catch tank after a shot was fired with 125 psia of hydrogen. The over pressure blew the large door off the catch tank and separated the target chamber from a slip joint connection to the spool connecting it to the catch tank. If one assumes that the tank was vented to air and at least one half an atmosphere (stiochiometric hydrogen air mixture) was in the tank, the complete burning of the hydrogen would produce about 100 psia in the 179 ft^3 volume. The assumption that the mixture burned in the tank is supported by the lack of evidence of burning in the environment exterior to but close by the tank openings. The difference between deflagration (slow burning behind a shock front) and detonation (rapid burning at the shock front) affects both the peak pressure and the impulse of the pressure wave. Hydrogen and air mixtures burn very rapidly at atmospheric pressures but do not detonate until the temperature reaches 460°C or until the pressure is increased drastically as by using at least 2 grams of explosive charge*. Thus we assume the worst case in the analysis, namely that the hydrogen air mixture burned in the tank in a deflagration mode.

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* See Enclosure I

When the overpressurized tank opened, the internal pressure propelled the door about ten feet and crushed a cabinet and produced cracking in the preformed concrete wall behind it. The overpressure wave reflected off the walls and ceiling and blew out a roll up door (12' x 14') at the end of the room and slightly lifted the roof/ceiling which was designed to do this.

This shot was the first to have a high voltage source in the target chamber and it was not shut off after the shot. While this could have been the ignition source, these shots produce many hot fragments that can ignite hydrogen air mixtures.

The incident was reviewed and the operating procedures were changed to minimize the chance for a reoccurrence. It was decided that ignition of hydrogen in the gun room is allowable but undesirable. Thus safety measures were adopted to minimize the chance for a reoccurrence, and safety measures were adopted to allow ignition to occur and for the tank end to be blown off without causing personnel injuries. The most significant safety measures are:

- A procedure check list is used, which names each operation in sequence. This procedure minimizes the time that the hydrogen is in the gun and catch tank, includes a pump tube pressure leak check, clears the range of all personnel, details the nitrogen purge procedure, and includes the reentry sequence and gun disassembly sequence.

- The catch tank vacuum interlock prohibits firing without a 200 micron vacuum.

- Power crowbarred safety interlocks were installed to eliminate all sources of electrical power from the target chamber and catch tank two seconds after firing.

- A fast nitrogen fill system was installed including a pneumatically operated backup system.

- A remote TV camera and monitor are utilized so that the gun room could be seen visually from the control room.

- The gun room is operated as an unmanned area when hydrogen is in the gun or catch tank.

- A decelerating bumper was installed between the tank end and the wall of the building.

- Breakaway bolts were designed and installed to allow the tank door to open at 10 psi differential pressure.

- The ceiling lighting fixtures were replaced with more acceptable lamps.

- Nitrogen is used to purge the gas in the lines on the other side of the scrubber valve.

- Nitrogen is backfilled into the previously evacuated line to the vacuum pump.

- The hydrogen fill valve and the vacuum valve are interlocked so that when one is open the other is closed.

- The area around the gun room is roped off so that debris from the roof or roll up door would not hit personnel.

- An audible horn was installed to warn personnel.

- The door to the control room was strengthened.

The different cases will be evaluated in regard to this operational environment.

CASE I A TO B*

After the pump tube is filled with H_2 it is monitored; the pressure is kept within 1 psi prior to firing. If the pressure drops by 10 psi in this period (gross leak) the pump tube is evacuated, the powder is removed and the pump tube is leak checked with nitrogen. The volume of the breech is 11 liters, the volume of the pump tube is 72 liters. If the pump tube leaked into the breech from 200 psi equilibrium would occur at 175 psia. which would terminate the operating procedure.

This would have increased the H_2 from 0 to 92% volume H_2 which is above the limits for flammability. Also there is no ignition source available so that combustion will not occur. With this size leak the pressure would drop when the pump tube is evacuated. Upon reentry the copper crusher gage is slowly removed and the breech would be vented prior to removal of the powder (Calc. 1).

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* Note that all leaks of H_2 from A are minimized by an initial pressure test with nitrogen. This includes all the preshot cases.

Assume that the leak is just below the 10 psi drop limit for the pump tube, this would allow 2 moles of H_2 to enter the breech increasing the pressure from 14.7 psia to 80 psia. Again there is no ignition source and combustion will not occur. When the breech is hit by the firing initiator combustion will occur when the powder burns through the enclosing plastic bags. This is covered in the postshot analysis case.

CASE II A TO B TO D

In this case assume that the H_2 leaks out through the breech and into the room. The probability of this occuring is much smaller than Case I; however, it would produce a localized area around the leak point with high H_2 concentration this would be lifted by convective forces and be dispersed into the room atmosphere. There is no ignition source around the breech or above it until the striking actuator of the solenoid is fired. Then it would be reasonable to assume that the flame front would advance through the leak path and ignite the external H_2.

The same flame front would impell the piston down the pump tube and terminate the leak source. The flame front would advance through the combustible H_2 mixture until it was consumed.

Thus if we had a leak source from A to B to D we could ignite about two moles of H_2. The over pressure produced would be .024 psi which might rattle the door but should do no damage (Calc. 2).

CASE III A TO D

In this case assume that the seals at the AR or at the velocity measuring pins start leaking after the initial inert N_2 pressure test and H_2 is vented into the room.

This is similar to Case II. Again the 2 moles of H_2 is the maximum value prior to firing. The H_2 would be in high concentration around the leak and would be convectively dispersed into the room. There is no ignition source prior to firing; however if we do supply one, the overpressure would be .015 psi maximum and would not be a problem (Calc. 2).

CASE IV A TO C

If the seal around the petal valve leaks, H_2 could be leaked into the space behind the projectile. If the leak were gross the pressure would rise until it overcame the static friction holding the projectile in place. At this point the projectile would move down the barrel and into the catch tank. This would drop the H_2 pressure in the pump tube past the 10 psi limit. No ignition would take place for lack of a combustible mixture in the tank and there would be little chance for rupture because of the very low velocity of the projectile.

If the leak was minor it would either move the projectile or not move the projectile. But in both cases the projectile would not move the length of the barrel and no H_2 would get into the catch tank. The result of this would be from nothing if the projectile did not move, to a reduced velocity on firing depending how far the projectile moved down the barrel.

CASE V A TO C WITH D TO C

In this case two low probability cases are combined with a coincidence that they both occur in a limited time.

The chance of developing a leak in the vacuum vessel (catch tank) is very small in the preshot case. And combining it with the leak past the petal valves is also very small; so that their coincidence is a very low probability. However, if it were to happen the loss of vacuum in the tank will break an interlock and prevent firing; the decrease in the pressure will also be observed by the operator. There is no ignition source in the tank (the projectile moving into the tank will be too slow to produce an ignition source). The operator will not be able to determine the quantities being mixed, but he will follow the procedure of evacuating the pump tube and purging the catch tank before personnel are permitted to enter the room.

CASE VI A TO C TO D

This case is essentially prohibited by the operating procedure. The catch tank is evacuated prior to introducing the H_2 into the pump tube. If 200 psia of H_2 in the pump tube is expanded into the catch tank the pressure would be 2.80 psia. This is below atmosphere. If there is a small leak from the outside into the catch tank the flow will be into the tank. In the time it takes for the operator to evacuate the pump tube and fill the catch tank with N_2 negligible H_2 will escape. The one psi over pressure will be followed by the N_2 purge. This time interval is short and the H_2 will be diluted to 17.8% in N_2. This would release into the room for only a short period of time - the time it takes to open the vent valve and for equilibrium to occur (Calc. 3).

CASE VII A TO E

In this case we are venting the pump tube. This would occur on all shots which are aborted after the pump tube has been filled with H_2 and in cases when the pump tube is being reduced in pressure to the correct pressure. The vent valve output goes through a section of flexible hose which is attached to a 3/4" stub which is expanded to 1 1/2" diameter line which tees into a 2" diameter line. All lines and fittings are streamline copper fittings. The line runs up the wall thru the roof and is vented 4 feet above the roof in a downward direction. The venting process would be venting 40.8 moles of H_2 which will rise convectively above the roof and disperse into the atmosphere. If ignition would occur at the pipe opening the four foot height minimizes the chance of igniting the roof surface (Calc. 4).

CASE VIII A TO C TO E

Thise case develops from Case IV where the H_2 leaks into the catch tank without the shot being fired. The procedure is to dump a N_2 cylinder into the catch tank which dilutes the H_2 to 17% in N_2. Prior to this the N_2 purge line has been flowing N_2 to the other side of the scrubber valve, Section 8 Firing Preparation, this flushes the air from the lines and the filters. When the scrubber valve (#1) is opened, pressure equilibrium occurs and the H_2 drops to 72.2 grams. Opening valve #4 allows "house" N_2 to flush the catch tank of the 17% H_2 mixture. The N_2 flows at 70 cfm, if one assumes complete mixing the H_2 concentration will drop per Figure 3. If no mixing occurs it will drop at a slightly faster rate (Calc. 5).

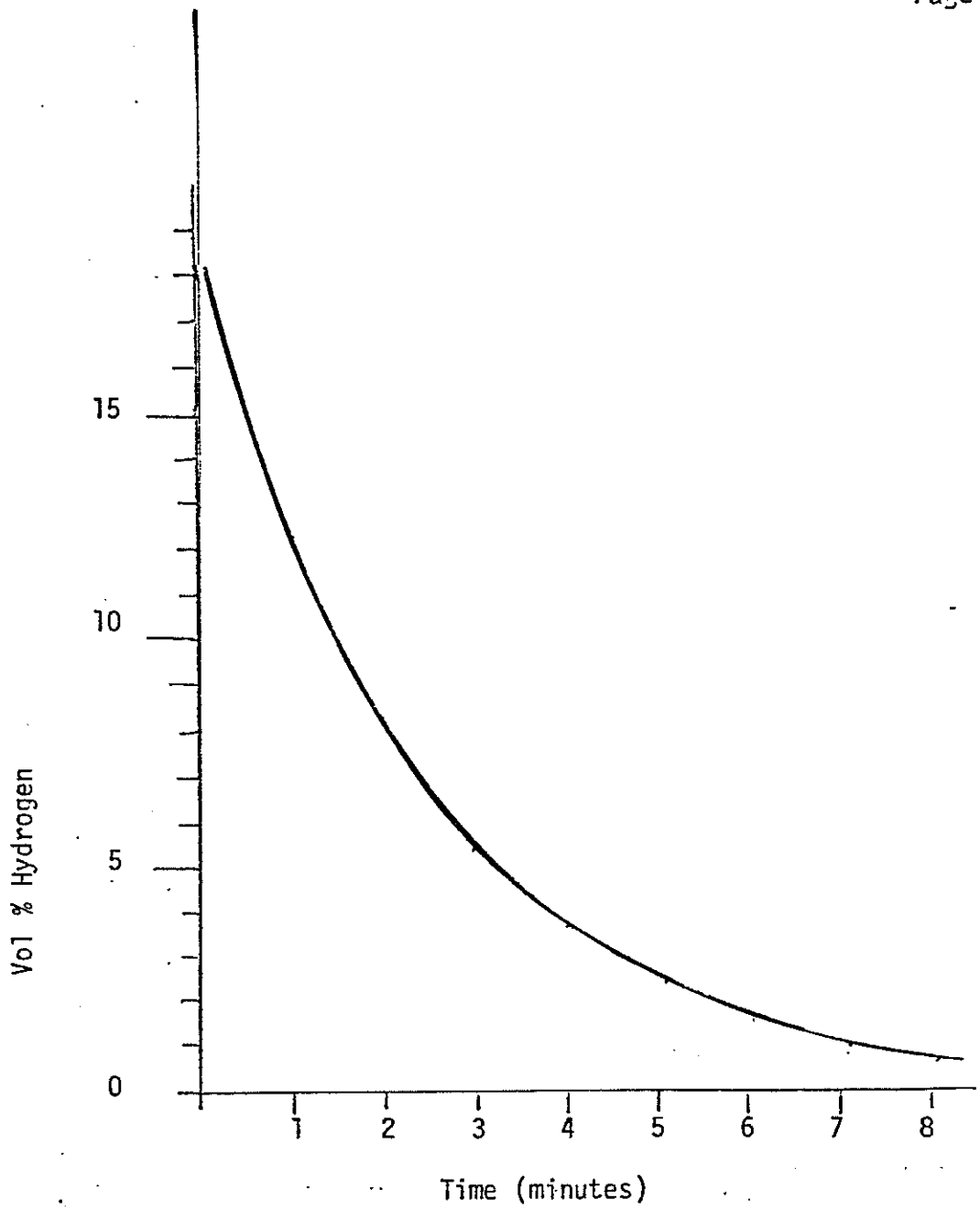


FIGURE 3 % H_2 vs. N_2 Flow Time

To get the H_2 concentration down below 4% will require purging for 11 minutes for the maximum H_2 load.

After the purge the valves are closed and the vacuum system pumps the catch tank down to 4 psia to remove more H_2. The tank is then let up to air.

CASE IX A TO D TO E

This case has the same limits as Case III with the addition that the gas is dispersed to the outside atmosphere which presents no problems.

CASE X D TO C

Here seals leak which allow the loss of vacuum in the catch tank, which closes the interlock and prohibits firing. The procedure is to remove the H_2 from the pump tube (Case VII) prior to reentry. Note that the operator can determine that the H_2 is not leaking into the catch tank by reading the pressure indicator in the control room. Again no problems are encountered.

CASE XI E TO C

This is a leak in the valving and produces the same results as Case X.

POSTSHOT (Starting from powder ignition)

CASE XII A TO B

If H_2 has leaked into the breech before firing, or is leaking around the piston during its course down the pump tube, the result is the same. The H_2 in the breech will burn, however the gunpowder is oxygen limited and thus the energy generated may vary slightly or the pressure rise at a slightly faster rate but this will have no effect other than to change the piston velocity slightly. Four grams of H_2 in relation to 425 to 3,000 grams of gunpowder is not a significant change.

CASE XIII A TO B TO D

This was discussed in Case II. If the leak occurs after ignition its duration will be short and will be terminated when the piston seals in the AR. The gas in the pump tube is vented shortly after firing thus only small amounts may escape and the percentage H_2 will be small compared to the 2,000 psi oxidation gas products. This is not a problem.

CASE XIV A TO D

Leaks around the seals of the AR can occur as the piston compresses the H_2 up to 200,000 psi. However the pressure pulse lasts about 8 millisecs and the gas expelled will jet away rapidly. The possiblity of this leak is very small; the leak should produce a very shrill whistle, and none has ever been heard. The seals are triangular cross-section stainless steel and brass rings with double "O" rings inside. The AR and connecting joints are encased by the AR housing. The housing plug is torqued to 12,800 ft. lbs., compressing the AR against the rings. The inner seal is stainless and the outer seals are brass. The brass seals expand to the diameter and are replaced after each shot. The stainless steel ring is replaced less frequently. Also there is no ignition source in this area, and none is supplied by the operation of the gun. It is difficult to place an upper limit on the amount of gas that could escape should a seal leak. If the "O" rings are in place they would be extruded into the leak path and would reseal it. This should limit it to about 2 moles. If the first two "O" rings were not in place a leak would occur in the N_2 pressure test and would be diagnosed. (The last four are on the other side of the petal valve). This is not a problem.

CASE XV D TO C

In this case either a piece of shrapnel ruptures the wall of the catch tank or a seal leaks. These leaks are initiated after firing. The catch tank has never been ruptured by shrapnel, but the magnesium x-ray windows have been ruptured twice. Cylindrical steel shields have been installed around these to minimize the chance of rupture. At 2 seconds after firing all electrical sources are removed from the catch tank. This eliminates electrical ignition sources after 2 seconds. The nitrogen from the N_2 cylinder is being pumped into the tank which raises the pressure to about 1 psi above atmospheric. It takes approximately one minute for the catch tank to come up to atmospheric pressure due to the N_2 fill. If one assumes a linear increase in N_2, the tank will sustain a 20 cu. ft./min. air leak without allowing the O_2 level to rise above 5%. The most critical time for combustion is in the first 8 seconds; however in this period there is very little oxygen in the tank: a 20 cfm leak gives .63 moles, 40 cfm gives 1.3 moles. Igniting this would raise the pressure and reduce the rate of leaking into the tank. After 8 seconds the nitrogen flow will allow larger leak rates without exceeding the 5% oxygen limit (See Figure 4).

If a .492" diameter hole (producing a leak of 40 cfm) is created by shrapnel at impact, and the N_2 is dumped into the tank within one minute; then assuming that ignition can occur at 8 seconds after impact (although the O_2 level is only 1.64% if mixed) burning the three-fourths of the O_2 would raise the temperature to 370°C and increase the pressure to 11.35 psia. This would reduce the inflow of air but not produce any damage.

If a .650" diameter hole (producing a leak of 80 cfm) is created, and if the N_2 is dumped into the tank within one minute; the temperature will rise to 668°C if ignition occurs. The pressure will increase to the 17.8 psia. This assumes ignition occurs 8 seconds after impact, and three-fourths of the O_2 is burnt. The N_2 is coming into the tank initially at about 200 cfm, and this reduces the O_2 concentration to below the flammability limit very quickly (Calc. 6). There is no problem if the shrapnel leak is at 100 cfm or below. This is equivalent to a shrapnel hole of .70" diameter, which is about twice the diameter of the largest hole encountered.

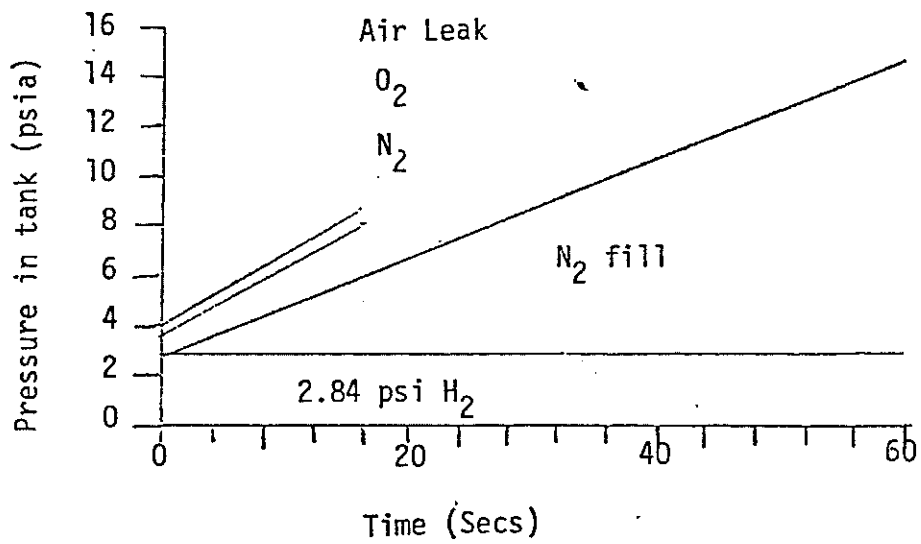


Figure 4

CASE XVI C TO D

This case follows Case XV. After the pressure has risen to 2 psi above atmospheric, the flow in the leak path would reverse and would flow into the gun room. In this situation the mixture of N_2, O_2 and H_2 would flow until the scrubber valve is opened (Average time estimate 30 secs.) If the scrubber valve was not opened and flow was allowed until equilibrium was reached, 5.11 moles of H_2 would be leaked into the room. However, there would be no ignition source available and no ignition would occur. If an ignition source was supplied the leak rate is low enough that burning would occur with a very minimal pressure rise (Calc. 7).

CASE XVII A TO E

This case could arise on a misfire where the piston is released or not released but does not have enough energy to break the petal valve or does break the petal valve but does not send the projectile out of the muzzle. This is then very similar to Case VII except that when the pump tube is evacuated either powder gas or H_2 may be vented. Venting one will reduce the pressure on one side of the piston; this may cause it to shift and then allow the other gas to vent. However, there is no ignition source present, if there had been the powder would have burnt and no misfire would have occurred.

CASE XVIII A TO C TO E

This occurs on normal shots (see Equipment and Operation). The H_2 forces the projectile out of the muzzle and into the target chamber.

The gas follows raising the catch tank pressure to a maximum of 2.84 psia. The five vacuum valves and two vent valves are interlocked so that none will open. The scrubber valve is vacuum interlocked so that it will not open (this is to protect the filters from a back flow). The line behind the scrubber valve has nitrogen flushing through it at 10 cfm. Immediately after firing, a cylinder of N_2 is dumped into the catch tank. The initial pressure in the cylinder is 2,000 psi and the final pressure when the catch tank is about one psi above atmospheric is about 200 psi. The scrubber valve is opened and "house" nitrogen is flushed at 25 cfm.

When the valve is opened the H_2 in the catch tank is at 18% (34.59 cu. ft.) and at 15.7 psia. This expands into the N_2 flushed lines (50 cu. ft. vol.). When the pressure drops to 14.7 psia, there is 18% (32.39 cu.ft.) in the catch tank. If the flush time is 6 minutes at 70 cfm, the resultant H_2 concentration will be from 1.73% (3.09 cu. ft.) assuming complete mixing to .79% (1.41 cu. ft.) assuming partial mixing. If at this time, the scrubber valve is closed and the vacuum valve is opened (the backside of the valve has been filled with N_2 giving 14.09 cu. ft.) and the vacuum pump started. The vacuum pump reduces the pressure to 4 psi, at this point there is a maximum of 0.84 cu. ft. of H_2 and 51.70 cu. ft. N_2 in the tank and vacuum lines. The vacuum lines are valved off and air is vented into the target chamber and flushed through the scrubber valve (Calc. 8). This process has previously been thoroughly reviewed and the only change recommended is to increase the nitrogen flush time.

CASE XIX E TO C

Here a leak occurs either through the vacuum pump, roots blower and vacuum valve or thru the scrubber valve.

The leak must occur after firing but less than one minute later. If the leak occurred through the scrubber valve immediately, 50 cu. ft. (minimum) of N_2 (Calc. 9) will be dumped into the tank before air would enter. Thus, we can stand a leak of 50 cfm without chance of ignition. The chance of a leak thru the vacuum system is much smaller because of the clearances of the vacuum pump. Here we could stand a 14 cfm (minimum) leak without letting air in the tank. In either case there is no ignition source in the tank after 2 seconds. If we assume some air does get in, 44 cu. ft. of air would be needed to bring the oxygen above the 5% volume required. This has previously been reviewed and no changes are recommended.

CASE XX B TO A

Leakage of the powder gas around the piston and into the H_2 gas may occur, however, the powder gas is completely oxidized and ignition cannot occur.

CASE XXI A TO C

This is normal and is covered in CASE XVIII.

CATCH XXII FILL THE CATCH TANK WITH AIR AND IGNITE IT

This is the calculation which answers the question, "What if everything failed"? The addition of 85 cu. ft. of air to the catch tank will produce a stiochiometric mixture. This will occur at 9.77 psia. If this was completely ignited it would produce 2.8×10^6 calories or 8.62×10^6 ft. lbs., or the energy of 5.59 lbs. of TNT (Calc. 10).

The following calculation assumes that complete burning occurs.

The static overpressure (assuming no venting)

$$P = 4000 \frac{hW}{V} \text{ psi (adiabatic pressure increase due to heat input)}$$

Where h = heat of combustion = 34.15 k cal/gm

W = weight in lbs. = $\frac{82}{454}$ lbs

V = room volume = 50,000 ft^3 (25' x 20' x 100')

$$P = \frac{4000 \times 34.15 \times 82}{50{,}000 \times 454} = .493 \text{ psi or } 71 \text{ lbs/ft}^2$$

The following calculations are based on the assumption that you detonate 5.59 lbs of TNT.

The shock pressure - time estimate

One way to calculate a peak pressure and impulse is to use TM 5-1300 (See END 76-908, pg. 20).

From Fig. 4-15 N = 3 (25' wide, 20' high and 100' long),

$$\frac{h}{H} = \frac{1}{2}; \frac{\ell}{L} = \frac{1}{2}; \frac{L}{H} = 5 \quad \frac{L}{Ra} = 8 \text{ and } Z_a = \frac{Ra}{(W)^{1/3}}$$

$$= \frac{12.5}{(5.59)^{1/3}} = 7.05$$

From Chart 4-51 (Assume $\frac{L}{H} = 6$) the scaled unit blast impulse

$$\bar{i}_b = 15 \text{ psi . ms/}^{1/3} \text{ lb}$$

$$\bar{i}_b = 15 \text{ psi . ms/}^{1/3} \text{ lb} \times (5.59)^{1/3} = 26.59 \text{ psi . ms}$$

an estimate of the time duration is given by

$$t_o = \text{duration of loads (ms)} = \left[t_A\right]_F - \left[t_A\right]_A + 1.5\left[t_o\right]_F$$

equation 4-1

$$t_o = W^{1/3}\left[\left(\frac{t_A}{W^{1/3}}\right)_F - \left(\frac{t_A}{W^{1/3}}\right)_A + 1.5\left(\frac{t_o}{W^{1/3}}\right)_F\right]$$

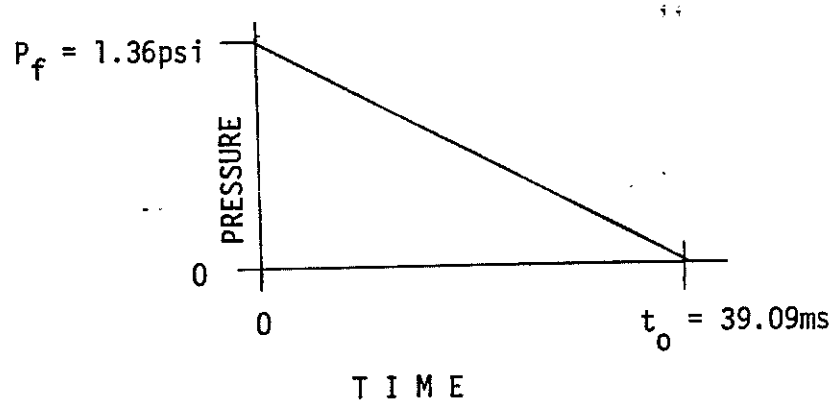
$$Z_F = \frac{R_F}{W^{1/3}} = 28.21 \qquad Z_A = \frac{R_A}{W^{1/3}} = 7.05$$

From Figure 4-5

$$t_o = 1.77\left[20 - 2.6 + 1.5\ (3.1)\right] = 39.09 \text{ ms.}$$

From Equation 4-2

$$P_f = \frac{2i_b}{t_o} = \frac{2*26.59}{39.00} = 1.36 \text{ psi or } 196 \text{ lb/ft}^2$$



Using the wall strength calculated in END 76-908 we have an Ultimate Resistance of 3.3 psi and an elastic resistence of 1.5 psi. This puts the wall at 90.6% of its elastic resistence. However, this must be modified by the following considerations, the hydrogen-air mixture will burn and not detonate (See Enclosure 1). To be realistic consider that the target chamber-catch tank is 17.5 ft. long. If ignition occurred at the center and propagated at one third the velocity of sound, the complete burning would occur in 26 ms. Instead of the instantanous energy release assumed in the TNT case. The end door of the tank will open at 15 psi above atmosphere (END 78-926) if this occurred at 16 ms the gas would flow into the room over a period of greater than 35 ms making the peak pressure much lower and the time duration much longer. This makes the "TNT equivalent" assumption very improbable.

Another way to model the peak pressure and impulse is to use the computer code KO which gives better initial conditions - a volume of compressed gas. KO uses an initial spherical volume of gas at an elevated pressure and lets it expand. To develop a worst case assume that the door opens at 100 psi (this is a factor of 6.6 high), treat the gas as a sphere 3.5 ft. radius (a 2.5 ft. radius would be more normal, but the 3.5 R gives the 179 cu. ft. tank volume) and let this expand. The result is shown on Figure 5, 6, 7, and 8. Figure 5 shows the pressure at 90" away. This would produce an over pressure of 9.56 psi for about 3 milliseconds. This wall has an 8" I beam directly behind it. Figure 6 shows the pressure at 17 feet away. This would produce an overpressure of 2.06 psi for 6 millisecs, followed by a negative pressure of 1.47 psi for 6 millisecs. This is the distance to the ceiling. The pressure pulse would raise the roof then pull it back down.

Figure 7 is 25 feet away; it would produce an overpressure of .88 psi for 8 ms followed by a negative pressure of 1.03 psi for 8 ms. This would be felt on the outside wall. And finally Figure 8 which is 68 feet away: it would produce an overpressure of .29 psi for 12 ms.

The wall 90" away is backed by an I beam and shielded by the hinge of the door in front of it so that its load will be considerably reduced. The ceiling is allowed to go and an overpressure of 1.18 psi on the outside wall would be 78% of the elastic resistence of the wall. This is more realistic than the TNT Case, but this would be lower if the door opens below 100 psi. If the door opens between 10 and 20 psi differential then all the pressures drop by a factor of at least 5 and the pulse duration increases correspondingly. This is a much more probable and less hazardous case.

IMPACT OF CATCH TANK DOOR

The calculations of END 76-908 assume an initial overpressure of 156 psi accelerating the door, plate, and hinge (3300 lbs.) to a velocity of 33 ft./sec. The decelerating device is a water filled Energy Systems. Absorption System which consists of water filled cylinders with orifices at the top. They are 40" deep 57" wide and 52" to the wall.

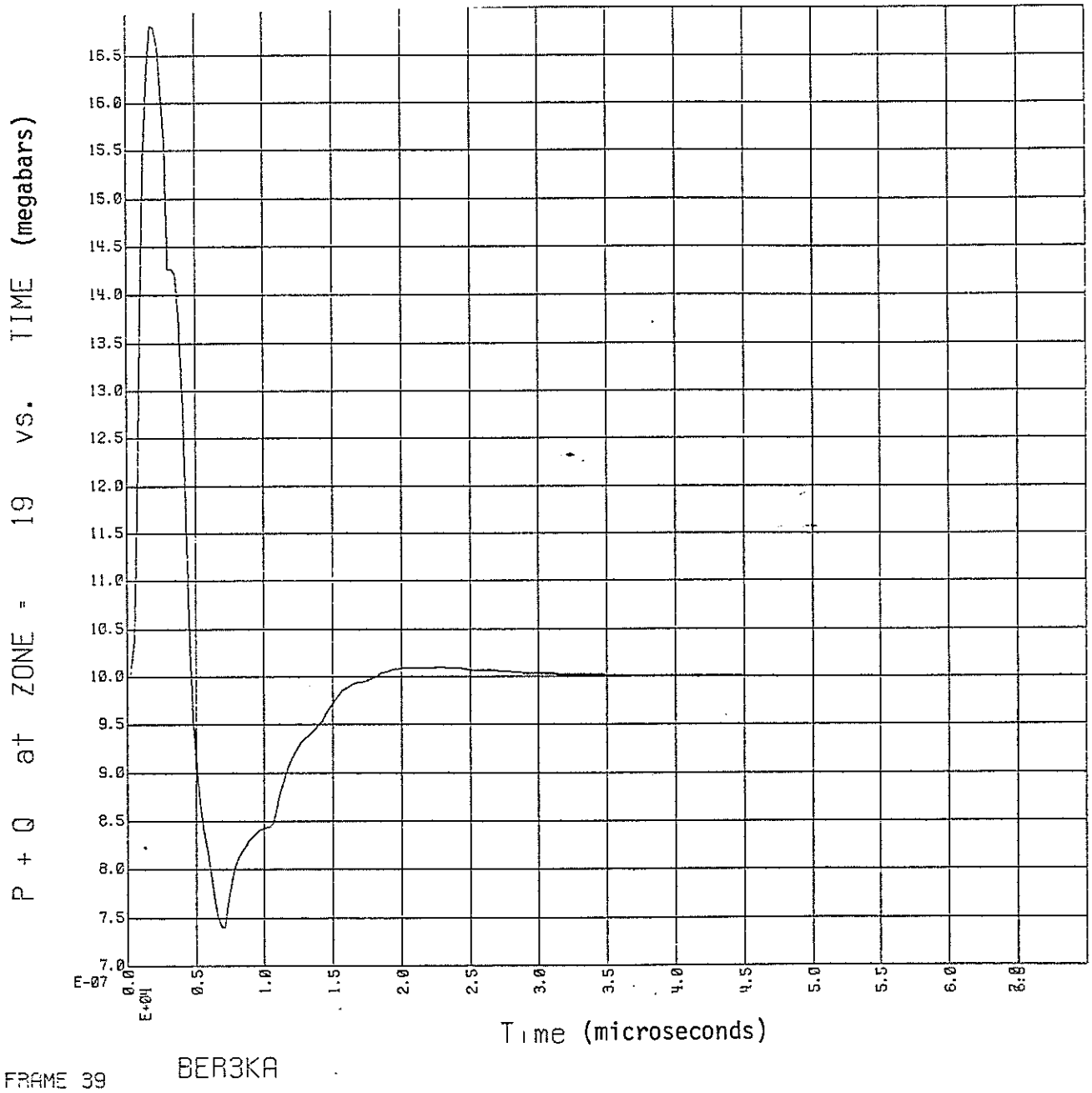


Figure 5 KO PRESSURE PULSE 90 INCHES AWAY

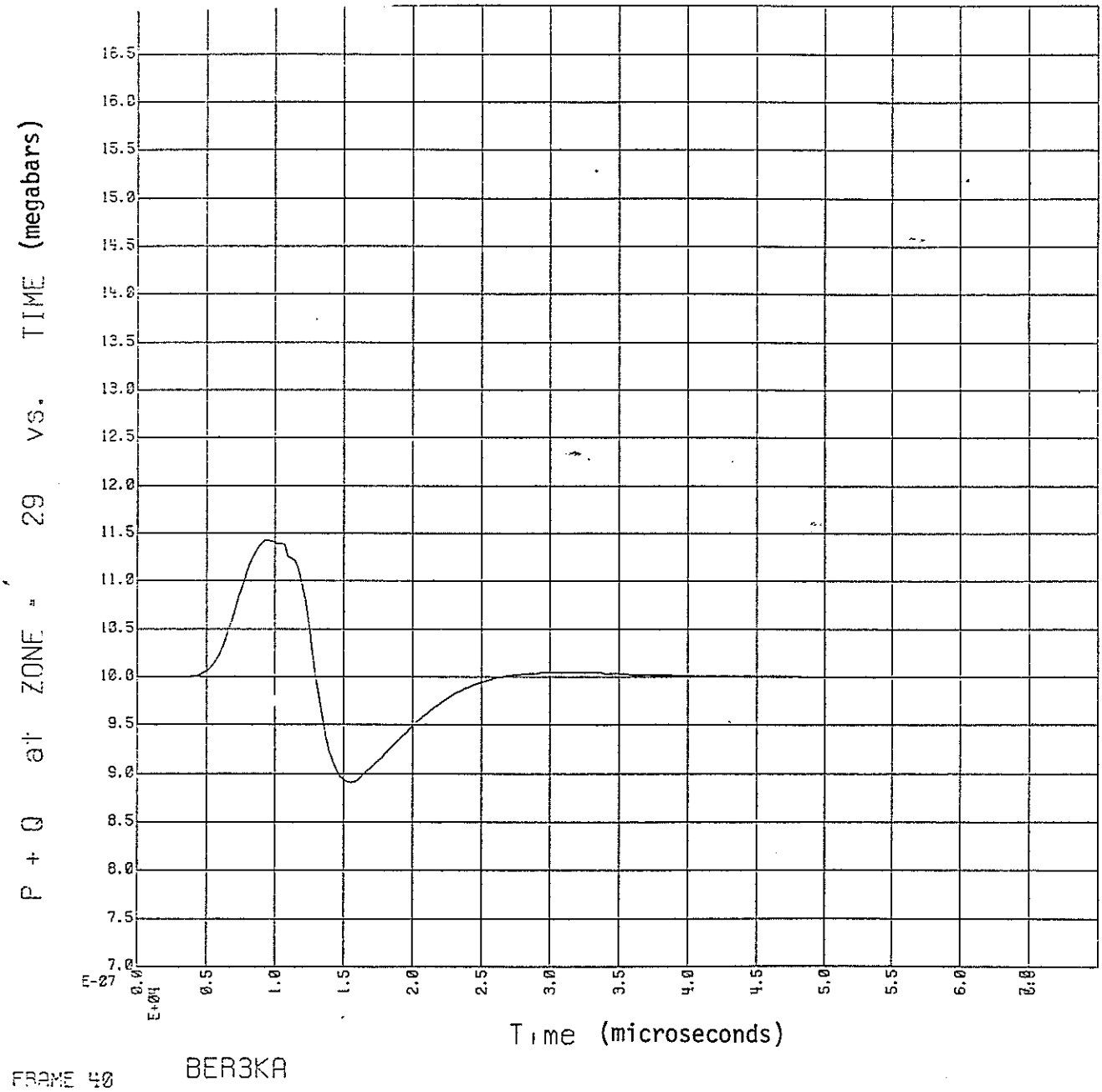


Figure 6 KO PRESSURE PULSE 17 FT AWAY

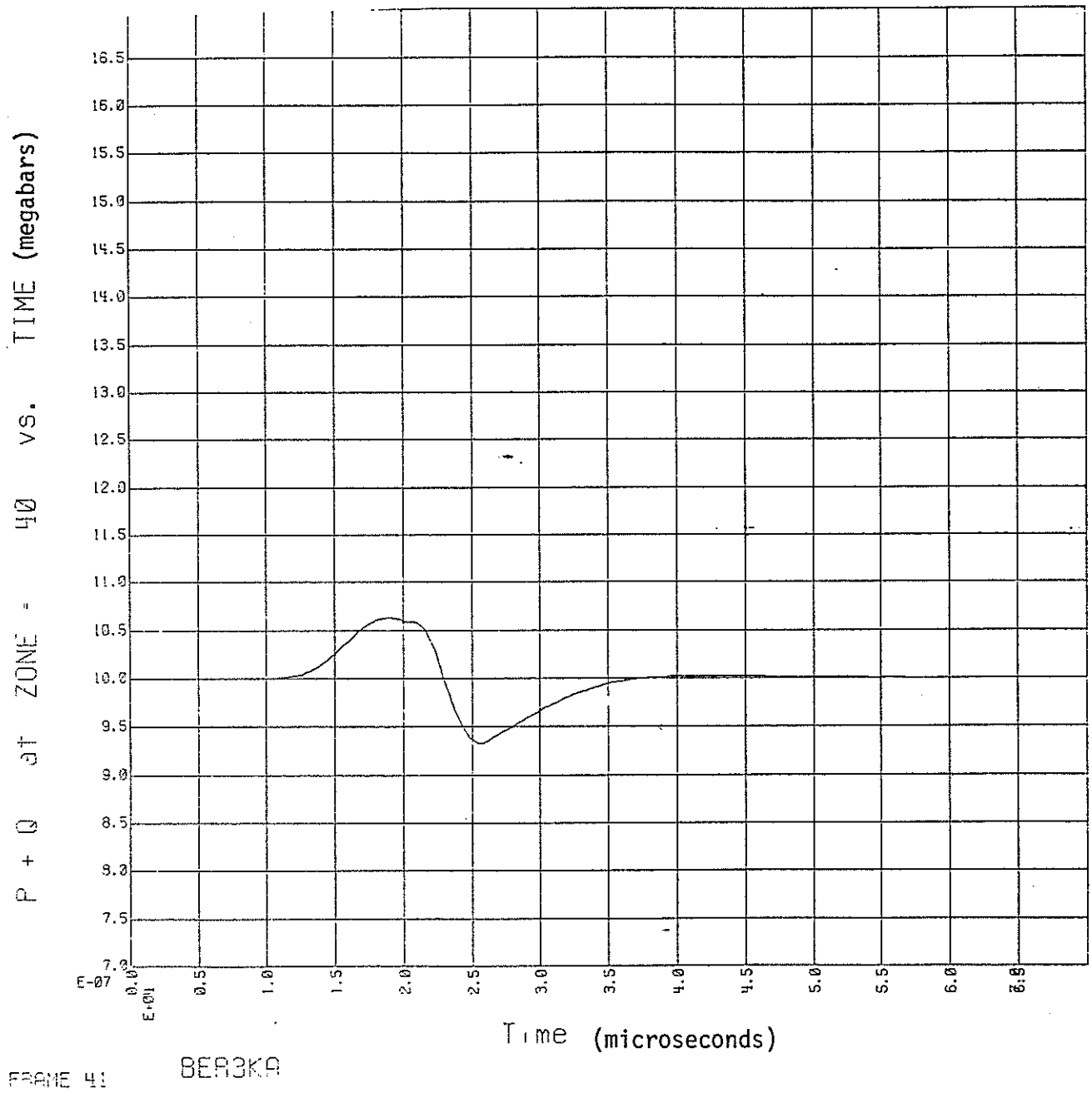


Figure 7 KO PRESSURE PULSE 28 FT AWAY

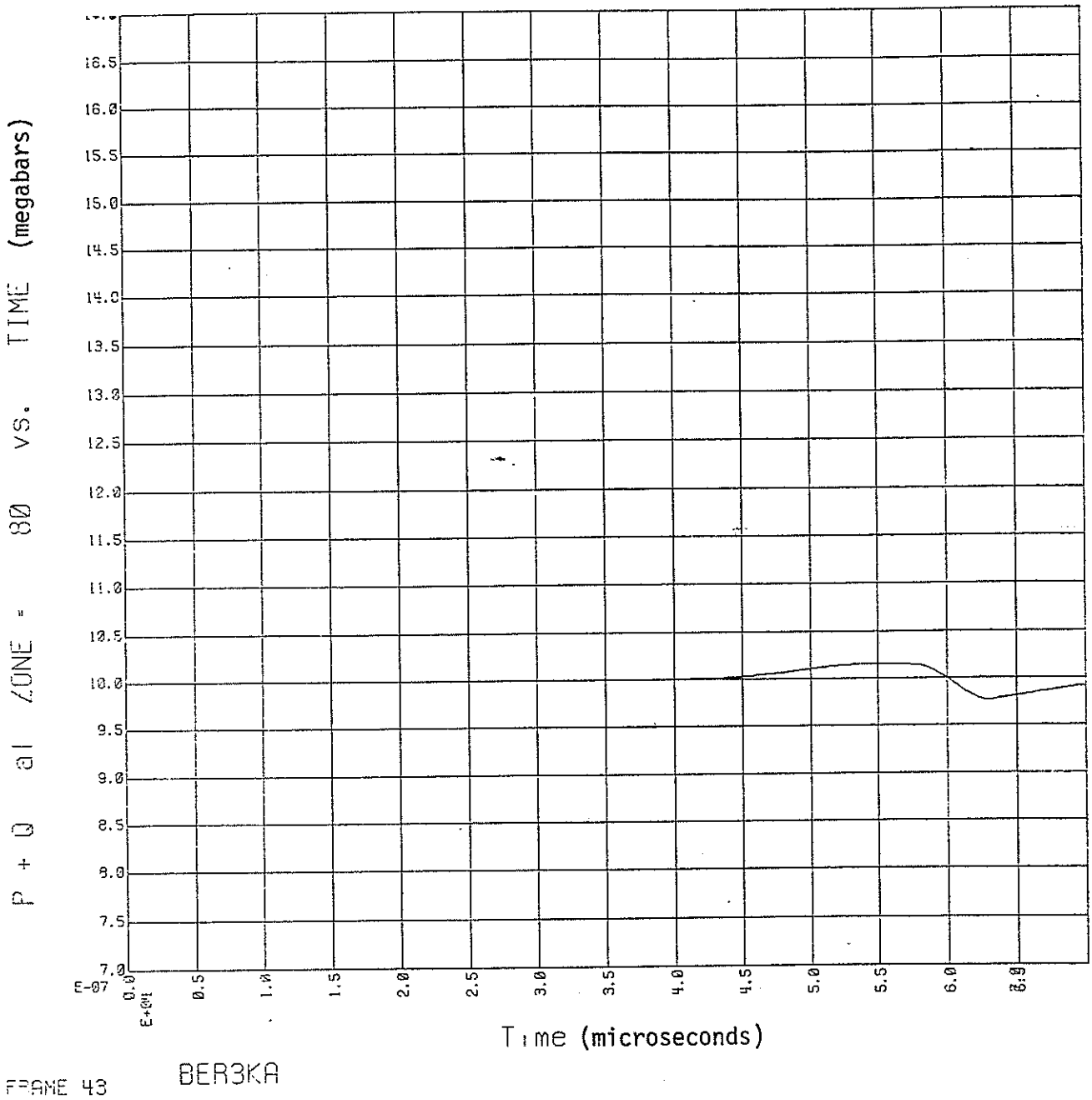


Figure 8 KO PRESSURE PULSE 68 FT AWAY

If the door, hinge, and plate start with an initial velocity of 44 ft./sec. (estimate of maximum credible initial velocity)

$$\frac{V^2}{2S} = a$$

$$\frac{44^2}{2(4.33)} = 223.38 \text{ ft/sec}^2$$

$$F = ma$$

$$F = \frac{3300}{32.2} * 223.38 = 22{,}893 \text{ lbs. (the required decelerating force)}$$

$$P = \frac{F}{A}$$

$$P = \frac{22{,}893}{40*57} = 10.04 \text{ psi}$$

With this pressure the water should rise 23 ft. However, the door will open at a lower pressure, (set for 24.7 psia) will have a lower velocity and thus require a lower decelerating force.

CALCULATIONS

Calculation 1

$P1 = 200$ psia $\quad P_2 = 14.7$ psia $\quad P_3 = ?$

$V1 = 72$ liters $\quad V2 = 11$ liters $\quad V3 = 83$ liters

$$P3\ Vs = P1V1 + P2V2$$

$$P3 = (P1V1 + P2V2)/V3$$

$$P3 = (200 \times 72 + 14.7 \times 11)\ /83 = 175.4 \text{ psia}$$

% H_2 = (175.4 - 14.7)/175.4 = 91.6% H_2

P1 = 10psi drop V1 = 72 liters

P2 = ? V2 = 11 liters

P_2 = P1V1/V2 = 10 x 72/11 = 65.45

P_3 = 65.45 + 14.7 = 80.15 psia

Calculation 2

The source of the leak is P2 of Calculation 1. Convert this to liter-atmospheres and divide by 24 liters/mole at room temperature.

Liter-Atm = (P1V1)/P2 = 65.45 x 11/14.7 = 48.98

Moles = Liter-Atm/24 = 2.04 moles H_2

The static over-pressure (assuming no venting)

ΔP = 4000 HW/V

Where h = heat of combustion = 34.15 K cal/gram

W = weight in lbs = 2 x 2.016/454 = .0089 lbs

V = room volume = 50,000 cu ft (20' x 25' x 100)

ΔP = 4000 x 34.15 x 34.5 x .0089/50000 = .024 psi

Calculation 3

P1 = 200psia V1 = 72 liters V2 = 5069 + 72 = 5141

P2 = P1 V1/V2 = 200 x 72/5141 = 2.80 psia

$\%H_2 = 2.80 \times 100/15.7 = 17.8\% \ H_2$

Calculation 4

Liter Atm = 200 x 72/14.7 = 979.59

Moles of H_2 = Liter-Atm/24 = 40.8

Calculation 5

The tank has the H_2 and is filled with N_2 to 15.7psia, a valve is opened to 14.7 psia and some H_2 escapes. The N_2 is flushed into the tank at 70 cfm. Assuming complete mixing the % H_2 will drop logrithmically.

$\frac{dH}{dt}$ = Amount In - Amount Out (cu ft/min)

The amount of H_2 originally in the tank =

Liter-Atm = 200 x 72/14.7 = 979.59 Liter-Atm

after the scrubber valve opened the H_2 is:

Liter-Atm = 979.59 X 14.7/15.7 = 917.20L-A = 32.39 cu ft.

which is 18.1% H_2, the tank volume being 179 cu ft.

The amount out = $\frac{H}{179} \frac{dV}{dt}$ (cu ft/min.) where $\frac{dV}{dt}$ = N_2 flow

$$\frac{dH}{dt} = 0 - \frac{H}{179} \frac{dV}{dt}$$

$$dV = \frac{-179}{H} dH$$

$$V = \frac{179}{} = -179 \ln H + C$$

at t = o V = 0 and H = 32.39 cu ft.

C = 621.98 cu ft.

V = 179 ln H = 621.98 cu ft.

H = e_{xp} (621.98 - V)/179 cu ft.

evaluating H by calculating the V's at required time limits

Time Min.	V ft^3	H ft^3	V% H_2
1	70	21.84	12.20
2	140	14.77	8.25
3	210	9.99	5.58
4	280	6.76	3.77
5	350	4.57	2.55
6	420	3.09	1.73
7	490	2.09	1.17
8	560	1.41	.79
9	630	.96	.53
10	700	.65	.36

Calculation 6

There is 34.59 cu ft. of H_2 in the tank

$$P2 = P1V1/V_2 = 34.59 \times 14.7/179 = 2.84 \text{ psia of } H_2$$

Using the 5% O_2 limit from Figure 2.

X = psi due to leak

at the 5% O_2 limit at t = o

$$\frac{.205X}{X + 2.84} = .05 = 5\% \ O_2$$

$$.205X = .05 \ (X + 2.84)$$

$$.155X = .142$$

$$X = .142/.155 = .916 \text{ psia}$$

V = .916 x 179/14.7 = 11.1 cu ft of air at time = 0

The 5% O_2 limit at t = 6secs $H_2 + N_2$ fill = 4 psia (Fig. 4)

O_2 Pressure = .205X = .05(X + 4)

$$.155 \ X = .2$$

$$X = .2/.155 = 1.290 \text{ psia}$$

V = 1.290 X 179/14.7 = 15.7 cu ft which has flowed in 6 secs.

$$\text{cfm} = \frac{15.7}{6} \ X \ 60 = 157 \text{ cfm of air}$$

Using a 20 cfm leak of air

.2 X 20 x 8/60 = .5333 cu ft = .15.1024 liters

15.1024/24 = .629 moles of O_2

With a 40 cfm air leak starting at projectile impact, after 8 seconds the air in the tank would be:

$$\text{Air} = \frac{40\text{scfm} \times 8}{60 \text{ sec}} = 5.33 \text{ scf} = 151.02 \text{ liter-atm}$$

Air O_2 .20 x 151.02 = 30.20 literatm O_2 = 1.26 moles

N_2 + others = .80 X 151.02 = 120.81 liter atm N_2 + others =

$$N_2 \text{ fill} = \frac{15.7 * 8 * 179}{60 \quad 14.7} = 25.49 \text{ scfm} = 721.80 \text{ liter atm } N_2$$

N_2 fill + N_2 + others = 842.61 liter atm N_2 = 35.11 moles

H2 = 976.19 liter atm H_2 = 40.67 moles

Although the O_2 is only 1.64% volume, its original concentration was 20% at the leak point and its flammability limit is 5%. Assume it is not mixed and that we can burn it to its flammability limit.

$$1.26* \frac{.15}{.20} = .945 \text{ moles } O_2$$

burning this would produce:

ΔE = 68.3 K Cal/Mole H_2 *2* .945 = 129,090 Cal

$$\Delta E = E_1 - E_o = \frac{5}{2} R (M_1 T_1 - M_o T_o)$$

where R = gas constant = 2 $\frac{\text{cal.}}{\text{Mole } ^oK}$

$$Mo = 1.26 + 35.11 + 40.67 = 77.04 \text{ moles}$$

$$M_1 = 1.89 + 35.11 + (1.26 - .945) + (40.67 - 1.89) = 76.10$$

$$T_o = 300\ ^oK$$

$$M_1T_1 = \frac{2}{5}\ \frac{\Delta E}{R} + M_oT_o$$

$$T_1 = \frac{\frac{2}{5}\frac{\Delta E}{R} + M_oT_o}{M_1}$$

$$T_1 = \frac{2}{5}\ \frac{(129{,}090) + 77.04\ (300)}{*2\ X\ 76.10 \qquad 76.10} = \frac{48930}{76.10} = 642.9^oK$$

$$P_1V_o = M_1RT, \quad P_oV_o = M_o\ RT_0$$

$$\frac{M_1\ RT_1}{P_1} = V_o = \frac{M_o\ RT_o}{P_o}$$

$$P_1 = \frac{M_1T_1P_o}{M_oT_o} = \frac{76.10\ (642.97)\ P_o}{77.04\ (300)} = 2.12\ P_o$$

$$P_o = \frac{(1.26 + 35.11 + 40.67)\ *\ 24\ *\ 14.7}{5069} = 5.36 \text{ psia}$$

$$P_1 = 11.35 \text{ psia}$$

With an 80 cfm air leak starting at projectile impact, eight seconds later the amount of air in the tank would be

$$\text{Air} = \frac{80*8}{60} = 10.66 \text{ scf} = 302.04 \text{ liter-atm}$$

$$O_2 = 20*302.04 = 60.40 \text{ liter atm } O_2 = 2.52 \text{ moles}$$

Air

$$N_2 + \text{others} = .80*302.04 = 241.62 \text{ liter atm } N_2 + \text{others}$$

$$N_2 \text{ fill} = \frac{15.7*8*179}{60*14.7} = 25.49 \text{ scf} = 721.80 \text{ liter atm } N_2$$

N_2 fill + N_2 + others = 963.42 liter atm N_2 + others = 40.14 moles

H_2 = 976.19 liter atm H_2 = 40.67 moles

Here the O_2 is 3.02% volume if mixed.

Igniting $2.52 * \frac{.15}{.20} = 1.89$ moles of O_2 will produce

ΔE = 68.3 K Cal/Mole H_2 *2*1.89 = 258,174 cal.

$$\Delta E = E_1 - E_o = \frac{5}{2} R (m_1 T_1 - m_o T_o)$$

m_o = 2.52 + 40.14 + 40.67 = 83.33 moles

m_1 = 3.78 + 40.14 + (2.52 -1.89) + (40.67 -3.78) = 81.44 moles

$$T_1 = \frac{\frac{2}{5}\frac{(258,174)}{2} + 83.33\ (300)}{81.44} = 940.98\ ^oK$$

$$P_o = \frac{(83.33)*24*14.7}{5069} = 5.8 \text{ psia}$$

$$P_1 = \frac{81.44\ (940.98)\ 5.8}{83.33\ (300)} = 17.78 \text{ psia}$$

CALCULATION 7

Consider that the tank is at 16.7 psia

Cu ft H_2 = 2 psi * 179 * .178/14.7 = 4.33 cu ft H_2 - 122.75 liter atm

Modules of H_2 = 122.75/24 = 5.11 Moles of H_2

CALCULATION 8

The 2.84 psia H_2 is from calculation 6 the 34.59 cu ft, 32.39 cu ft and the 3.09 cu ft are from Calculation 5.

The partial mixing estimate is applicable since the N_2 flush line is away from the scrubber valve. It is an estimate. If no mixing took place adding 420 cu ft to a 179 cu ft tank would drop the concentration to 0%.

$$\frac{310\pi\ (5)^2}{12^3} = 14.09 \text{ cu ft}$$

$$3.09 \text{ cu ft} * \frac{4}{14.7} = 0.84 \text{ cu ft}$$

$$\frac{(179 + 14.09 - 3.09)\ 4}{14.7} = 51.70 \text{ cu ft of } N_2$$

CALCULATION 9

The volume of the lines are

$$V_1 = \frac{19" * 23" \text{ X } 23"}{12^3} = 5.8166 \text{ cu ft}$$

$$V_2 = \frac{13\ 3/4" * \pi\ (3.5)^2}{12^3} = .3062 \text{ cu ft}$$

$$V_3 = \frac{51" * \pi\ (2.75)^2}{12^3} = .7012 \text{ cu ft}$$

$$V_4 = \frac{73\ 1/4" * \pi\ (3.0)^2}{12^3} = 1.1986 \text{ cu ft}$$

$$V_5 = \frac{90'' * \pi (3.0)^2}{12^3} = 1.4726 \text{ cu ft}$$

$$V_6 = \frac{70'' * \pi (18)^2}{12^3} = 41.2334 \text{ cu ft}$$

TOTAL 50.73 cu ft

CALCULATION 10

$$\frac{34.59}{2 * .205} = 84.37 \text{ cu ft of air}$$

$$H_2 + \text{Air} = \frac{(84.37 + 34.59)}{179} * 14.7 = 9.77 \text{ psia}$$

See Calc. 4, 40.8 * 2.016 X 34.15K Cal/gm = 2808 K Cals.

$$2.808 * 10^6 * .737 \frac{\text{ft lbs}}{\text{Joule}} * 4.186 \frac{\text{Joules}}{\text{Cal}} = 8.662 \text{ X } 10^6 \text{ ft lbs}$$

$$\frac{8.662 * 10^6}{1.55 * 10^6} = 5.589 \text{ lbs of TNT.}$$

TESTING

No testing required.

CHANGES TO ASSOCIATED PROCEDURES

CHANGE THE PROCEDURE CHECKLIST

Post Shot Section, from 4 minutes of N_2 flow to 6 minutes of N_2 flow for shots having 200 psi H_2 in the pump tube.

Subscripts

- f = conditions at outer edge of combustion zone
- g = property of gas
- r = property of reactant species
- S = property of solid
- W = conditions at propellant surface

References

1 Green L., Jr., "Some Properties of a Simplified Model of Solid-Propellant Burning," Jet Propulsion, vol. 28, 1958, p. 386.

2 Hart, R. W. and McClure, F. T., "Combustion Instability: Acoustic Interaction with a Burning Propellant Surface," *J. Chem. Phys.*, vol. 30, 1959, p. 1503, or see Appl. Phys. Lab. Rep. TG-309, Johns-Hopkins Univ., Oct. 1958.

3 Bird, J. F., Haar, L., Hart, R. W. and McClure, F. T., "Effect of Solid Propellant Compressibility on Combustion Instability," *J. Chem. Phys.*, vol. 32, 1960, pp. 1423–1420.

4 Shinnar, R. and Dishon, M., "Heat Transfer Stability Analysis of Solid Propellant Motors," in *Solid Propellant Rocket Research* (M. Summerfield, ed.), Academic Press, N. Y., 1960, pp. 359–373.

5 Smith, A. G., "A Theory of Oscillatory Burning of Solid Propellants Assuming a Constant Surface Temperature," ibid., pp. 375–391.

6 Cheng, S. I., "Resonance Burning in Solid-Propellant Rocket Engines," presented at Eighth Symposium on Combustion, Calif. Inst. of Tech., Pasadena, Calif., Aug. 29–Sept. 2, 1960.

7 Von Kármán, T., "The Present Status of the Theory of Laminar Flame Propagation," Sixth Symposium (International) on Combustion, The Combustion Inst., Aug. 19–24, 1956; Reinhold Publishing Corp., N. Y.

8 Erdelyi, A., *Tables of Integral Transforms*, Vol. 1, No. 33, McGraw-Hill, N. Y., 1954, p. 132.

9 Whittaker, E. T. and Watson, G. N., *A Course of Modern Analysis*, Macmillan, N. Y., 1946 p. 152.

Experimental Investigation of Detonation in Unconfined Gaseous Hydrogen-Oxygen-Nitrogen Mixtures[1]

LEON H. CASSUTT[2]

Arthur D. Little, Inc.
Cambridge, Mass.

An experimental program has been conducted to determine the detonability of unconfined hydrogen-oxygen-nitrogen mixtures during venting of a missile employing liquid hydrogen as a fuel or during an accidental spill from a storage or missile propellant tank. The mixtures investigated ranged from those formed by hydrogen combining with air to those in which there is no nitrogen dilution. During the tests, the gaseous mixtures were contained in 100-cu ft latex balloons; and upon initiation, measurements were made of the resulting peak overpressures. Initiation was accomplished by ignitors varying in strength from electric sparks to 100-gm explosive charges. The results of the experimental program have demonstrated that any mixture capable of sustaining a stable detonation wave when confined in a tube will detonate under unconfined conditions if the initiating impulse is sufficiently intense. For many hydrogen-oxygen compositions with no nitrogen dilution, initiation by a spark or flame source can produce full detonation. For hydrogen-air mixtures, detonation requires initiation by at least a 2-gm explosive charge.

BECAUSE large missile systems will be needed for outer-space research, emphasis has recently been placed on increasing overall specific impulse through the use of liquid hydrogen as a fuel. Before storing and handling this liquid in large quantities, however, the Air Research and Development Command asked Arthur D. Little, Inc., to study the characteristics of liquid hydrogen and to develop realistic safety criteria. Such criteria could bring about substantial savings in capital equipment costs of production, storage, and user facilities, and could point out safety devices which would prevent major losses.

After analyzing the probable causes of both known accidents at liquid hydrogen facilities and those which might oc-

Received Dec. 30, 1960.
[1] This work was sponsored by the United States Air Force Air Research and Development Command under Contract AF 18(600)-1687.
[2] Senior Chemical Engineer.

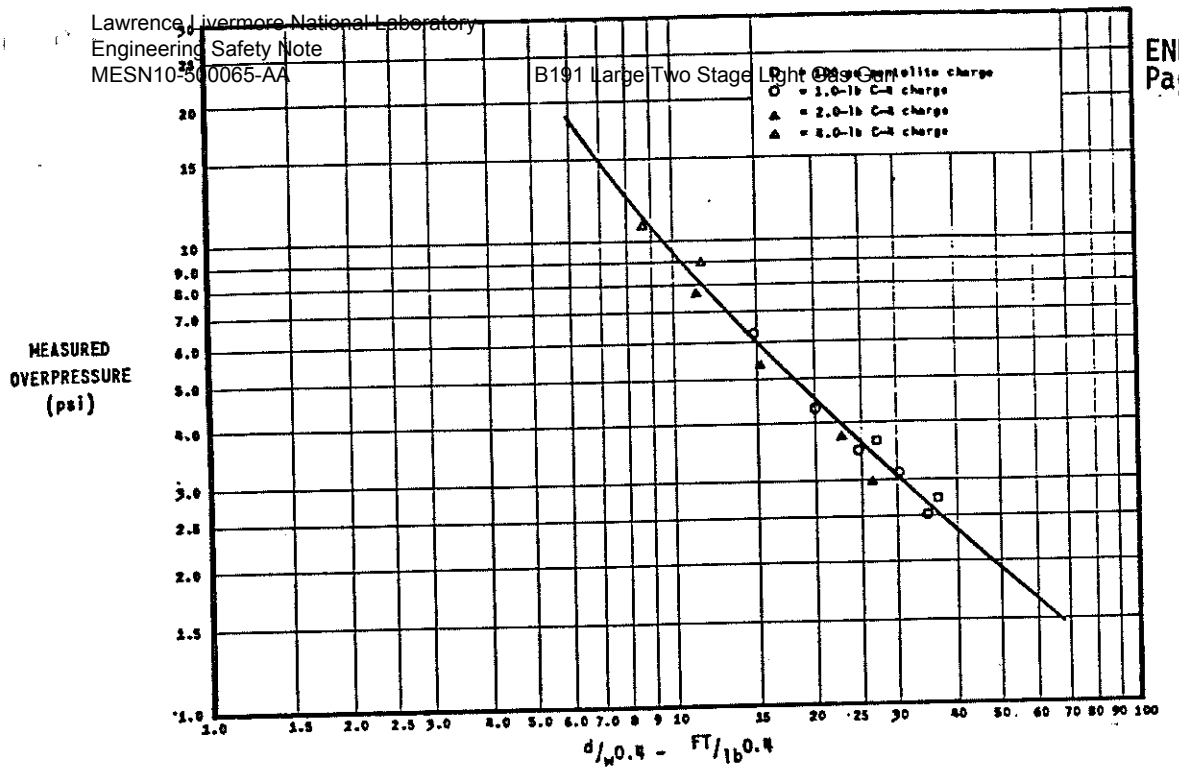


Fig. 1 Measured overpressures for small explosive charges

cur, ADL identified a number of possible hazardous situations. One of these concerned the detonability of unconfined hydrogen-oxygen mixtures. If these mixtures were detonable, venting of a missile utilizing the cryogenic fuel or an accidental spill from a storage or missile propellant tank could be disastrous. The composition of these mixtures could range from those with no nitrogen dilution (as in a missile where liquid oxygen is also being vented) to those where the only oxygen is that supplied by the surrounding atmosphere (as in a hydrogen-spill situation). It was important, therefore, to establish the conditions which might cause detonation.

Previous Experimental Information

Considerable experimental data are available on the reaction of hydrogen-oxygen mixtures confined in tubes (1,2).[3] It has been shown that the detonable mixtures range from 15 to 90 mol % hydrogen and that the ignition energy requirements are among the lowest of any combustible fuel-oxygen mixture. The addition of nitrogen inhibits detonation to a certain extent, but the limits of detonability in air are still wide: 18–59 mol % hydrogen.

These data cannot be readily transferred from the two-dimensional to the three-dimensional case, however, because the mechanisms of plane detonation wave propagation and of spherical detonation wave propagation differ. Only in recent years had investigation revealed the existence of stable spherical detonation waves (3–8), and this work has been limited by the methodological difficulties involved; i.e., large volumes of gas are necessary for even a short path for the detonation wave in a spherical container. These studies indicated that in spherical detonation stronger initiation is generally required and detonation limits are reduced. Little of these data, however, pertain to the specific conditions necessary for spherical detonation of hydrogen-oxygen mixtures.

[3] Numbers in parentheses indicate References at end of paper.

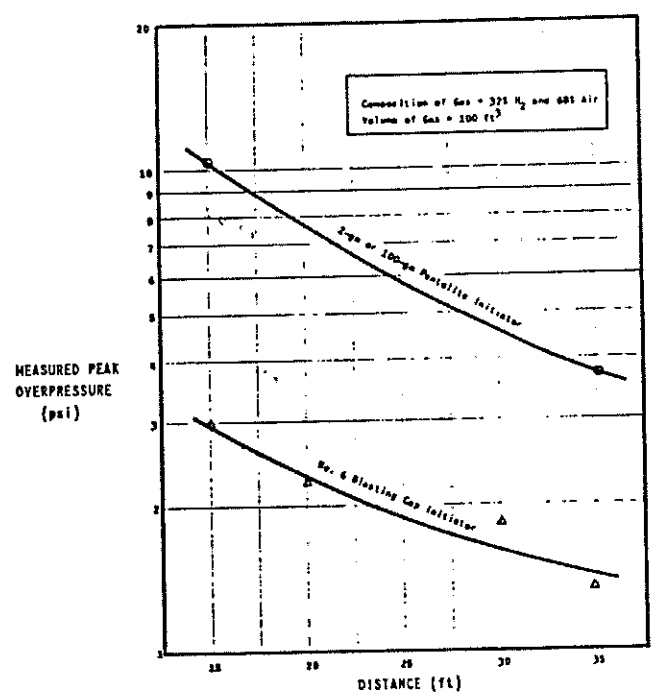


Fig. 2 Effect of initiator energy upon detonation yield of hydrogen-air mixtures

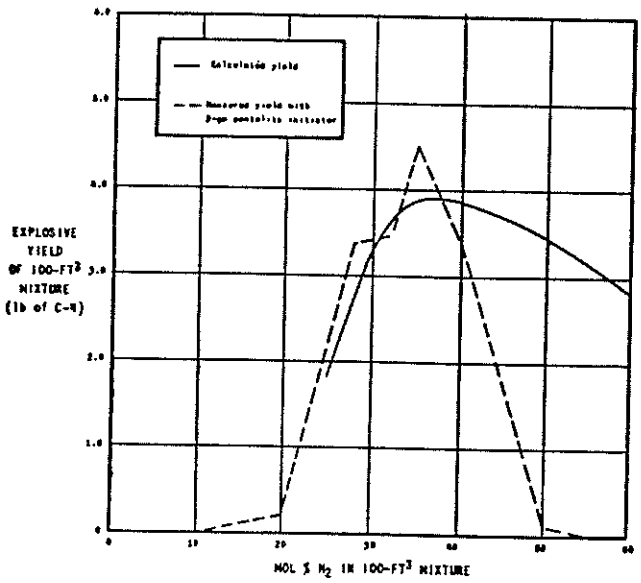


Fig. 3 Explosive yield of hydrogen-air mixtures in free space

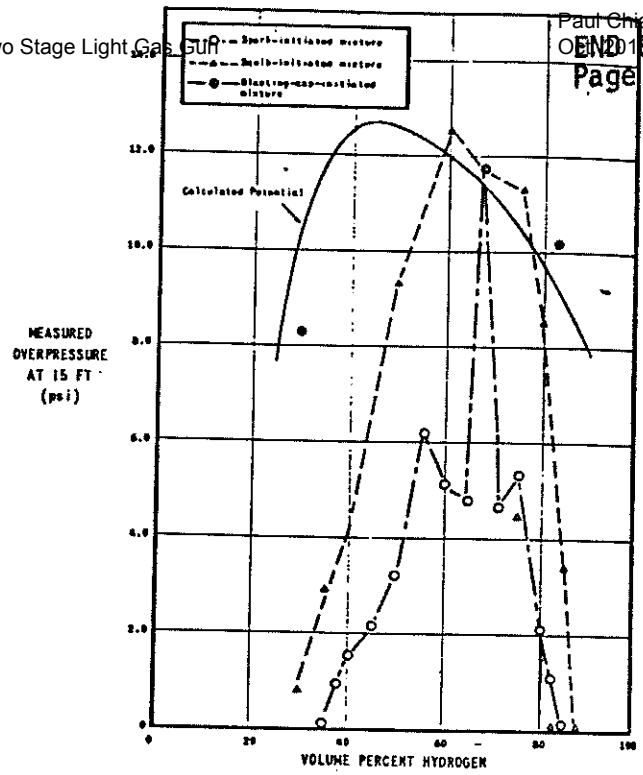


Fig. 4 Comparison of theoretical and experimental overpressures from reaction of hydrogen-oxygen mixtures

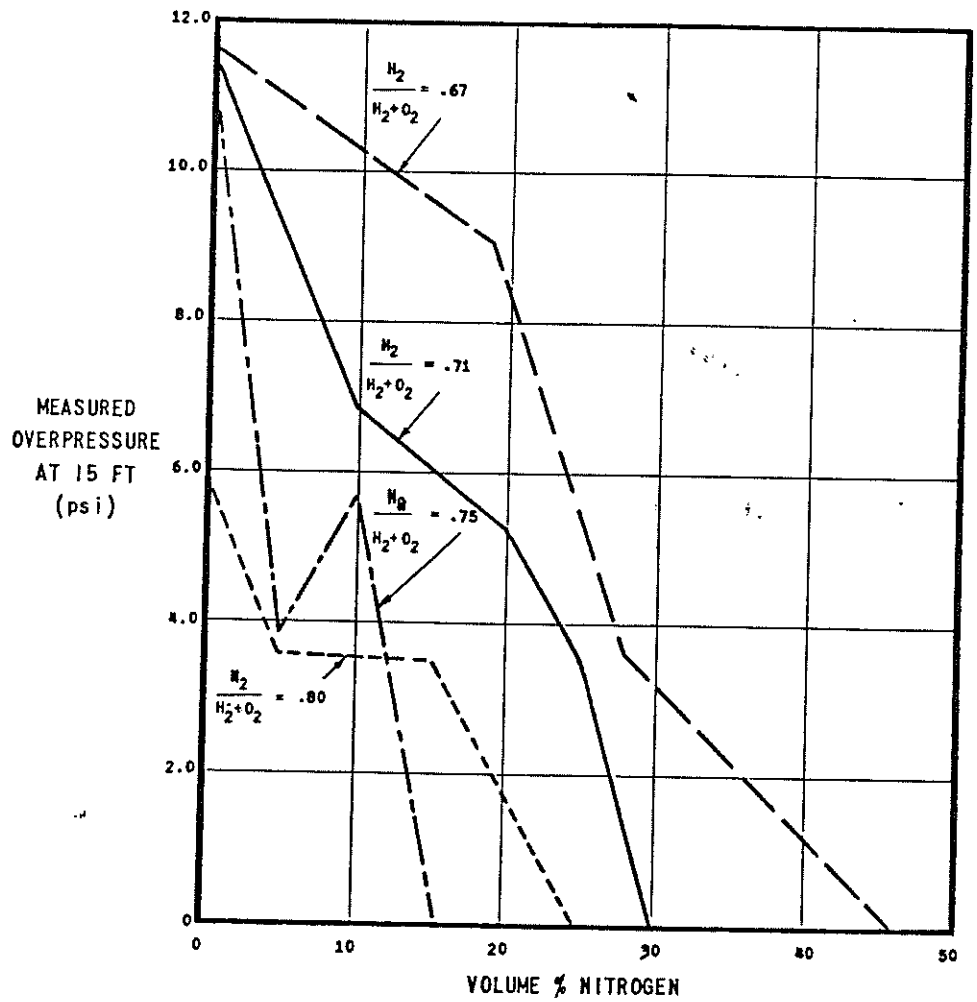


Fig. 5 Effect of nitrogen dilution on the detonability of fuel-rich hydrogen-oxygen gas mixtures, S-68 squib ignition

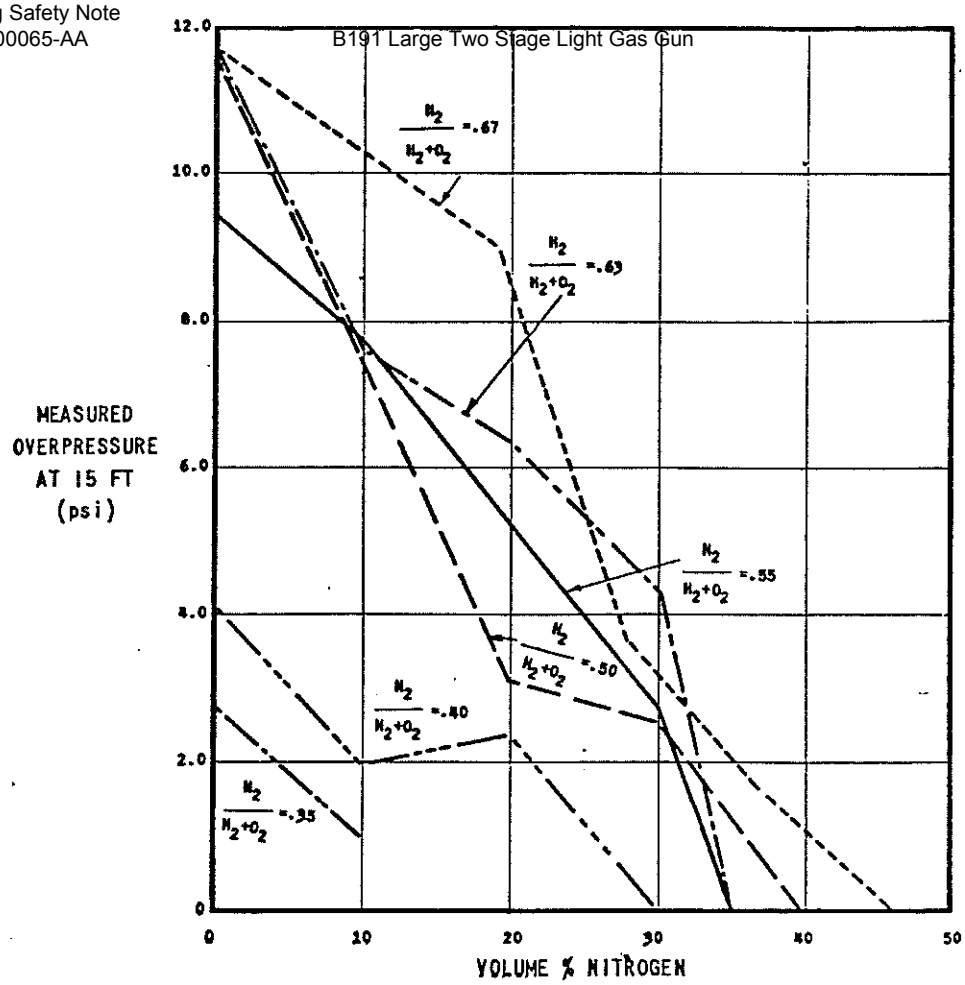


Fig. 6 Effect of nitrogen dilution on the detonability of fuel-lean hydrogen–oxygen gas mixtures' S–68 squib ignition

Experimental Procedure

The experimental program undertaken sought to establish those mixtures which were detonable and the level of initiation energy they required. The experimental conditions were idealized in that uniform mixtures of the gases were tested rather than nonhomogeneous compositions, which would result from actual venting or spilling. The experimental setup consisted of a 6-ft diameter latex balloon (having a volume of 100 cu ft) filled with the mixture to be tested—the accuracy of gas metering being within 2.5%.

Since the filling pressure for the balloon was less than one inch of H_2O, essentially unconfined conditions were provided by the balloon. The initiating charge was located at the center of this sphere, and the magnitude of the peak overpressure was assumed to be the criterion for the existence of a detonation wave. The pressure was measured with five ceramic type blast gages spaced at 5-ft intervals and at a distance of 15–35 ft from the charge to be tested. The signal from each blast gage was fed through a cathode follower and isolation amplifier to an oscilloscope, where the scope trace was recorded with a Polaroid camera. The oscilloscope was activated by a trigger gage placed 10 ft from the charge.

The experimental setup was calibrated by the initiation of small C-4 and pentolite charges. The results of these tests are presented in Fig. 1, in which the distance from the explosive at which the overpressures were measured is divided by the explosive's weight raised to the 0.4 power. The 0.4-power function was employed because it best fit the rate of pressure fall off for the charges. Its value, however, would be affected by both the size and shape of the charges and the degree of the shockwave's ground reflection.

Tests With Hydrogen-Air Mixtures

Initial experiments with 100-cu ft balloons were conducted with hydrogen-air mixtures, since the first phase of the overall program was concerned with the storage and handling of liquid hydrogen alone.

The first test series was designed to establish minimum initiation energy requirements through the ignition of near-stoichiometric mixtures containing 32 mol % hydrogen and 68 mol % air (see Fig. 2).

The measured overpressures demonstrated the following:

1 The mixtures detonated completely when initiated by 2-gm or 100-gm pentolite charges. Based on the calibration data in Fig. 1, the explosive yield was equivalent to 3.5 lb of C-4 (i.e., 0.64 lb of C-4 per pound of gas mixture).

2 When No. 6 or No. 8 blasting caps were used as initiators (either cap is equivalent to about 0.5 gm of explosive), overpressures one third as high as those obtained with the pentolite charges were achieved. The explosive yield, therefore, was less than 0.2 lb of C-4, or a reduction of 95%.

3 Neither squib nor spark sources, when used as the initiator, gave significant overpressures, and there was no discernible evidence of a detonation. Combustion of the gases produced only slight charring of the wood dowel supporting the initiator.

Since the 2-gm pentolite charge had been established as the minimum amount of energy that was required for complete

detonation of the near-stoichiometric hydrogen-air mixture, further tests incorporated this initiator so that the limits of detonability could be explored. The results of these additional tests are presented in Fig. 3. Because the energy supplied by the 2-gm charge was less than the minimum required for the borderline compositions, overpressures measured for these compositions varied significantly from one test to another. For this reason, only those data representing the maximum for the mixture were used to establish the limits. Fig. 3 compares these maximum yields for the various mixtures with their computed theoretical potential. It was assumed that the theoretical potential was equivalent to that of conventional explosives having the same heats of explosion. Full detonation is shown for mixtures containing less than 40 mol % hydrogen; only partial detonation occurs with the richer mixtures. The limits for significant yield (20–50 mol % hydrogen) were quite close to those reported for confined hydrogen-air mixtures: 18-59 mol % hydrogen. These results therefore substantiated conclusions based on the theoretical analysis (8), namely, that any mixture capable of sustaining a stable detonation wave when confined in a tube will detonate under unconfined conditions if the initiating impulse is sufficiently intense.

A few tests were made with hydrogen-air mixtures containing 35 mol % hydrogen in 400-cu ft balloons in an effort to determine whether a greater path length and larger gas volume would provide a transition from deflagration to detonation. In these limited tests, the blasting cap and 2-gm pentolite initiator produced yields that were directly related to the greater mass of gas involved; there was no evidence of a transition to full detonation with the blasting cap.

Tests With Hydrogen-Oxygen Mixtures

The second phase of the experimental program was devoted to an evaluation of the detonability of unconfined hydrogen-oxygen mixtures without nitrogen dilution. Three initiating sources, representing several levels of ignition energy, were used: (a) spark source (of the order of 1–5 millijoule); (b) duPont 6-gr squib, which provided a strong flame source with some pressure amplification, (c) A No. 6 blasting cap (approximately 0.5 gm), which is a near minimum shockwave energy source.

The first series of tests, conducted with the stoichiometric ratio of hydrogen and oxygen, was designed to establish the minimum energy for full detonation. As shown in Fig. 4, all three initiating sources gave essentially the same overpressures. Based on the calibration curve (Fig. 1) their yield was equivalent to 1.30 lb of C-4 per pound of mixture, compared with the theoretical yield of 1.33 lb of C-4 per pound of mixture.

When it could be seen that the squibs and the spark source provided enough energy to completely detonate the stoichiometric mixtures, further tests were made with other ratios of hydrogen and oxygen. At this point, only one firing was made with each composition and initiator, since only the limits of detonability were being sought. The results of these tests are shown in Fig. 4.

Fig. 4 illustrates only the overpressures measured at 15 ft, but similiar curves would result if data for other gage positions had been plotted. Points of zero overpressure in the experimental curve designate compositions for which no detectable shock-wave was recorded. A small pressure rise (less than 0.2 psi at 15 ft) usually occurred; however, it resulted from the rapid combustion of the gases. Also presented in Fig. 4 is a curve which gives the estimated overpressures resulting from the complete detonation of these compositions as determined by theoretical computations. Although the specific values of measured overpressures can be considered only approximate—because of the limited testing with each composition—one can frame some general conclusions by comparing them with the theoretical values:

1 With the spark source as initiator, a decrease from full explosive yield occurred when the hydrogen content of the stoichiometric quantity was increased or decreased by only 4%. The approximate limit of detonability for 100-cu ft mixtures was 35–85 mol % hydrogen.

2 When squib initiation was used, a full explosive yield was obtained with mixtures containing 50–75 mol % hydrogen. The limit of detonability appeared to be 25–87.5 mol % hydrogen.

In tests made with No. 6 blasting caps as the initiator, a full explosive yield was achieved over a range of at least 30–82 mol % hydrogen.

Effects of Nitrogen Dilution

In the foregoing tests, it was demonstrated that at least a 2-gm pentolite charge was required for complete detonation of an unconfined hydrogen-air mixture and that a spark or flame source was sufficient for a hydrogen-oxygen mixture. It is evident, therefore, that nitrogen dilution has a great deal to do with the detonability of these mixtures. For this reason, a number of tests were conducted to assess the extent of this dilution effect (see Figs. 5–9). As expected, the limiting nitrogen dilution occurred for the stoichiometric hydrogen-oxygen ratio $H_2/H_2 + O_2 = 0.667$. Increasing or decreasing the ratio of hydrogen from stoichiometric significantly reduced the percentage of nitrogen that could be added before essentially no detonation effects resulted. In the stoichiometric mixtures, the limiting dilution with squib initiation was approximately 46 mol % nitrogen; with spark initiation it was 35 mol %. In general, the allowable dilution for all ratios of hydrogen and oxygen was less with the spark source than with the squibs—a clear demonstration of the squib's greater initiation energy.

A comparison of the stoichiometric mixtures' measured detonation effects with their calculated potential shows that an immediate decrease from full yield occurred in spark-initiated mixtures when nitrogen was added (see Fig. 9). With squib ignition, this decrease was evident for dilutions greater than 20 mol %. When the blasting caps were used, however, complete detonation was obtained with nitrogen dilutions up to 46 mol %; and with the stoichiometric hydrogen-air mixture (55.6 mol % nitrogen), an overpressure of 2.9 psi was obtained at 15 psi— a yield equivalent to 5% of the calculated potential.

A unique effect was noted in tests with the spark-initiated mixtures: Except when compositions were near-stoichiometric and contained no nitrogen, the pressure wave fronts were less steep than those produced by other initiators. This effect became more pronounced when the nitrogen was increased; in fact, near the end points, it was impossible to measure overpressures at other than the first blast gage position. Two possible explanations are suggested for this phenomenon:

1 A deflagation wave is initially formed in the reacting gas. Moving outward, the wave builds up in intensity until, near the periphery of the balloon, a transition to detonation occurs. Enough of the deflagation wave precedes the detonation wave at the first gages so that a pressure front of reduced slope is recorded.

2 An intense deflagation wave is formed in the reacting gas, and no transition to detonation occurs. The wave then steepens, creating a shock front in the air as it moves away from the balloon.

The second explanation seems to be more reasonable than the first, because the formation of a detonation wave just at the periphery of the balloon would require a unique combination of mixture and initiation energy. Moreover, the phenomenon has been observed in all borderline mixtures ignited by a spark source; no other initiation has produced a similar effect. Steepening of the pressure front as it progresses away from the reaction zone probably occurs independently

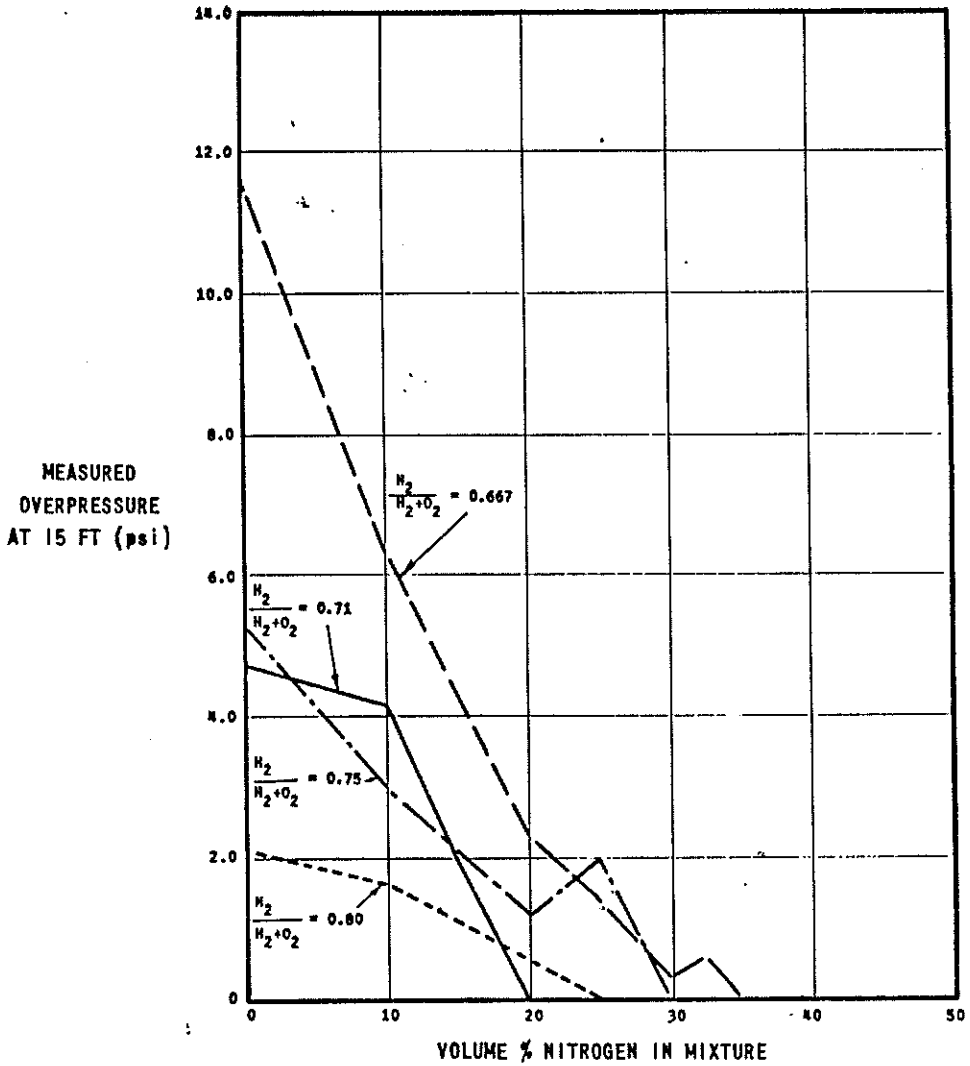


Fig. 7 Effect of nitrogen dilution on the detonability of fuel-rich hydrogen-oxygen gas mixtures' spark initiation

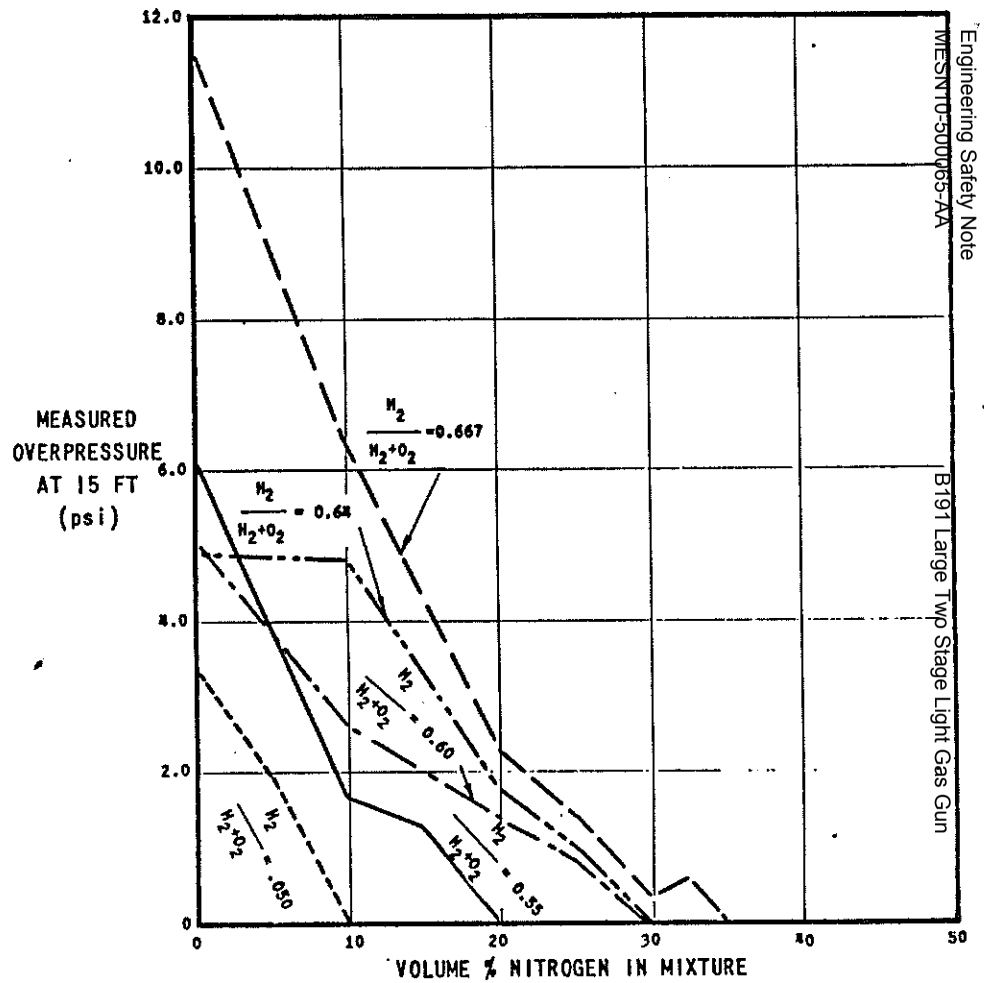


Fig. 8 Effect of nitrogen dilution on detonability of fuel-lean hydrogen-oxygen gas mixtures' spark initiation

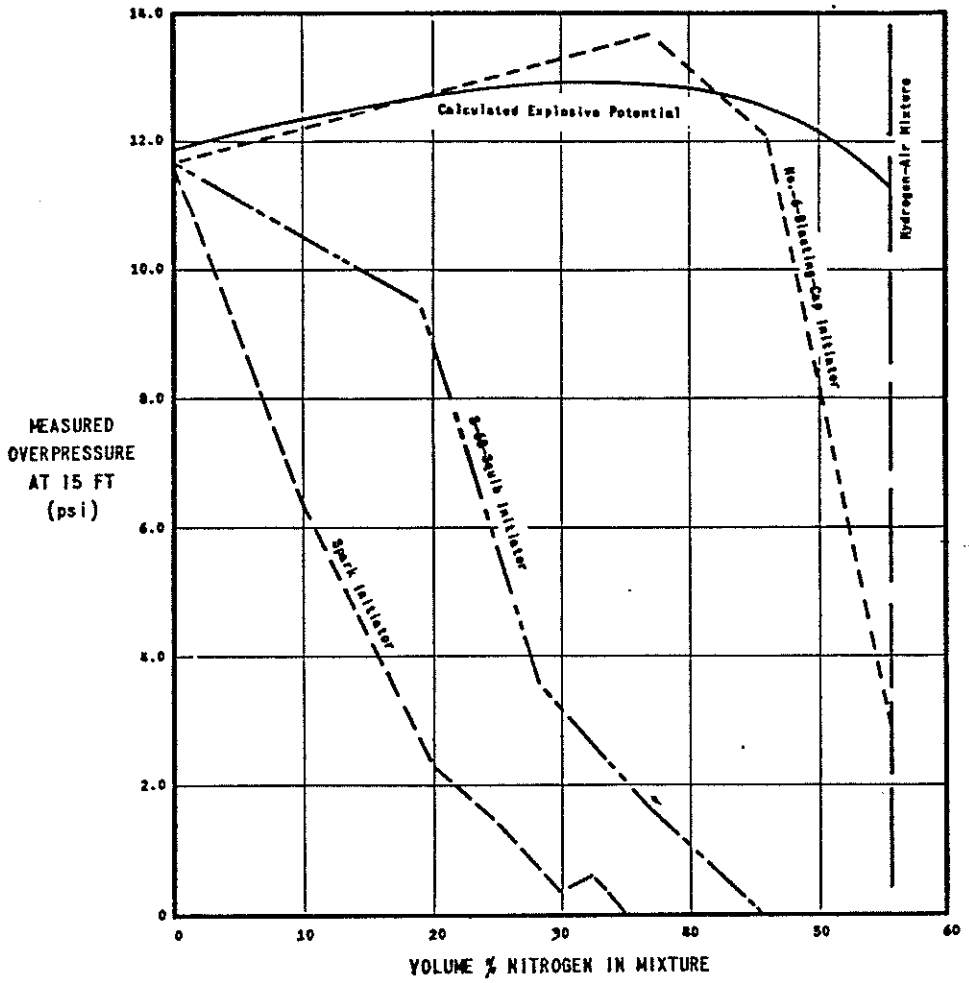


Fig. 9 Effect of nitrogen dilution on explosive potential of stoichiometric hydrogen-oxygen mixtures

of the sequence of events in the balloon; such an effect is normal in the degeneration of pressure waves. A better explanation of the shock fronts of low slope in the spark-initiated mixtures might be obtained if tests were made with larger volumes of gas (800 cu ft or more). If a stable detonation were being formed near the periphery of the 100-cu ft balloons, most of the gas in the larger volume would probably detonate fully. If the opposite sequence of events took place, it is unlikely that a significant increase in explosive effects would occur.

Conclusions

On the basis of the experimental work carried out in this program, a number of conclusions can be drawn about the detonability of unconfined hydrogen-oxygen-nitrogen mixtures:

1 Any mixture capable of sustaining a stable shock wave will fully detonate under unconfined conditions if the initiating impulse is sufficiently intense.

2 An unconfined stoichiometric hydrogen-oxygen mixture will detonate completely if it is initiated by a spark or flame source.

3 Initiation by at least a 2-gm explosive charge is needed to fully detonate an unconfined hydrogen-air mixture.

4 The level of energy required for complete detonation rises as the percentage of hydrogen changes from stoichiometric and as nitrogen dilution increases.

References

1 Lewis, B. and von Elbe, G., "Combustion, Flames, and Explosions of Gases," Academic Press, N. Y., 1951.

2 Ordin, P. M., "Hydrogen-Oxygen Explosions in Exhaust Ducting," NACA TN 3935, April 1958.

3 Zeldovich, Ya. B., "Distribution of Pressure and Velocity in the Products of a Detonating Explosion, and in Particular in the Case of a Spherical Propagation of the Detonation Waves," *J. Exper. Theor. Phys.*, (USSR) vol. 12, 1942, pp. 389–406.

4 Taylor, G., "The Dynamics of the Combustion Products Behind Plane and Spherical Detonation Fronts in Explosives," *Proc.* Royal Soc London, vol. A-200, 1950, pp. 235–247.

5 Freiwald, H. and Ude, H., "Spherical Explosion Waves in Mixtures of Acetylene and Air," *Comptes Rendus*, vol. 236, 1953, pp. 1741–1743.

6 Manson, N. and Ferrie, F., "Contribution to the Study of Spherical Detonation Waves," Fourth Symposium (International) on Combustion Baltimore, Williams and Wilkins Co., 1953, p. 486.

7 Jost, W., *Explosions und Verbrennungsvorgange in Gasen*, Berlin 1939, pp. 185–186.

8 Zeldovich, Ya. B., Kogarko, S. M. and Simonov, N. N., "An Experimental Investigation of Spherical Detonation of Gases," *Soviet Physics, Technical Physics*, vol. 81, 1957, pp. 1689–1713.

Appendix D. Catch Tank Closure Bolts

LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

SUBJECT 2 Stage Gas Gun		NAME A. Van Dyk
Catch tank closure bolts		DATE 10/12/78

FILE NO END 78-926 PAGE 1

Engineering Safety Note

A. Description

This note deals with catch tank closure bolts for the 2 stage light gas gun, Building 341, Room 1200. The need for this effort was set forth in END 76-908 (pgs. 32 & 33) wherein it is specified that "Use of this data assumes blowout of the catch chamber door to provide venting" and "Catch tank door flange should be held only by swing-away type clamps or bolts of strength sufficient to obtain the initial vacuum seal and also to allow a positive pressure of 10 psig. This provides a predictable failure mode."

Bolts, rather than clamps were elected to do the job because of superior predictability as well as quality control. In normal operation, the bolts are designed to function under the following loads; 1) pretorquing to 50 ft-lbs, 2) gasket and door warpage loads when tank vacuum is released and 3) pressure load when tank pressure is increased to a maximum operational pressure of 2 psig. Then outside of normal operation, the bolts must, fail in the 10 to 15 psig tank pressure range in order to perform as a pressure relief divice.

Drawings & Related Information

76-117283	Breakaway bolt
72-104286	2 Stage gun assembly
72-113778	Catcher tank
END 76-908	ME Safety Note (R.L. Waldron)
osp 341, App. F	Operational Safety procedure

LAWRENCE LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

FILE NO. END 78-926

SUBJECT: 2 Stage Gas Gun

NAME: A. Van Dyk

Catch tank closure bolts

DATE: 10/12/78

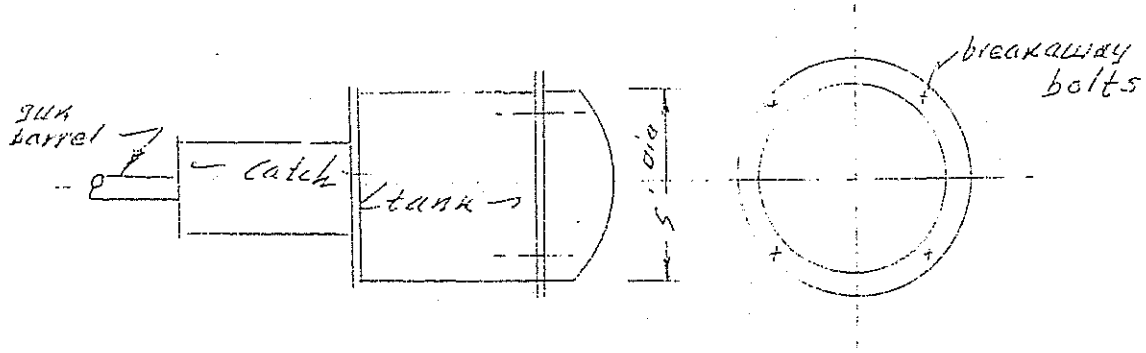
Hazard

The door bolts are to prevent a hazardous condition. They are to fail in the event of a energy release inside the tank which might cause a detrimental situation to occur to other parts of the gun system, such as tank rupture. Refer to END 76-908 for system safety evaluation.

Calculations

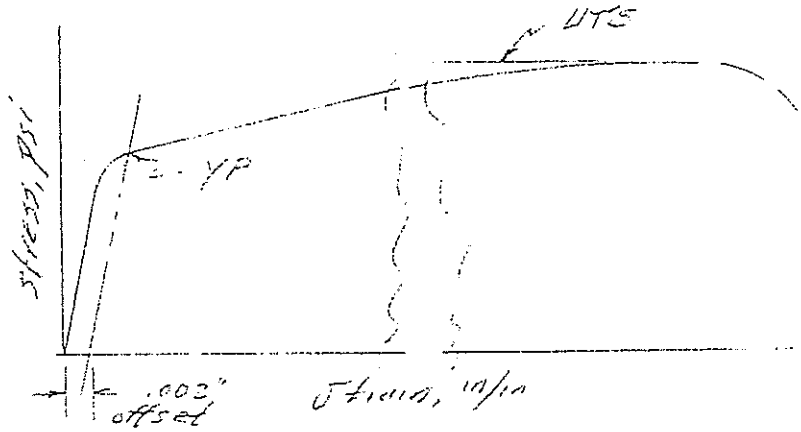
The following design considerations existed or were selected:

1. Number of bolts; 4 bolts, uniformly spaced.



2. Bolt material; 6061-T6 aluminum select for strength and elongation characteristics.

Uts	43,900 psi
ys	40,000 psi
E	9.8 x 10^6 psi
Elog	9% In 2 in.



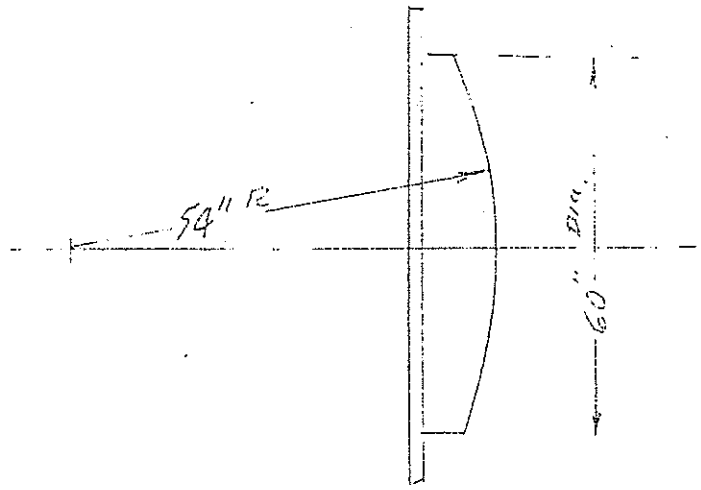
Typ Stress-Strain Curve for Al. Alloys

LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

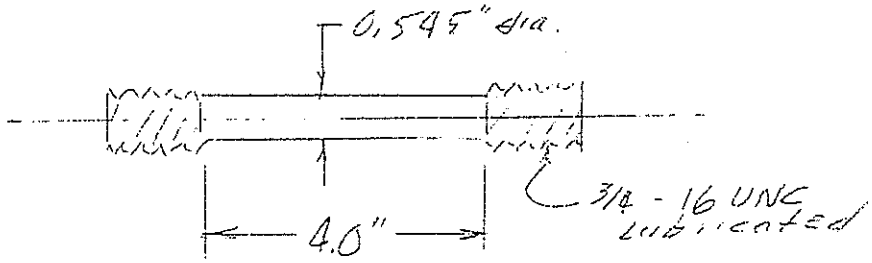
SUBJECT: 2 Stage Gas Gun	FILE NO: END 78-926 / PAGE: 3
	NAME: A. Van Dyk
Catch tank closure bolts	DATE: 10/12/78

3. Door Configuration



door Inner Surface area = 2830 □" (End 76-908)

4. Bolt Configuration



LAWRENCE LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

FILE NO. END 78-926 PAGE 4

SUBJECT 2 Stage Gas Gun

NAME A. Van Dyk

Catch tank closure bolts

DATE 10/12/78

5. Bolt Diameter

The bolt diameter was initially determined by calculating a size compatible with operational conditions and considering bolt failure to occur at tank pressure of 10 psig; such as the following:

a) Total load on door at 10 psig

$F_T = PA$

A = door area = 2830 □ in^2 (END 76-908)

P = tank pressure = 10 psig

$F_T = 10 \times 2830 = 28{,}300$ lbs

b) the load per bolt

$F_b = 28300/4 = 7100$ lb

c) then the bolt area (based on failure at ult. tensile stress of Mat'l) is

$$A = \frac{F_b}{S_{UTS}}$$

$$= \frac{7{,}100}{43900}$$

$$= 0.161 \text{ □}''$$

and

$$D = \sqrt{\frac{4A}{\pi}}$$

$$= \sqrt{\frac{4(.161)}{3.14}}$$

$$= .454''$$

LAWRENCE LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

B191 Large Two Stage Light Gas Gun

FILE NO. END 78-926 Oct. 2010 PAGE 5

SUBJECT: 2 Stage Gas Gun

NAME: A. Van Dyk

Catch tank closure bolts

DATE: 10/12/78

However, when bolts in this size range were used, the door warpage and related torquing of the bolts caused them to elongate excessively. Ensuing tests established 0.545" diameter as the size to satisfy the conditions. In reversal of the calculations above, this diameter would fail at a tank pressure of 14.5 psig. Bolts of this size will also elongate under the operational conditions: 3 of the 4 bolts will be strained to .0015 in./in., within the elastic limit; the 4th bolt will stretch beyond the elastic limit and after a number of cycles will develop a permanent set of about .010 (or .0025"/in.) at this point the bolts will be replaced with a new set. The attached material test data indicates an elongation between original and final gage length of 0.017 in/in at failure. The bolts will have lubricated threads and will be under surveilance as part of the operational safety procedures.

Dist.
W. Arnold, ME Dept., L-123
R. Carr, NEED, L-122
C. Henry, H Div., L-355
W. Nellis, H. Div., L-355
D. Bakker, NEED, L-374
D. Montgomery, HC, L-112

Prepared by

A. Van Dyk

Reviewed by

David C Hilton

Approved by

Ron Carr

LL-398 (REV. 8/71)

Appendix E. Pressure and Purge System

Appendix E.1 Introduction

The Two-Stage Light Gas Gun includes systems that require the use of high pressure. The Pump Tube Pressurization System allows the user to select the driving gas for the gun. This system contains capabilities to evacuate the contents of the Pump Tube with a mechanical vacuum pump, fill the Pump Tube with the selected driving gas (N_2, He, H_2), and safely vent the Pump Tube. Two components in this system are also responsible for containing the pressure buildup in the Pump Tube during firing operations. These include the high pressure flex hose (rated to 21 ksi) and the spring loaded Autoclave fill valve (rated to 20 ksi).

The Nitrogen Purge System is used to safely inert the Target Chamber Assembly and Catch Tank volume from the threat of hydrogen detonation following a shot. The system contains capabilities to dump a large content of nitrogen into the volume, then flow nitrogen through the volume, and then draw vacuum on the volume to ensure that a safe air-fuel mixture is always maintained. For more details of the systems, see MESN04-519-AA, contained in section E.8 of this appendix.

With the move of the gun from B341 to B191, the theory of operation remains unchanged. However, the control system was upgraded and therefore, many of the components were also upgraded. All of the components in both of these systems are comprised entirely of commercial parts. The following lists some broad changes. Included in this appendix are updated P&IDs of the two systems, and a list of all the components and their commercial pressure ratings.

Changes include:

- Replacement of all electrically actuated valves with pneumatically actuated solenoids.
- All new valves have position indicators in both the open and the closed position
- Replacement of visual flow meters with digital flow meters
- Constant monitoring of the house air system to insure that the pneumatic devices will work

Appendix E.2 Hazard

See MESN04-519-AA for the hazards.

Appendix E.3 Calculations

The system will be used in the same manner as before. See MESN04-519-AA for the calculations. The stored energy is within the HEAF Gun-Bay energetic limits of 500 grams of TNT equivalence.

Nitrogen Purge System

Pressure Safety Component	Model Number	Description	MAWP (PSI)	Commercial Rating (PSI)
Nitrogen Skid		Nitrogen source for Nitrogen Purge System	2400	2400
S.S. Pressure Lines		Stainless steel lines for components	2200	3000
R1, R2, R3	Victor VTS-450E	Regulators to the Nitrogen Purge, Foreline Fill, and Scrubber Purge lines	2200	3000
V4, V5, V11	Swagelok SS-63EF8-33C-L2	Valves for Nitrogen Fast Fill and Emergency Fast Fill	2200	3000
Flowmeter	Teledyne Hastings HFM-I45	Nitrogen flow meters for slow purge lines	150	1500
Flowmeter	Teledyne Hastings HFM-I45	Nitrogen flow meters for scrubber purge line	15	1500
V6, V7	Swagelok 6LVV-DPHFR4-P1-CM2	Foreline and Scrubber Line supply valves	5	3000
V3, V8, V1, V2	Vacuum Research	Gate valves for the scrubber and vacuum pump	5	17.6
V251*	MKS	Bypass valve for high vacuum and vacuum side	10	Unknown (Vacuum Component
V17*	MDC	Manual vent valve	10	Unknown (Vacuum Component)
V13*	Swagelok 6LVV-DPHPFR4-P1-CM2	Catch Tank vacuum gauge isolation valve	10	3000
Catch Tank pressure transducer*	Dynisco PT270DN-150	Transducer measuring the Catch Tank pressure	10	250
V253, V254*	Swagelok 6LVV-DPHPFR4-P1-CM2	High Vacuum Isolation Valves	10	3000
V250, V252, V9, V12*	Vacuum Research	Gate valves for the high vacuum	10	17.6
Vacuum Gauges*	Granville Phillips 275G	Vacuum Gauges	10	8
Filter Housing*	MSA	Vacuum Filter	10	Unknown (Vacuum Component)

*These components are vacuum components that could be exposed to pressure if one of the regulators (R1, R2, R3) **and** a pressure valve (V4, V6, V7) were to fail. There is no risk to personnel because the area is mustered during operations involving pressure. There is only a risk to programmatic equipment.

Pump Tube Pressurization System

Pressure Safety Component	Model Number	Description	MAWP (PSI)	Commercial Rating (PSI)
V31	Autoclave 20SM9071-CH	Sealing valve for the pump tube	15,000	20,000
Pump Tube Supply Flex Hose	Spir-Star Hose ASSY-6/4, SST 3/8 ends	Flexible hose from the V31 to the pump tube	15,000	21,000
V29, V30, V32	Autoclave 20SM9071-CH	Valves for the gas fill line, vent line, and vacuum line	400	20,000
Fill Line pressure transducer	Dynisco 12-31-09307102	Transducers measuring the pump tube fill pressures	400	2500
Fill Line Flex Hose	Gates 10TH18NC	Fill line flex hose for driving gas	400	3000
Vacuum Line Flex Hose	Gates 10TH18NC	Vacuum Line hose	8	3000
Vent Line Flex Hose	Gates 10TH18NC	Vent Line hose	150	3000
V36, V37, V38, V39, V40	Swagelok SS-6UG-6C-M2	Hydrogen-rated Gas Selection Valves	2200	2500
V34, V35	Dragon 10M057	Manual Gas Selection Valves	2200	6000
Gas Selection Check Valves	Circle Seal	Check valves on Gas Selection Panel	2200	5000
V41	Autoclave SS-6NB68	Nitrogen Skid Supply Valve	2400	6000
V42	Swagelok SS-14DKS4	Supply line relief valve	2400	3000
R12	Atheson Model 3066	Regulator for Nitrogen supplied by outside skid	2200	6000
R10	Parker P/N 41600836 Model HPR800B5P10404	Gas supply regulator	400	4000
V33	Circle Seal A9559T_2PP	Manual Vacuum Vent Valve	8	2000

Appendix E.4 Re-test/Re-inspection

See MESN04-519-AA.

Appendix E.5 Labeling

See MESN04-519-AA.

Appendix E.6 Associated Documents

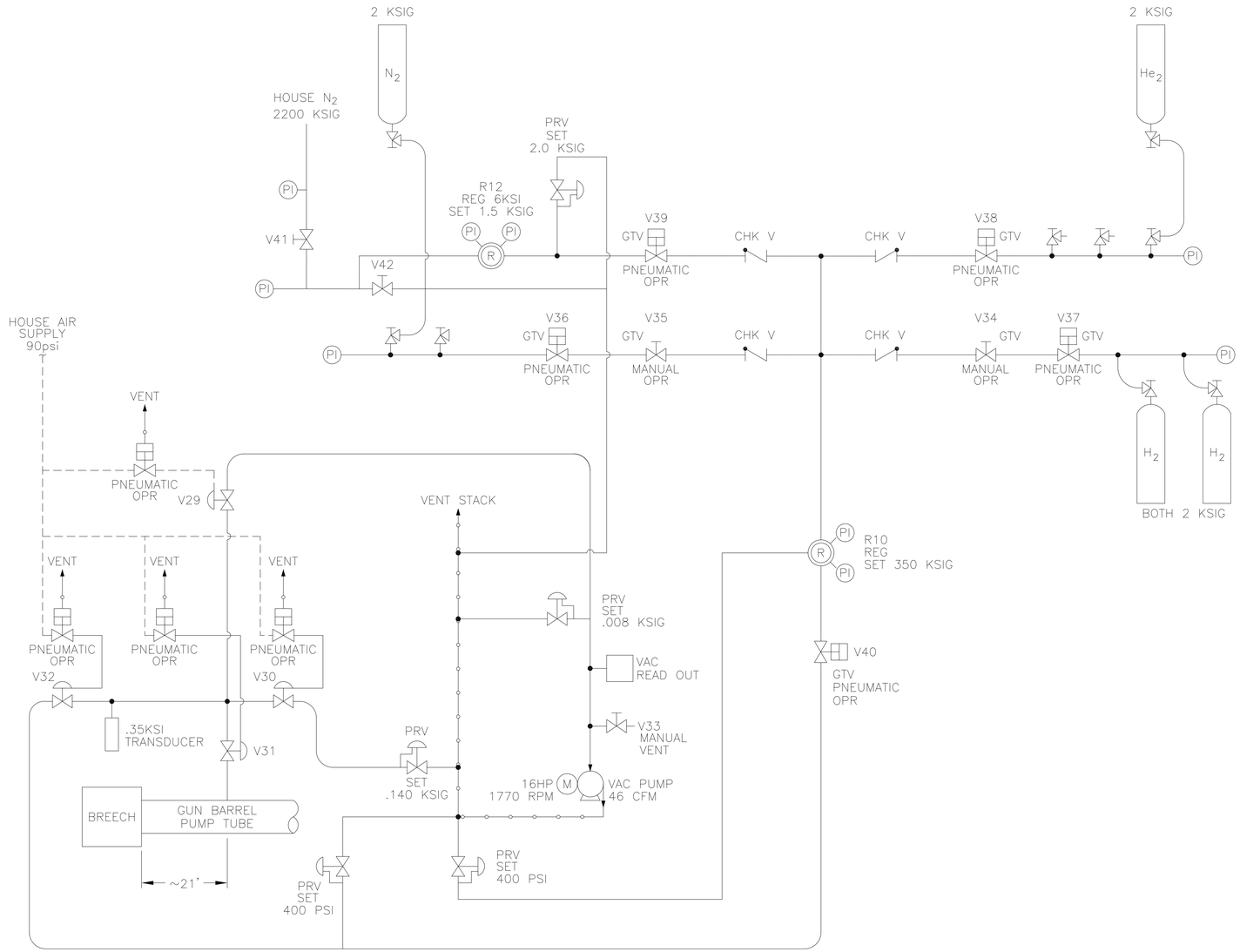
HEAF 08-026 Rev. 0	HEAF Two-Stage Gun Record of Operational Procedures
HEAF 08-027 Rev 0	Pre-Shot Data Sheet and Gun Firing Sequence Checklist
HEAF 08-029 Rev 0	Minor Maintenance (10 Shot) Checklist
HEAF 08-030 Rev 0	Intermediate Maintenance (30 Shot) Checklist
HEAF 08-031 Rev 0	Major Maintenance (60 Shot) Checklist

Appendix E.7 References

See MESN04-519-AA.

CLASSIFICATION:
UNCLASSIFIED

REVISIONS						
ZONE	REV	DESCRIPTION	DRAWN	CHECKED	APPROVED	DATE
	OA	REVISED	DP			1/77
	OB	ADDED VALVE #'S & REG #'S	CP			3/31/77
	OC	UPDATED TO EXISTING HARDWARE	ROB	ROB		3/31/85
	OD	REVISED & REDRAWN	lum3	chiao3	chiao3	12/19/08
	OE	UPDATED TO AS BUILT	lum3	chiao3	chiao3	10/14/10



NOTE: NON-FIRING MOP = 350 PSI
FIRING MOP = 15000 PSI

CLASSIFICATION: UNCLASSIFIED

DRAWING NUMBER AAA76-117296-OE | REV | SH 1

INCH
THIRD ANGLE PROJECTION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
DECIMALS ± ANGLES ±
DO NOT SCALE THIS DRAWING

NEXT ASSY | USED ON
APPLICATIONS

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CONTRACT NO.

APPROVALS	DATE
ORIGINATOR	12/21/76
DRAWN D. PARGETER	11/22/76
CHECKED C. PARKINSON	12/21/76
APPROVED C. PARKINSON	12/27/76
ENGINEERING GROUP EE/NSED	DRAWING LEVEL: II

LAWRENCE LIVERMORE NATIONAL LABORATORY
LAWRENCE LIVERMORE NATIONAL SECURITY, LLC

TITLE
B191, 2 STAGE LIGHT GAS GUN PUMP TUBE PRESSURIZATION SYS P & ID

SIZE	CAGE CODE	DWG NO.	REV.
D	14067	AAA76-117296-OE	

SCALE NONE | SHEET 1 OF 1

CLASSIFICATION:
UNCLASSIFIED

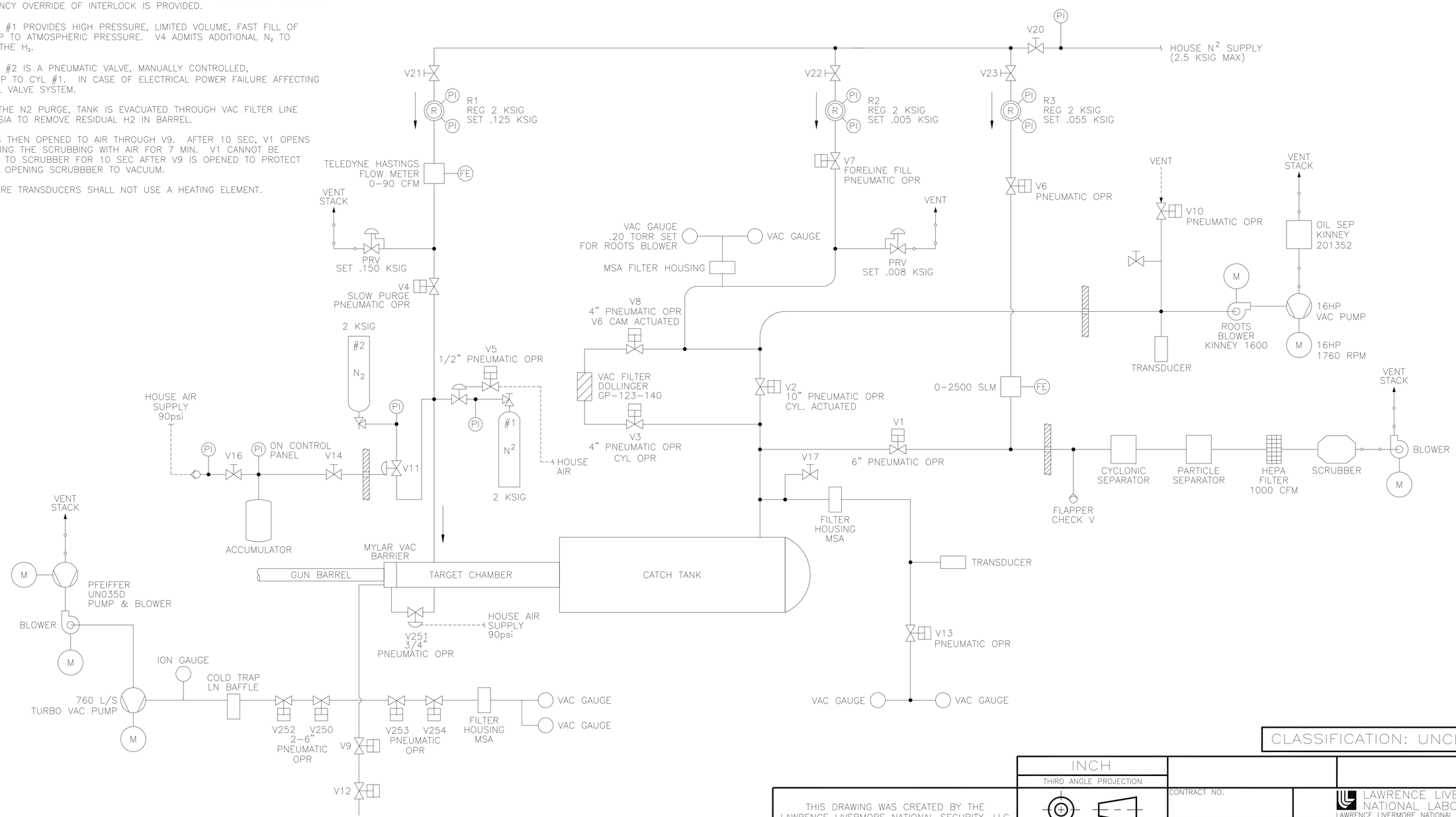
DRAWING: AAA76-117296-OE.dwg MODEL: ACAD 2006

CLASSIFICATION:
UNCLASSIFIED

REVISIONS						
ZONE	REV	DESCRIPTION	DRAWN	CHECKED	APPROVED	DATE
	OA	REVISED	DP			1/77
	OB	ADDED VALVE #'S & REG #'S	CP			3/31/77
	OC	UPDATED TO EXISTING HARDWARE	ROB	ROB		3/4/85
	OD	REVISED & REDRAWN	lum3	chiao3	chiao3	12/19/08
	OE	UPDATED TO AS BUILT	lum3	chiao3	chiao3	10/14/10

NOTES: UNLESS OTHERWISE SPECIFIED

1. FIRING OF SHOT IS INTERLOCKED TO V6 BEING OPEN, THAT IS, A 30 SEC. FLOW OF N2 PURGES LINE OF AIR OUT TO PARTICLE SEPARATOR.
2. V1 IS INTERLOCKED SO IT CANNOT OPEN UNTIL PRESSURE IN CATCHER TANK IS 1 PSI ABOVE ATMOSPHERIC PRESSURE. INTERLOCK CANNOT RESET V1 AFTER TANK IS VENTED THROUGH SCRUBBER. HOWEVER, EMERGENCY OVERRIDE OF INTERLOCK IS PROVIDED.
3. N2 CYL #1 PROVIDES HIGH PRESSURE, LIMITED VOLUME, FAST FILL OF TANK UP TO ATMOSPHERIC PRESSURE. V4 ADMITS ADDITIONAL N_2 TO DILUTE THE H_2.
4. N2 CYL #2 IS A PNEUMATIC VALVE, MANUALLY CONTROLLED, BACK-UP TO CYL #1. IN CASE OF ELECTRICAL POWER FAILURE AFFECTING THE CYL VALVE SYSTEM.
5. AFTER THE N2 PURGE, TANK IS EVACUATED THROUGH VAC FILTER LINE TO 2 PSIA TO REMOVE RESIDUAL H2 IN BARREL.
6. TANK IS THEN OPENED TO AIR THROUGH V9. AFTER 10 SEC, V1 OPENS PERMITTING THE SCRUBBING WITH AIR FOR 7 MIN. V1 CANNOT BE OPENED TO SCRUBBER FOR 10 SEC AFTER V9 IS OPENED TO PROTECT AGAINST OPENING SCRUBBBER TO VACUUM.
7. PRESSURE TRANSDUCERS SHALL NOT USE A HEATING ELEMENT.



CLASSIFICATION: UNCLASSIFIED

DRAWING NUMBER AAA76-117903-OE | REV | SH 1

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INCH
THIRD ANGLE PROJECTION
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CONTRACT NO.

APPROVALS	DATE
ORIGINATOR	11/30/76
DRAWN D. PARGETER	11/30/76
CHECKED C. PARKINSON	12/21/76
APPROVED C. PARKINSON	12/21/76
ENGINEERING GROUP EE/NSED	DRAWING LEVEL: II

NEXT ASSY | USED ON
APPLICATIONS

LAWRENCE LIVERMORE NATIONAL LABORATORY
LAWRENCE LIVERMORE NATIONAL SECURITY, LLC

TITLE
B191, 2 STAGE LIGHT GAS GUN PURGE SYSTEM
P & ID

SIZE D | CAGE CODE 14067 | DWG NO. AAA76-117903-OE | REV.
SCALE NONE | SHEET 1 OF 1

DRAWING: AAA76-117903-OE.dwg MODEL: ACAD 2006

CLASSIFICATION:
UNCLASSIFIED

A

Safety Note

Safety Note Number

Two-Stage Gas Gun Pressure & Purge System

Date: 2/10/2004
Written By: Keith D. Stickle
Author Signature 2-11-04

Responsible Individual Signature 2-11-04
Please Print Name Ricky Chau
Division/Group/ section PAT Directorate – H Divison

Pressure Consultant Signature Chuck Borzileri 2-11-04
Please Print Name Chuck Borzileri
Division/Group/ section Hazards Control Safety Programs

Division Leader Signature 2/13/04
Please Print Name Satish Kulkarni
Division/Group/ section New Technologies Engineering Division

Distribution:
Engineering Records Center - ERC L- 118
Pressure Safety Manager - Chuck Borzileri L-383
Responsible Individual - Ricky Chau L-041
NTED Tech Supervisor - Neal Hinsey
Pressure Consultant - Vern Switzer L-373
Pressure Consultant - Marita Spragge L-373
Division Leader - Satish Kulkarni L-113
System Users - Keith D. Stickle L-374
ES&H Safety Team - Brenda Staley L-143
P&ST Safety Manager – Bill Ulm L-401
Industrial Safety - Ray Nehem L-143
H&S Technician - Bryan Mason L-143
B-341 FPOC - Chuck Henderson L-374

A. Description:

This Engineering Safety Note covers the house supply nitrogen skid, gas selecting manifold (nitrogen, hydrogen and helium) and pressurizing manifold, pump tube manifold (fill, seal, vacuum and vent) and target chamber nitrogen purge manifold (slow tank purge, foreline fill and scrubber purge) for the Two-Stage Gas Gun. The operators of these systems are Keith D. Stickle and Leon Raper.

The house supply fifteen tube nitrogen skid (D.O.E. # 0829548) is used to supply nitrogen to the Two-Stage Gas Gun for pressure testing the pump tube, purging the pump tube, target chamber, scrubber system and vacuum system. Service pressure of the skid is 3000 psig. The maximum allowable working pressure (MAWP) relief device setting is 2850 psig, the **maximum operating pressure** (M.O.P.) **is 2200 psig**. The skid is located outside Building 341 in the Northeast corner in the fenced yard. Existing 1" iron pipe is used from the skid to the building.

The gas selecting and pressurizing manifold is used to test the pump tube system to 10 psia over the required firing pressure (eg. 60-300psig{400 psig MAWP}), purging to assure the purity of the required shot gas and pressurizing the pump tube system with the selected gas pressure required for the shot. Nitrogen gas is supplied by ½" S.S.(stainless steel) tubing through the building to the manifold. The manifold consists of four bottle racks (nitrogen, hydrogen, helium and one unused rack). There are five Circle Seal Controls valves rated at 3000 psig (400 psig MAWP), (four model # SV432A2NC6P435, and one #SV432A2NO6P435) with 3/8" S.S. tubing and Swagelok fittings. The manifold also contains a pressure relief device with a setting of 400 psi, one Veriflo regulator with a relief device setting of 550 psig, and four Circle Seal 3000 psig check valves. This gas selecting and pressurizing manifold is located in Building 341, Room 1200 on the East wall. The gas selecting and pressurizing manifold is operated in a manned area. The gas selection and pressurizing manifold schematic for the pump tube may be reviewed on drawing # AAA76-117296-OC.

The pump tube manifold consists of fill (pressurizing), seal, vent and vacuum valves. The pump tube manifold is used to select between pressurizing, venting gas after pressure test, venting after purge, or after shot to relieve pressure from a mixture of propellant gas and gas used for the shot. This manifold is also used for selecting the vacuum for evacuating the pump tube system below 2 psia between purges, and before purging and pressurizing the pump tube for the shot. This manifold consists of four Autoclave 20,000 psig valves (part # 20SM9071-OH, and # 20SM9071-CH), with 9/16" S.S. coned and threaded nipples (part # CNLX99) by Autoclave Engineers. The pressure of the pump tube is read from the manifold with an Omega 0-500 psig transducer (model # PX5500D1-500A5T). This manifold contains a pressure relief device set at 8 psig to protect vacuum system. The pump tube manifold is located in Building 341, Room 1200 in the middle section on top of the pump tube. The pump tube manifold is operated in a manned area. The pump tube manifold schematic may be reviewed on drawing # AAA76-117296-OC.

The nitrogen purge manifold consists of a slow tank purge, foreline fill, and scrubber purge valves. The target chamber nitrogen slow purging manifold is used to purge the target chamber after the shot has occurred for 4 minutes displacing any hydrogen gas residual left in the tank. The tanks slow purge of 25 cfm is provided with a pressure relief device set at 200 psig. The manifold also provides nitrogen gas to purge the scrubber system during the shot in case of leaks between the tank and scrubber system. The scrubber purge flow is set to be not less than 20 cfm, and is provided with a flow meter. Finally the manifold is used to back fill the vacuum foreline

A. Description:(cont'd)

with nitrogen gas to 1 psia above atmosphere (or 15.7 psia) to assure no oxygen will leak into the tank past the vacuum foreline seal valve after the shot. The foreline fill system contains a pressure relief device set at 2 psig. The manifold consists of three Victor Equipment Co. regulators, 3/8" and ½" S.S. lines with Swagelok fittings, two Asco valves (#8211D1) and one Autoclave valve (# 20SM9071-OH). The purging manifold can be operated either manned or remote. The target purge manifold is located on the West Side of the target tank in Building 341 Room 1200. The purge system schematic may be reviewed on drawing # AAA76-117903-OC.

B. Hazard

The stored energy of pressurized nitrogen gas in the skid and S.S line going to the gas selecting and pressurizing manifold is a hazard to personnel in case of a sudden depressurization or rupture. The gas selecting and pressurizing manifold, pump tube manifold, pump tube, target tank and line going to and from manifolds represents hazard to personnel, equipment and facility in case of a sudden depressurization, rupture or fire.

The Two-Stage Gas Gun room 1200 is not manned while the pump tube is pressurized over 100 psia, pressurized with H_2 or during H_2 purge. These operations will be performed remotely from control room 1122. In the event of a power outage, the pump tube will vent through the manifold vent valve automatically.

As will be shown in the calculations, there will be no hazards. The gas selection and pressurizing manifold (400 psig MAWP) along with the pump tube manifold (15000 psig) systems have been completely upgraded and inspected to comply with their respective MAWP established in this Engineering Safety Note.

C. Calculations:

Gas: Isentropic expansion of a confined gas

$$E = \frac{P_1 V_1}{K-1}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]$$

Where: E = stored energy K = ratio of specific heats

P_1 = MAWP V = volume

P_2 = atmospheric pressure B = liquid bulk modulus

C. Calculations: (cont'd)

E(Hydrogen)= $[54000ft.^2lbs. \times 2.5ft.^3 \div (1.14-1)] \times [1-(2116.8ft.^2lbs. \div 54000ft.^2lbs.)]^{(1.14-1)\div 1.14}$ = 316470.10ft.lbs.; $E(H_2)$ = 316470.10ft.lbs. ÷ $3420^{grams\ TNT}/_{ft.lbs}$ = 92.54grams TNT

E(Nitrogen)= $[54000ft.^2lbs. \times 2.5ft.^3 \div (1.41-1)] \times [1-(2116.8ft.^2lbs. \div 54000ft.^2lbs.)]^{(1.41-1)\div 1.41}$ = 200856.9ft.lbs.; $E(N_2)$ = 200856.9ft.lbs. ÷ $3420^{grams\ TNT}/_{ft.lbs}$ = 58.73grams TNT

E(Helium) = $[54000ft.^2lbs. \times 2.5ft.^3 \div (1.66-1)] \times [1-(2116.8ft.^2lbs. \div 54000ft.^2lbs.)]^{(1.66-1)\div 1.66}$ = 148117.5ft.lbs.; E(He) = 148117.5ft.lbs. ÷ $3420^{grams\ TNT}/_{ft.lbs}$ = 4.31grams TNT

Stored energy (E) = $E(H_2)$ = 92.54grams TNT

Stored energy (E) = $E(N_2)$ = 58.73grams TNT

Stored energy (E) = E(He) = 4.31grams TNT

MAWP (P1) = 400 psi

atmospheric pressure (P2) = 14.7 psi

ratio of specific heats (K) = H_2 = 1.14; N_2 = 1.41; He = 1.66 Values can be found in reference section H.

volume (V) = Pump Tube = 72 liters (2.5 $ft.^3$); Target Tank = 5152 liters (181.5 $ft.^3$)

TNT stored energy equivalents. ie
Ft.lbs. divided by 3420 = grams of TNT .

D. Pressure Testing / Leak Testing:

Pressure test procedure performed by an LLNL High Pressure Technician and witnessed by an LLNL Pressure Inspector.

Nitrogen Supply Line from Skid: Open the nitrogen skid valves and valve between the skid and the supply line. Once the nitrogen supply lines are charged, close the skid valves. Note the pressure on the gage located on the East Wall in Room 1200. If the pressure drops in 1 hour, check for leaks using snoop leak detection fluid or soap solution.

Nitrogen Purge Manifold: Set the slow-fill regulator for 160 psig, scrubber purge at 55 psig and the foreline fill at 55 psig. With the skid open and the nitrogen supply charged, open the purge manifold valves located on the West Side of the target chamber in Room 1200. Check for leaks using snoop leak detection fluid or soap solution.

Pressure Testing:(cont'd)

Pump Tube Preparation: (As per Preshot Data Sheet check list page 4 Rev.3/10/2000.) Install the piston, orifice ring and the breech plug. Install the piston velocity pins (four each) in the pump tube. Clear all loose objects from the breech platform. Open the air cushion valve. Traverse the pump tube into firing position. Place the traverse stops into position and connect hydraulic rams to the pump tube.

Accelerator Reservoir: (As per Preshot Data Sheet check list page 4 Rev.3/10/2000.) Check and install all o-rings and diamond seals in accelerator reservoir, retainer ring, pump tube and launch tube. Position petal valves and retainer ring into accelerator reservoir. Check installation of petal valves with the grooves facing muzzle end of launch tube. Check launch and pump tube hydraulic system connected and clamps tight. Check that the air is on for the accelerator reservoir housing and breech housing. Hold accelerator reservoir in position with launch and pump tube hydraulic system. Move accelerator reservoir housing into firing position. Secure large coupling nut to accelerator reservoir housing.

Pump Tube pressure Fill Preparation: (As per Preshot Data Sheet check list page 5 Rev.3/10/2000.) Open the nitrogen skid valves and valve between skid and supply line. On the control panel in Room 1122, close the N_2 fill valve. Open the pressure line valve. Close the pump tube vent valve. Open the pump tube fill and seal valves. Remove the run safe key from the control panel. Open the manual valves on the gas bottle racks for the pressure test (Note: If gas bottles are below 500 psig. Replace with new bottles.). Open the manual N_2 valve on the supply line (Note: If pressure of N_2 skid is under 1000 psig, have skid replenished.). Set the run safe boxes to unsafe (3 each) and return key to control panel.

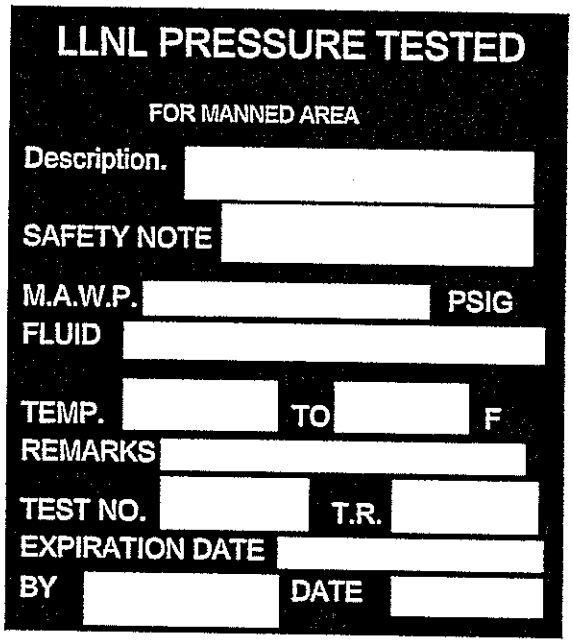
Pump tube Pressure Leak Check: (As per Preshot Data Sheet check list page 6 Rev.3/10/2000.) Close and lock all the exterior doors to the Gun Range. Check that the control panel run/safe interlocks are set to unsafe. Turn the outside warning lights on. Clear the range of all personnel. Sound one short blast on the range horn. Select the N_2 gas for the pressure test. Pressurize the pump tube to 90.0 psi. If the pressure does not hold $\pm$ 0.1psi for one minute, check for leaks using snoop leak detection fluid or soap solution. Once the system holds 90 psi $\pm$ 0.1 psi for one minute and the range is cleared of all personnel pressurize pump tube to 1.5 x M.A.W.P. or 560 psia and hold for one minute. Vent the gas before reentering the gunroom. If the pressure does not hold $\pm$ 0.1 psi for one minute bleed the pressure down to 90 psia, and re-leak test. Pressure test as prescribed above with each type of gas on the system.

E. Re-test/Re-inspection:

The entire system will be re-inspected every 3 years. The gas selecting, pressurizing manifold, and target chamber nitrogen purge manifold will be retested every 6 years as prescribed in the pressure test procedure by an LLNL High Pressure Technician and witnessed by an LLNL Pressure Inspector. The re-test shall be done at M.A.W.P. or 400 psia.

F. Labeling:

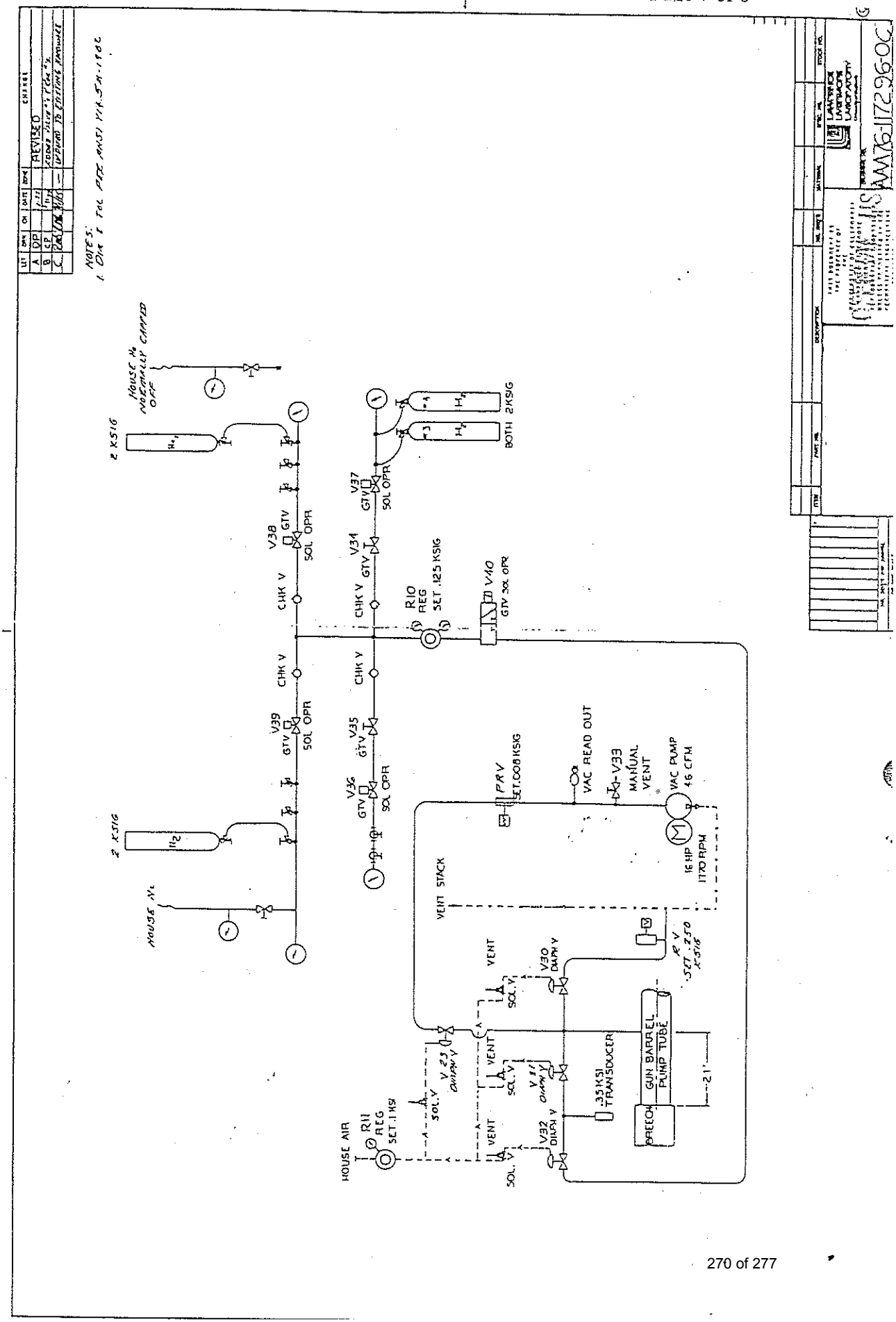
Description Two Stage Light Gas Gun
Safety Note
MAWP 400 psig
Fluid Nitrogen / Helium / Hydrogen **Temp.** Ambient
Test No.
Expiration Date

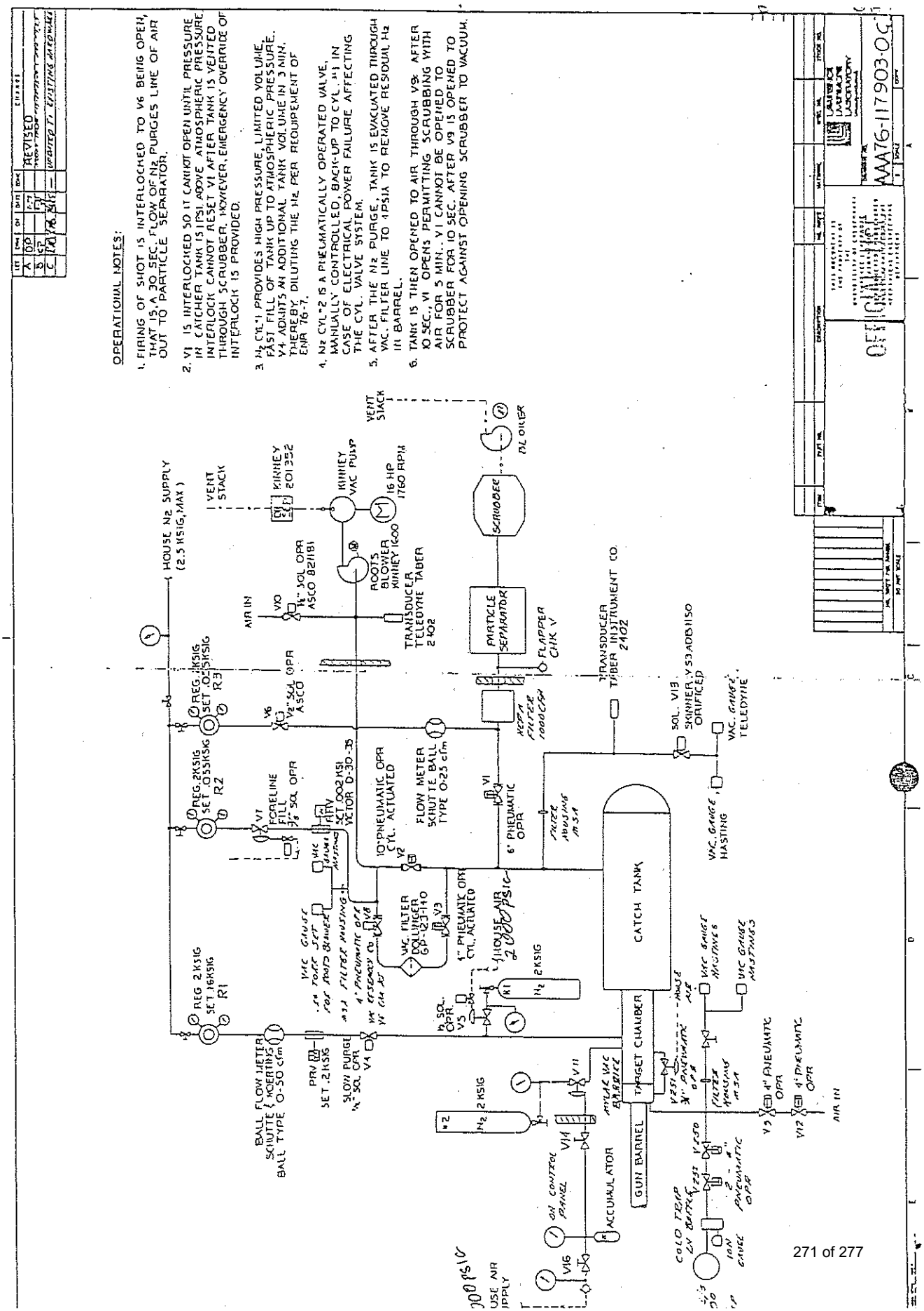


G. Associated Procedures:

1. Facility Safety Procedures FSP-341
2. Operating Safety Procedures OSP 341.139 Two Stage Light Gas Gun System
3. SP341.139
4. Two Stage Gas Gun Preshot Data Sheet Rev. 3/10-2000

Safety Note Number MESN04-519-AA
Page 7 of 8




OPERATIONAL NOTES:
1. FIRING OF SHOT IS INTERLOCKED TO V6 BEING OPEN, THAT 15.A 30 SEC. FLOW OF N2 PURGES LINE OF AIR OUT TO PARTICLE SEPARATOR.
2. V1 IS INTERLOCKED SO IT CANNOT OPEN UNTIL PRESSURE IN CATCHER TANK IS 1 PSI ABOVE ATMOSPHERIC PRESSURE. INTERLOCK CANNOT RESET V1 AFTER TANK IS VENTED THROUGH SCRUBBER, HOWEVER, EMERGENCY OVERRIDE OF INTERLOCK IS PROVIDED.
3. H2 CYL-1 PROVIDES HIGH PRESSURE, LIMITED VOLUME, FAST FILL OF TANK UP TO ATMOSPHERIC PRESSURE. V4 ADMITS AN ADDITIONAL TANK VOLUME IN 3 MIN. THEREBY DILUTING THE H2 PER REQUIREMENT OF ENR 76-7.
4. N2 CYL-2 IS A PNEUMATICALLY OPERATED VALVE, MANUALLY CONTROLLED, BACK-UP TO CYL #1 IN CASE OF ELECTRICAL POWER FAILURE AFFECTING THE CYL. VALVE SYSTEM.
5. AFTER THE N2 PURGE, TANK IS EVACUATED THROUGH VAC. FILTER LINE TO 4PSIA TO REMOVE RESIDUAL H2 IN BARREL.
6. TANK IS THEN OPENED TO AIR THROUGH V9: AFTER 10 SEC., V1 OPENS PERMITTING SCRUBBING WITH AIR FOR 5 MIN.. V1 CANNOT BE OPENED TO SCRUBBER FOR 10 SEC. AFTER V9 IS OPENED TO PROTECT AGAINST OPENING SCRUBBER TO VACUUM.
REVISED
HOUSE N2 SUPPLY (2.5 KSIG, MAX)
VENT STACK
KINNEY 201352
KINNEY VAC PUMP
16 HP 1760 RPM
ROOTS BLOWER KINNEY 1600
TRANSDUCER TELEDYNE TABER 2402
SCRUBBER
N2 OILER
PARTICLE SEPARATOR
FLAPPER CHK V
TRANSDUCER TIBER INSTRUMENT CO. 2402
SKINNER-Y53ADB1150 ORIFICED
VAC. GAUGE TELEDYNE
VAC. GAUGE HASTING
VAC GAUGE HASTINGS
CATCH TANK
TARGET CHAMBER
GUN BARREL
ACCUMULATOR
ON CONTROL PANEL
COLD TRAP
ION GAUGE
4" PNEUMATIC OPR
AIR IN
FLOW METER SCHUTTE BALL TYPE 0-25 cfm
10" PNEUMATIC OPR CYL. ACTUATED
6" PNEUMATIC OPR
VAC. FILTER COLUMBIA GP-23110
1" PNEUMATIC OPR CYL. ACTUATED
HOUSE AIR 2000 PSIG
REG 2KSIG SET 16KSIG R1
REG 2KSIG SET .05KSIG R2
REG 2KSIG SET .02KSIG R3
BALL FLOW METER SCHUTTE HOERTING BALL TYPE 0-50 cfm
PRV SET 2KSIG
SLOW PURGE N2 SOL OPR
FOREELINE FILL 3/8" SOL OPR
AIR IN
TRANSDUCER TELEDYNE TABER 2402
FLOW METER SCHUTTE BALL TYPE 0-25 cfm
OPERATIONAL
AAA76-117903-OC