NASA TECHNICAL MEMORANDUM

NASA TM X-52454

NASA TM X-52454

(NASA-TM-X-52454) HYDROGEN SAFETY MANUAL (NASA)

N75-72909

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HYDROGEN SAFETY MANUAL

Advisory Panel on Experimental Fluids and Gases
Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

This manual details the technical know-how and long experience of the Lewis Research Center in the handling and utilization of hydrogen. It is an integral component of the Lewis safety program. However, the information contained herein is also believed to have general applicability as an acceptable standard for meeting minimum safety requirements.

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1. INTRODUCTION

a. Scope

This manual is designed to cover most aspects of hydrogen handling and usage. Both personnel and equipment are concerned. It is the intent to present here acceptable hydrogen standards and practices for minimum safety requirements only. More extensive safety precautions should be employed when there is extra hazard, as in highly-congested areas or in operations with equipment that has little safety margin.

b. Approach to Hydrogen Safety

(1) Hydrogen operations must be carried out in such a way that the life and health of personnel are not jeopardized and that the risk of damage to property is minimized. The following principles shall be adopted:

(a) Inherent Safety - Hydrogen systems and operations shall have a high degree of built-in safety. This will be attained by proper design, construction, and procedure, observing all three of the basic axioms for hydrogen safety: adequate ventilation, leak prevention, and elimination of ignition sources.

(b) Two Lines of Defense - In addition to the inherent safety features, at least two barriers or safeguards shall be provided to prevent a given failure from mushrooming into a disaster. For instance: one safeguard against spillage might be a leak detector which automatically shuts off the flow; a second might be a shield to protect other equipment and a safe shelter for personnel.

(c) Proper Controls - Safety functions such as leak detection and ventilation shall be automatically controlled. Operating functions such as flow rate and pressure may be controlled either automatically or manually, as appropriate to the system. However, even simple tests will require automatic control if prolonged or repetitive, because of the tendency for personnel to become inattentive and careless. In any case, manual controls must be constrained by automatic limiting devices to prevent over-ranging.

(d) Fail-safe Design - Whenever possible, failure (including momentary failure) of equipment, power, or other service shall cause the system to revert to the condition which will be safest for personnel and property.

(e) Alertness - Employees must be ever alert to all aspects of safety. They must constantly re-examine procedures and equipment to be sure safety has not been compromised or impaired by changes in program or test methods, over-familiarity with the work, deterioration, or stresses due to abnormal conditions, etc.

2. NATURE OF THE HAZARD

a. Properties and Hazards of Gaseous Hydrogen

Specific gravity 68°F (air = 1.00)	0.06953
Density lb./ft^3 (60°F and 30" of Hg)	0.00532
Density lb./ft^3 (-422.9°F + 30" Hg)	0.084
Specific volume ft.^{3}/lb. (60°F and 30" of Hg)	187.9
Critical temperature	-399.8°F
Gross heat of combustion BTU/ft.^{3}	325.1
Gross heat of combustion BTU/lb.	61.084
BTU/ft.^{3} of stoichiometric gas/air mixture (F/A ratio, 0.418 vol., 0.029 wt.; or 29.5 H_2 by vol.)	81.3
Ft^3 of air required per ft^3 of combustible	2.382
Lb. air required per lb. combustible	34.226
Maximum flame temperature (F/A ratio 0.462 vol., 0.0313 wt.; or 31.6% H_2 by vol.)	3865°F
Autoignition temperature in air	1065°F
Autoignition temperature in oxygen	1040°
Flammability limits, % vol. H_2 in air	4.0 - 75.
Flammability limits, % vol. H_2 in oxygen	4.5 - 94.
Detonation limits, % vol. H_2 in air	18.3 - 59.
Detonation limits, % vol. H_2 in oxygen	15.0 - 90.
Nonflammable limits, air-hydrogen-carbon dioxide,	less than 8% O_2
Nonflammable limits, air-hydrogen-nitrogen,	less than 5% O_2

Minimum spark ignition energy in air (atmospheric pressure) 0.000019 joule
Minimum spark ignition energy in oxygen (atmospheric pressure) 0.000007 joule

(1) Hydrogen gas is colorless and odorless, thus it is not detected by the senses.

(2) Although not toxic, hydrogen gas can cause suffocation by diluting air to exclude oxygen.

(3) At normal temperatures, hydrogen gas is lighter than air so that it tends to rise. But, if the temperature of hydrogen gas is less than -418°F, as just after evaporation from the liquid, it is heavier than air at normal temperatures and tends to fall; however, wind or forced ventilation will affect the direction of motion of released hydrogen regardless of its rising or falling tendency.

(4) When mixed with air or oxygen, hydrogen gas forms a highly flammable mixture over a wide range of mixture ratios. (See foregoing)

(5) Ignition of explosive mixtures occurs with very low energy input, one-tenth that of a gasoline-air mixture. An invisible spark can cause an explosion.

(6) Temperatures of about 1,000°F are usually required for the ignition of hydrogen and air or oxygen mixtures. (See foregoing) However, at less than atmospheric pressure, i.e., at 2/10 to 5/10 atmosphere ignition will occur if temperatures as low as about 650°F are maintained long enough.

(7) Hydrogen flames are colorless. Any visibility is caused by impurities.

(8) Severe burns have been suffered by persons exposed to hydrogen flames resulting from the ignition of hydrogen gas escaping from small leaks in laboratory apparatus.

b. Properties and Hazards of Liquid Hydrogen

Melting point at atmospheric pressure	-434.6°F
Boiling point at atmospheric pressure	-422.9°F
Critical temperature	-399.8°F
Critical pressure	12.8 atmos.
Specific gravity (liquid, water = 1.00)	0.07 (4.37 lbs./cu. ft.)

Specific heat BTU/lb./°F	0.57
Heat of fusion BTU/lb.	25.2
Viscosity (at normal b.p.)	132×10^{-6} poises
Heat of vaporization (nearly all para)	190.5 BTU/lb.
Vapor pressure (psig):	-433°F -12.8
	-423°F 0
	-420°F 9.0
	-402°F 147.3

(1) All of the hazards which exist when gaseous hydrogen is present are equally serious with liquid hydrogen because of the ease with which the liquid evaporates.

(2) People have died from exposure to rather small local flash fires resulting from the ignition of gas produced by the evaporation of small amounts of liquid hydrogen.

(3) The continuous evaporation of liquid hydrogen in a dewar causes the constant generation of gaseous hydrogen which must be either vented to a safe location or temporarily confined safely.

(4) Vents from storage dewars containing liquid hydrogen may be closed by accumulations of ice frozen from moisture in the air. Excessive pressure may then rupture the container and release a quantity of hydrogen.

(5) Liquid hydrogen is subject to contamination with air condensed and solidified from the atmosphere or by accumulation of traces introduced in manufacturing. This mixture is unstable and may detonate with effects similar to those produced by TNT and other high explosives.

(6) Liquid hydrogen splashed on the skin or in the eyes can cause serious "burns" by freezing.

c. Explosion and Detonation of Hydrogen-Air Mixtures

Hydrogen gas, like other fuels, can burn in two modes. The ordinary mode of burning is called deflagration, in which the flame travels through the mixture at subsonic speed. This happens, for instance, when an unconfined cloud of hydrogen-air mixture is ignited by a small ignition source. Under these circumstances, the flame will travel anywhere from ten to several hundred feet per second. The rapid expansion of hot gases produces a pressure wave. Witnesses will hear a noise, often a very loud noise, and may say that an explosion occurred. The pressure wave from rapid unconfined burning is not extremely severe, although it may well be strong enough to damage nearby structures.

(1) The other mode of burning is called detonation, in which a flame and shock wave travel together through the mixture at supersonic speed.

(2) A detonation will often build up from an ordinary deflagration that has been ignited in a confined or partly-confined mixture. This is true even though ignition may have been caused by a minimal energy source.

(3) On the other hand, it takes a powerful ignition source to produce detonation in an unconfined hydrogen-air mixture. Something like a blasting cap, a few grams of high explosive, or an exploding wire, is required.

(4) The pressure ratio across a detonation wave in hydrogen-air mixture, as seen when the wave passes a detector mounted flush in a confining wall, is about 20. (A pressure ratio of 20 means 300 psi if the mixture is at atmospheric pressure.) When the wave strikes an obstacle, the pressure ratio seen by the obstacle is multiplied 2 to 3 times, or 40 to 60. Even larger pressure ratios occur locally in the region where a deflagration transforms to a detonation.

d. Diffusion and Leakage of Hydrogen

(1) Diffusion

(a) Hydrogen diffuses approximately 3.8 times faster than air. A spill on the ground of 500 gallons of liquid hydrogen will have diffused to a non-explosive mixture after about one minute.

(b) Air turbulence increases the rate of hydrogen diffusion.

(2) Leakage

Hydrogen in both the liquid and gaseous states is particularly subject to leakage because of its low viscosity and low molecular weight. Leakage is inversely proportional to viscosity. Because of its low viscosity alone, the leakage of liquid hydrogen will be roughly 100 times that with JP-4 fuel, 50 times that with water and 10 times that with liquid nitrogen. Likewise, the leakage of gaseous hydrogen will be approximately twice that for air.

3. DESIGN PRINCIPLES

a. Safety Approval of Design

(1) Before hydrogen facilities, equipment or systems are constructed, fabricated or installed, approval for safety of design shall be obtained from the appropriate safety authority.

(2) To assure a proper safety review, information in writing or sketch form must be presented for a safety of design review and approval in these stages:

(a) preliminary or lay-out; hazard and failure-mode analyses
(b) final drawings; design details, structure and containment
(c) draft of operational procedures; instrumentation, detection

b. Detection of Combustible

Means shall be provided for detecting the presence of free hydrogen in all areas in which there is a possibility of a hazardous accumulation. Because hydrogen is both odorless and transparent, detection by odor or vision is not feasible. The cloud of frozen air and moisture which accompanies leaks from liquid hydrogen is visible. Detection of leaks by observation of such clouds may not be reliable, however, because clouds of water vapor also rise from cold exposed surfaces when no hydrogen leak is present. Detection of leaks by observation alone is not adequate.

(1) Response of Detection Equipment

(a) In order to be effective, detection equipment must respond with sufficient rapidity to avoid a hazardous accumulation. Large leaks in small rooms require fast detection and shut-off means. Detector pickups must be located so as to minimize sampling times.

(b) The number and distribution of detection points and time required to effect shut-off should be based on factors such as: possible leakage rates, ventilation, and volume of room. If time permits, the detection signal may actuate warning alarms, otherwise it should automatically effect shut-off.

(2) Gas Detectors

(a) Approved Types

The response and the sensitivity of the detector may be influenced by the presence of moisture or by mixtures of gases such as nitrogen, helium, and carbon dioxide. The result would be a false reading of the atmosphere being probed. In addition, unless the device is equipped with the proper flash back arrestor, it may become the trigger for an explosion. Therefore, only units validated for hydrogen-air atmospheres shall be used.

1. Manually carried portable gas detectors shall not be used as the gas detection means for test installations which require that personnel be located remotely during test periods.

c. Design of Buildings and Chambers

(1) Test Buildings

(a) Hydrogen operations are safest when conducted out-of-doors where leaks of hydrogen are diffused and diluted to non-combustible proportions most easily.

(b) However, if protection from the weather is required, the order of preference of buildings is as follows:

1. roof without peaks and no sides
2. well-ventilated roof and removable sides
3. well-ventilated "expendable" building
4. well-ventilated permanent building

(c) When hydrogen operations must be carried on in permanent buildings, reliable and plentiful ventilation or inerting atmosphere must be provided. Ignition sources must be eliminated or rendered harmless. Suspended ceilings and inverted pockets are to be avoided or adequately ventilated.

(d) Non-combustible materials shall be used for building or equipment construction. The only combustible material allowed in the hazard area shall be that required for test purposes.

(e) Window panes shall be made of plastic, not glass, and hinged to swing outward in case of an explosion.

(f) Hydrogen test-supply dewars and trailers shall be kept out-of-doors and located so that any leaks will not get into any building.

(g) Dikes, trenches or ground slope shall be used to confine or divert spillage from buildings, sewers, etc.

(h) Amounts of hydrogen in test rigs inside of buildings shall be kept at a minimum and the permissible amount shall be approved by the appropriate safety authority.

(2) Control Rooms

(a) A pill-box type of control room, located remotely from the hydrogen test site, is advisable.

(b) No hydrogen piping shall enter the control room. Any control valve shall have a double diaphragm between the hydrogen line and the control room. Conduits shall be sealed at the test rig end. The seal shall be tested to prove its effectiveness.

(c) If wall openings, etc. cannot be sealed, any hydrogen-containing cell with openings to other rooms shall be maintained at a negative pressure relative to communicating rooms.

(d) Any window opening into a test cell where excessive pressures or ricocheting fragments could be present must be considered a hazard. If a window is required, it should be made as small as practical and should be of bullet-proof glass or the equivalent. A mirror system or a movable steel panel can be used to advantage in some cases.

(3) Ventilation

(a) Test Buildings

1. Any test cell or chamber containing hydrogen system components shall be adequately ventilated at all times while hydrogen is in the system. Air quantities or other inerting means shall be sufficient to avoid an explosion and shall be based upon the potential volume of the leakage gases relative to the room volume, the time available for instituting corrective measures, and the flammability limit. Ventilation shall be established prior to entry of hydrogen into the system involved and continued until the system

has been purged. Ventilation shall not be shut off as a function of an emergency shutdown procedure.

2. Warm hydrogen gas rises rapidly and is trapped by inverted pockets. Avoid covers or any form of pocket which may trap hydrogen gas.

(b) Control Rooms

Particular attention shall be paid to the ventilation or source of air for control rooms that may, in case of emergency, be enveloped in combustible or the products of combustion.

(4) Inert Atmosphere by Exclusion of Oxidant

(a) Use of Inert Gas

Test chambers, etc. which cannot be ventilated sufficiently to cope with potential hazards may be rendered non-hazardous by providing an inert atmosphere of N_2, CO_2, He, or other inert gas. In such cases, it is desirable to have the chamber pressure higher than atmospheric to avoid inward leakage of air.

(b) Use of Partial Vacuum

Oxidant may be restricted in a test chamber by partial vacuum. The vacuum should be sufficient to limit the pressure of an explosion to a value that the tank can withstand. In this case, the chamber shall be capable of withstanding 20 times the maximum operating pressure, except for heads, baffles and other obstructions in a pipe run, which must withstand 60 times the maximum operating pressure. Because the reaction time during a detonation is of such short duration, ultimate stress values may be used.

d. Design for Vessels

(1) Storage Vessels for Hydrogen (General)

(a) Liquid Hydrogen

Liquid hydrogen is stored out-of-doors in dewars (multiple walled insulated containers) that are designed to minimize the evaporation losses. Heat flux into the stored product via conduction, convection, and radiation is kept at a minimum with proper construction and maintenance practices. Materials for construction of the surfaces exposed to the cryogen must retain the necessary mechanical properties and not tend towards low temperature embrittlement. Face centered cubic metals and alloys such as aluminum, copper, nickel and austenitic stainless steels are generally used. The outer wall or vacuum jacket may be fabricated from mild steels since it is not subjected to the cryogenic temperature. Section VIII of the ASME Boiler and Pressure Vessel Code is generally followed for the vessel structural design. The types of insulation employed are:

1. high vacuum (1 to 50 microns measured with the dewar at ambient temperature)

2. high vacuum plus powders such as perlite, silica aerogel, diatomaceous earth, fused alumina, phenolic spheres, etc.

3. multiple layers of highly reflecting radiation shields separated by spacers or insulators plus a high vacuum.

4. Insulation is maintained at the supports by using materials with a low thermal conductivity, (Hastelloy, titanium). Long reach techniques are used to connect plumbing to the product tank so as to increase the resistance of the heat path.

Note: Liquid nitrogen radiation shielded dewars are rapidly being superseded with one of the dry insulation types.

Portable laboratory dewars shall be of the dual entry or the modified entry type to avoid plugging hazards. (See Appendix 6)

(b) Gaseous Hydrogen

Large volumes of gaseous hydrogen are stored out-of-doors in mobile or fixed cylinders. Mobile tube trailers of approximately 70,000 SCF capacity, filled to about 2400 psig, have been state-of-the-art for many years and have not exhibited any undue operating problems. Vessels for very large volumes and/or higher gas pressures have not always been trouble-free. Part of the problem is in fabricating very large vessels, and part of it is due to hydrogen embrittlement at high pressures.

1. Based on experience gained from use, a number of materials are acceptable for hydrogen use at elevated pressures, namely, A 302-B, A 212-B, A-372 grade 4 for side walls, and ASTM A225 grade B heads. Austenitic stainless steel and other more exotic materials are acceptable but costly and may be considered for liners. (Martensitic stainless steels such as 403 should not be used for gaseous hydrogen.)

2. No unrelieved side-wall penetrations should be made. If pressure gage or liquid drain holes are needed, consider entry through the forged heads, using dip-tube where appropriate.

3. For large diameter vessels, include a manway for regular visual inspection.

4. Avoid use of T-1 steel until more uniform and better controlled fabrication procedures can be established.

(2) Design Criteria for Dewars and Cylinder Trailers

(a) Shut-Off Valves

1. Dewars (mobile size) for filling test rigs may be equipped with manually-operated shut-off valves providing:

   a. the valve is attended by the "buddy-system" during filling, and

   b. the dewar pressure does not exceed 20 psig during filling operations.

2. Dewars actively used as part of a test rig shall have remote-operated "fail-safe" shut-off valves adjacent to the dewar, upstream of any coupling or flexible piping. A manual over-ride shall be provided for use in case of power failure.

(b) Electrical Equipment

Electrical equipment shall conform to the National Electric Code requirements for Class 1, Group B, Division 2 as a minimum.

(c) Electrical Grounding

Electrical grounding and lightning protection shall be provided. Grounding shall be by at least #8 AWG cable with readily attachable and detachable connectors. The integrity of the grounding system shall be verified routinely.

(d) Connections

All mobile dewars and tube trailers must have anchored flexible connections to any rigidly mounted test cell equipment to allow for flat tires, or rear trailer jacks or axle shoring must be used to prevent sagging motion.

(e) Vents

All dewars shall be equipped with a vertical unobstructed vent designed to prevent entry and accumulation of atmospheric precipitation. Dewar vent system shall be connected to a building hydrogen vent system when the dewar is parked near a building; the system shall be designed to carry vented hydrogen to a safe release location above the roof of the building.

(f) Plumbing

1. Liquid plumbing and components that are wetted by the cryogen shall be vacuum jacketed. The plumbing jacketing shall be separated from that of the main void or product vessel jacket.

2. Valves and other components that are subject to cold gas flows or low temperatures shall be suitable for this cryogenic service.

(g) Bottom Openings

1. Bottom openings on liquid hydrogen containers shall be avoided wherever possible.

2. Low points (traps) on liquid discharge piping are to be avoided to prevent accumulation of contaminants. If they are unavoidable, provide low point drains.

(h) Gas Tube Trailers

Gas tube trailers used for different gases shall have different connecting fittings so as to prevent cross connection of different gases. Gas tube trailers shall be equipped with normally closed safety shut-off valves which require sustained control power to remain open and will automatically return to full "closed" upon removal of power. This is an addition to the manually operated cylinder and main stop valves. Relief devices are to conform to ICC regulations for this service.

(i) Valve Cabinets

Valve cabinets shall be well ventilated.

(j) Visibility

The research dewar and test rig shall be visible from the control room or a safety observer. Closed circuit TV is satisfactory.

(3) Protection of Dewars

(a) Barricades

All dewars shall be protected from shrapnel. Barricades shall be installed near the test rig to protect the dewar if blast fragments or disintegration of high speed machinery could cause hazard. In the case of a high rotational speed test rig, the housing may be designed as the shrapnel shield between the rig and the dewar.

(b) Pressure Relief Devices

All pressure vessels are to be equipped with burst diaphragms set for a pressure which is not more than 25 percent above the maximum working pressure of the vessel. The burst disc housing should be located so that its temperature does not vary appreciably, and its material and design should be selected according to temperature. A relief valve, set to not more than 10% above the maximum working pressure of the vessel, shall be installed in parallel with the rupture disc. The outlet of the burst diaphragm and relief valve should be ducted away from the work area in the same manner as the tank vent lines.

(c) Redundant Burst Discs

The mobile dewars shall be equipped with two burst disc safety assemblies connected to the product vessel through a 3-way selector valve to permit isolation of a ruptured element for safe replacement. The valve shall not have a center-off position.

(4) Transfer Connections

(a) Gaseous Hydrogen Transfer Connections

1. Gaseous hydrogen trailer connections to rigidly mounted test cell piping shall conform to established standards of the ASME and API. Hoses shall be restrained by a Chinese-finger assembly (cable grip) to prevent lashing in the event of rupture.

2. To prevent infiltration of air, the cylinder pressure should not be allowed to fall below 25 psig.

(b) Liquid Hydrogen Transfer Connections

1. Dewar connections to rigidly mounted test cell piping shall use a supported and anchored flexible metal hose insulated by vacuum or other method for low temperature service at the desired pressure.

2. Bayonet-type couplings shall be used. The fasteners may be of the bolted flange, spanner nut or V band coupling types designed for the required operating pressure. See Appendix 1 for suitable V-band types.

3. Gasket materials suitable for this cryogenic service shall be employed. (Reference: Ballistic Systems Division memo dated 12-17-62; see Appendix 2) Loose fibre gasket material that can readily be fretted shall not be used since the loose particles may contaminate the system. Properly sized gaskets shall be used. "O" ring and "O" ring grooves shall be matched properly for the design service conditions.

e. Material and Hardware

(1) Summary of Typical Metals

In general, permissible materials of construction for liquid hydrogen systems include aluminum, copper, monel, inconel, austenitic stainless steels (types 304, 304L, 308, 316, and 321) and brass and bronze. Stainless steel of type 347 is very sensitive to cracking during welding and should not be used unless proper welding precautions are taken. The actual selection of materials depends on requirements of the specific application such as thermal conductivity, strength, porosity, weight, and cost.

(2) Dissimilar Metals

Contact of dissimilar metals in liquid hydrogen systems or containers is to be avoided, as this may encourage corrosion. Also, differences in thermal contractions and expansions must be considered.

(3) Piping Systems

(a) Threaded joints are acceptable for use on gaseous hydrogen systems with suitable thread seal. Threaded joints inside a building are to be back welded to prevent leaks. Threaded joints are to be avoided on liquid hydrogen systems.

(b) Cryogenic liquid piping should be vacuum jacketed for low heat leakage. Provision for expansion or contraction shall be provided. Adequate supports shall be provided.

(c) High pressure gas manifolds are to be constructed of 300 series (with 347, special welding precautions required) stainless tubing and are to be welded construction wherever possible. Provisions for expansion or contraction shall be provided; adequate supports shall be provided.

(d) In vent piping a check valve shall be located near the atmospheric discharge to prevent back-flow of air. If over one-inch in diameter, the vent piping shall be purged (with nitrogen preferably) immediately before, and immediately after flowing hydrogen. Purging during hydrogen flow or of a vent pipe of one-inch diameter or less is not required.

(e) A burst diaphragm or a relief valve should be installed in every section of a line where liquid can be trapped. This condition exists most often between two valves in series. A burst diaphragm or relief valve may not be required if at least one of the valves will, by its design, relieve safely at a pressure less than the design pressure of the liquid line. This procedure is most appropriate in situations where bursting of the diaphragm could create a serious hazard.

(f) In critical areas where pipes, vessels, or instruments containing hydrogen are subject to failure, the container shall be shrouded and the shroud vented.

(g) Important equipment should not be placed over hydrogen containers or systems where a hydrogen leak-fire would cause damage.

(4) Tube Fittings

(a). For Steel and Stainless Steel Tubing

Steel and Stainless Steel Fittings	Maximum Size	Pressure Limit
Flareless	1/4 inch	Tube strength with proper safety factor
Flared	* 1 inch	Tube strength with proper safety factor
Flared	** 1 1/2 inch	** 125 psig

** Use flanged or welded joints for steel tube sizes greater than 1 inch and pressures greater than 125 psig.

** It may be desired to use flared fittings in some cases involving pressures higher than 125 psig and tube sizes larger than 1 inch. If so, these cases are to be considered special and shall be submitted to the appropriate safety authority for decision.

* Use of flared fittings requires high quality tools and workmanship. For tube sizes larger than 3/4-inch power machines are necessary to obtain the required quality of flare.

Aluminum Fittings	Maximum Size	Pressure Limit
Flareless	Not approved	Not approved
Flared	3/8 inch	Tube strength with proper safety factor

(b) For Copper-Base Tubing and Aluminum Tubing

Copper-Base Fittings and Aluminum Fittings	Maximum Size	Pressure Limit
Flareless	Not approved	Not approved
Flared	Industrial practice	Tube strength with proper safety factor

(c) Only stainless steel should be used where there are limitations on fittings as a result of fire hazards for hydrogen, oxygen, and hydraulic systems. Aluminum or copper would melt and release the hydrogen, etc. to increase the extent of the damage. Of course, for specific applications such as heat exchangers in the research apparatus other materials may be required.

(d) Tightening of fittings shall be in accordance with the manufacturer's recommended limits.

(5) Teflon and Similar Compounds

(a) Kel-F (polytrifluorochloroethylene) or teflon (polytetrafluoroethylene) can be used in liquid hydrogen systems for:

1. Valve seats: May be modified teflon (Fluorogreen is preferred)

2. Soft coating on metallic O-rings to provide more positive seal.

3. Flat-thin gaskets for tongue-and-groove type flanges where gasket is shrouded on four sides.

4. Spacers in vacuum area between liquid flow tube and vacuum pipe.

5. Gland packing or seal only if it is maintained near ambient temperatures as in an extended bonnet of a shutoff valve. The contraction or shrinkage of teflon when cooled from ambient to cryogenic temperatures allows leakage.

(b) For gaseous hydrogen at ambient temperature, the valve seat materials can be the conventional composition type.

(6) Metal O-Rings

(a) Metal O-rings have proven satisfactory for sealing flanges on liquid hydrogen piping and vessels only when coated with a soft material and when used on smooth surfaces.

(b) Type 321 stainless steel O-rings, with a coating such as teflon or silver, should be used in stainless flanges with stainless bolting.

(c) Likewise, teflon coated aluminum O-rings should be used in aluminum flanges with aluminum bolting. Using similar materials avoids the leakage possibility from unequal contraction of dissimilar metals.

(d) Surface finishes in the O-ring groove and contact area should be at least 32 microinches r.m.s. All machine or grind marks must be concentric.

(7) Allowable Stresses

For liquid or gaseous systems, the stress for vessels or tubing shall be no greater than 50 percent of the minimum yield of the material at 70°F.

(8) Thermal Contraction

Thermal contraction of a liquid hydrogen system of stainless steel is usually calculated from ambient to minus 420°F as 0.35% of the original length. Long runs of piping require a support at intervals to allow for the axial motion, with lateral and/or vertical motion restrained.

f. Fabrication Methods for Fused Joints

(1) General

The fused joint, because of its simplicity and high reliability, finds many applications in both gaseous and liquid hydrogen systems. Soft soldering, hard soldering, and welding can often meet the bonding requirements; however, for safety reasons the welded joint takes first preference and in numerous cases is mandatory. In addition to the high structural efficiency and fatigue resistance of a properly executed weld, it is often the only fused joint which has a melting point substanti·'ly equal to that of the bulk structure. This is a potent safety factor where, in the advent of an accidental fire, a melted joint could release additional large quantities of fuel. In large systems, such failures could develop into a "chain reaction" affair. For this reason all general purpose liquid or gaseous hydrogen systems should be constructed of high melting point materials.

(2) Welded Joints

Welding is the first preference for all hydrogen systems and all forms of welding can be used. The type of weld to be used is generally determined by factors other than the fact that the system is for hydrogen use. Heliarc is generally preferred for joining light gauge stainless steel and is often preferred for construction of vacuum jacketed equipment. Conventional arc techniques are also used extensively especially for heavy gauge material where cost is a strong factor. Filler material and stress relieving requirements are determined by the parent material to be joined and normal standard practices should be followed.

(3) Silver Solder Joints

No unique problems have been encountered with these materials. The choice of solder composition is determined by ease of application to the material to be joined. Silver solders are recommended for joining copper base materials and for joining dissimilar metals such as copper to stainless steel. The melting point must be greater than 1000°F.

(4) Soft Solder Joints

(a) Soft solder joints are not permissible in hydrogen systems except in non-critical locations such as wiring which, if it failed, would not result in a hazardous condition.

(b) Soft solder joints are unacceptable for two reasons. First, the solder has a low melting point and will quickly fail in case of fire, releasing more hydrogen. Second, soft solders containing tin may become crumbly and lose all strength at cryogenic temperatures.

g. Pressure Tests

(1) New equipment shall be tested in accordance with applicable codes.

(2) Tagging of Pressure Vessels

All pressure vessels shall be tagged to show the date and level of test.

(3) Leak Test

A helium leak test by mass spectrometer shall be made on liquid hydrogen containers before and after the vessel or piping is cold shocked by liquid nitrogen. No leak shall be permitted which can be detected at the most sensitive leak rate position on the mass spectrometer.

h. Contamination

(1) Use of Filters

Adequate filters shall be used on hydrogen and associated systems. The filter system shall be placed so as to effectively collect the impurities in the system and shall be accessible for cleaning.

(2) Types of Filters

Filters with sintered-metal elements are not recommended for liquid hydrogen or other cryogenic systems, because the little balls of metal tend to spall off and get into sensitive parts of the system. Filter elements made of non-calendered woven wire mesh are preferred. The filter should retain 100% of particles greater than 150 microns in diameter, as a general rule. However, some systems may require more stringent standards.

(3) Interconnected Systems

(a) Interconnection of Systems

1. When interconnection of different systems operating at

different pressure levels would damage a lower pressure system, adequate means to prevent such damage shall be provided.

2. For example: If a third system must be supplied at times from a high pressure supply system and at other times from a lower pressure system, the lower pressure system may be protected by:

   a. Providing a non-standard spool piece which can be placed in alternate positions in the interconnecting piping so as to isolate the high and low pressure systems from each other.

   b. Providing a non-standard elbow which can be swung into alternate positions so as to isolate the high and low pressure systems from each other. In this and the foregoing design, blank flanges will effect necessary changes. A tee may not be substituted for the elbow.

   c. If it is necessary to have piping installed so that the third system may be supplied through valves from either the high or low pressure system, a relief valve or frangible disc may be used to protect the low pressure system. If desired, a small relief valve, capable of relasing expected leakage through the control valve and set to release at a pressure below the breaking pressure of the frangible disc, may be used in parallel with the frangible disc.

   d. Pressure regulating valves, shut-off valves and check valves do not provide adequate protection for low pressure systems which are connected to high pressure systems. Because of this fact, means must be provided for pressure relief in the low pressure system.

3. Explosion hazards in interconnected process systems, dewars, tanks, storage bottles, etc., as might be caused by leakage of hydrogen from one system into another shall be prevented by application of the following principles:

   a. The tightness of valves of any type shall not be relied upon as a means of avoiding unwanted leakage.

b. Under circumstances similar to those described in the foregoing for over-pressurization, like means of protection may be employed.

c. In cases in which the pressure differences in the systems cannot be used in conjunction with relief valves for preventing unwanted leakage, the hydrogen supply shall be disconnected and capped when the system is not in active use. (A combustion chamber connected to an altitude exhaust system is an example of this kind.)

(b) Check Valves

1. For bubble-free tightness check-valves shall not be used.

2. Two check-valves in series have been found to be unreliable. In fact, in some cases, a single check-valve has been more leak proof because the larger pressure drop closes the check-valve more tightly.

3. Instances have occurred of the contamination of bottled gases, because of check valves leaking in interconnected systems. Suppliers of bottled gases specifically prohibit contaminating gases in their bottles. Further, the safety of laboratory operations requires that bottled gases must not be contaminated. Check-valves might be completely tight at the start of service and develop leaks after being in service. If the contaminant pressure must be higher than the bottle pressure, two shut-off valves with a bleed valve between them must be used. If desired, a check-valve may be used in the vent line, to limit the influx of air. Check-valves may be used if bottle pressures are not permitted to fall within 25 psig of the contaminating pressure. That is, a safety pressure margin must be maintained.

4. Check-valves may be used in cases where system contamination is not important.

i. Venting

Apparatus in which hydrogen is used must be equipped with vents for normal operating requirements. In addition, special vent capacity may be required to protect the equipment in the event of an explosion. Vents should be placed so as to avoid possible contamination of air intakes leading into a building. The vent discharge shall be at least 15 feet above any roof peaks or parapet.

(1) Vent Quantities

(a) Allowable vent quantities from a single vent are subject to conditions such as wind direction and velocity, proximity of airplanes, distance from dwellings, etc.

(b) The effect of wind is to prevent gas from a vent from accumulating and to channel the gas in a stream downwind. Generally, the higher the wind velocity, the farther the stream of gas extends before diffusion occurs, although turbulence greatly increases the rate of diffusion. If the wind direction is satisfactory, fairly large quantities of hydrogen can be dissipated from a single vent. Generally, however, wind velocity and direction are not sufficiently reliable for this purpose.

(c) At Lewis Research Center-Cleveland, the allowable quantity of unburned hydrogen from a single 2-inch pipe roof-vent has been fixed at 0.25 lbs/sec. released at least 15 feet above a roof peak. This limitation was adopted because the site is congested. Multiples of these roof vents may be used at spacings of 15 feet and across the prevailing wind. Use with wind parallel to the multiple vents is questionable.

(d) At Plum Brook Station, an uncrowded area, the allowable flow of unburned hydrogen is 0.5 lbs/sec. from a single vent released at least 15 feet above a roof peak.

(2) Interconnection of Vents

(a) If more than one vent discharge is connected to the same vent stack, there is danger of over-pressurizing parts of the vent system unless the size of the vent is sufficient to care for any eventuality. For example, if a burst disc ruptures and over-pressurizes the vent system, the flow may back into parts of the system incapable of taking the pressures involved. In another example, over-pressurization of the vent system changes the effective release pressure of all relief valves and burst discs connected to the vent system. In this manner, over-pressure in the vent system could cause over-pressure and failure of connected apparatus.

(b) Therefore, avoid the connection of high pressure, high capacity vent discharges and low pressure vent discharges to the same vent stack unless the vent capacity is sufficient to avoid over-pressurization of the weakest part of the system.

(c) The discharge from vacuum pumps handling hydrogen shall be ducted to suitable vents.

(3) Venting of Explosions

(a) Tests show that the maximum explosion pressure produced in a tank containing hydrogen-air mixture at atmospheric pressure is about 70 psi when the vent area is one square foot per 100 cubic feet of tank volume. With a ratio of 4 square feet per 100 cubic feet, the maximum explosion pressure drops to about 25 psig. In pipe lines or long narrow tanks, it may not be possible or practical to provide effective venting against an explosion.

(b) Explosion vents shall not be connected to vent systems for hydrogen gas.

j. Disposal

(1) Hydrogen Disposal by Burning

Disposal of larger quantities of hydrogen than can safely be handled by roof vent systems is best accomplished in a "burn-off" system in which the liquid or the gas is piped to a remote area and burned with air in a multiple burner arrangement. Such systems are operated with pilot ignition means, warning systems in case of flame-out, and means for purging the vent line. Attention shall be given to the stress, thermal contraction, and support problems of the long pipe lines involved. Consideration shall be given to removal of ignitable substances in the vicinity and hazards to low-flying airplanes. (See Appendix 5 for discussion of flame heights on hydrogen burn-offs.)

(2) Hydrogen Disposal Into Laboratory Exhaust Systems

Unburned hydrogen may be dumped into the exhaust systems only under the following conditions:

(a) Lean Mixture Operations

It shall be permissible to introduce into the exhaust system hydrogen-air mixtures leaner than 0.0068 by weight. This figure is based on known detonation limits and not on the lower limit of flammability. This statement applies to all phases of operation including engine blowout, failure to start, etc. In the calculation of fuel-air ratio, non-condensable inert gas which is added to the system may be considered as "air."

(b) Safe Operation by Design of System

Fuel-air mixtures richer than 0.0068, by weight, may be introduced into an exhaust system providing the entire system is capable of withstanding a detonation of the mixture. The system shall be capable of withstanding pressures 20 times the maximum operating pressure except for heads, baffles, elbows, and other types of obstructions which must withstand 60 times the maximum operating pressure. Because the reaction time is of such short duration, ultimate stress values may be used.

(c) Use of Water Sprays

No combustor or engine shall be operated without well-dispersed water sprays in the exhaust. Experience indicates that multiple bank sprays will partially suppress the detonation pressures and will reduce the number and temperatures of ignition sources in the exhaust system. Water sprays shall not be relied upon as a means of avoiding detonations. CO_2 may be used with the water spray to further reduce hazards.

4. ELIMINATION OF IGNITION SOURCES

a. General Procedure

(1) Even with the best of efforts to contain hydrogen, inadvertent leaks and accumulations will occur.

(2) The general procedure is to eliminate all likely ignition sources or place them away from fire hazard area.

(3) However, experience shows that escaped hydrogen is very easily ignited by unexpected means. Prudence dictates that the first emphasis must be on containment, ventilation, and detection. Elimination of ignition sources is the second, not the first, line of defense.

(4) If ignition sources are a required part of the hydrogen test, provision shall be made that any explosion or fire that may result will be an acceptable safety risk.

b. Potential Ignition Sources

(1) Friction Sparks

(a) Friction sparks are caused by hard objects coming into forcible contact with each other. That is metal striking metal, metal striking stone, or stone striking stone.

(b) A friction spark is a particle of burning metal which has been sheared off as a result of contact. Initially, the particle is heated by mechanical energy of friction and impact converted into heat. The freshly exposed surface of the particle may oxidize at the elevated temperature to cause an increase of temperature until the particle is heated to incandescence.

(c) Sparks struck from hand tools are considered as having low total energy. Sparks from mechanical tools such as drills and pneumatic chisels generate high energy sparks.

(Reference: Sparking Characteristics and Safety Hazards of Metallic Materials Technical Report No. NGF-T-1-57 NAVORD Report 5205)

(2) Impact Sparks

(a) Impact sparks are also caused by hard objects coming into forcible contact with each other.

(b) Impact sparks are produced by impact on a quartzitic type rock such as the sand in concrete. Quartz is piezo-electric and can convert mechanical into electrical energy. As in the case of friction sparks, small particles of the impacted material are thrown off. These particles, however, do not oxidize and, therefore, lose heat after the initial impact.

(Reference: As for Friction Sparks)

(3) Electrical Sparks

(a) Electrical sparks are caused by sudden electrical discharges between objects having different electrical potentials, for example, breaking electrical circuits or discharges of static electricity. These sparks may carry tremendous amounts of energy in comparison with friction sparks.

(Reference: As for Friction Sparks)

(b) Static electricity will generate sparks which will ignite a hydrogen-air or hydrogen-oxygen mixture. Static electricity is caused by many common articles such as hair or fur when combed or stroked or by a leather belt when operating on a machine. People generate high voltage charges of static electricity on themselves, especially when walking on dry ground, wearing nylon or other synthetic clothing, sliding on automobile seats, or combing the hair. Flowing liquid or gaseous hydrogen causes charges of static electricity. This is true also for all non-conductive liquids or gases. Turbulence in containers as well as laminar flow in systems has the same effect. Static charges may be induced during electrical storms.

(4) Hot Objects, Flames, Smoking

(a) Objects at temperatures over 1000°F will cause ignition of hydrogen-air or hydrogen-oxygen mixtures at atmospheric pressure (or about 650°F prolonged contact at less than atmospheric pressure).

(b) Both flames and smoking are easily capable of igniting hydrogen mixtures.

c. Elimination of Ignition Sources Due to Electrical Equipment and Wiring

(Reference: National Electrical Code (NEC))

(1) Electrical Classification of Hydrogen Areas

Areas where flammable hydrogen mixtures are normally expected to occur shall be classified as Class I Group B Division 1. Areas where hydrogen is stored, transferred, or used, and where the hydrogen is normally contained shall be classified as Class 1 Group B Division 2 as a minimum. In deciding whether an area will actually be made safer by the more expensive and difficult Division 1 installation, the NEC should be consulted and the following facts should be kept in mind:

(a) A Division 1 installation differs from a Division 2 install-lists the sizes of grounding conductors; however, the minimum size used for grounding fixed equipment in Class 1 areas shall be No. 2 A.W.G.

d. Elimination of Other Ignition Sources

(1) Lightning Protection

Lightning protection in the form of lightning rods, aerial cable, and ground rods suitably connected should be provided at all preparation, storage and use areas. All equipment in buildings should be interconnected and grounded to prevent inducing sparks between equipments during lightning strokes. A further development of this subject is in the National Bureau of Standards Handbook 46 "Code for Lightning Protection." The area protected by lightning rods or aerial cable is considered to be within 30 degrees of either side of the vertical.

(2) Static Electricity

In spite of all precautions, static sparks may still occur from unknown sources. Nevertheless, the following measures shall be taken:

(a) Ground all metal parts of a test rig and structure enclosing it.

(b) Use conductive machinery belts.

(c) Avoid combing the hair.

(d) Be sure personnel ground themselves before touching or using a tool on dewars or vents.

(e) Avoid wearing clothes made of nylon or other synthetic, silk, or wool. Ordinary cotton clothing is satisfactory.

(f) Keep furred animals out of hydrogen areas.

(3) "Spark-proof" Tools

(Reference: Sparking Characteristics and Safety Hazards of Metallic Materials," Tech. Rept. NGF-T-1-57 NAVORD Rept. 5205)

(a) Tests and experience have shown that so-called "spark-proof" tools are not spark-proof and do cause ignitions.

ation mainly in the degree of isolation of the area from ignition sources that may occur in the electrical system. A Division 1 installation relies heavily on explosion proof enclosures.

(b) An explosion-proof enclosure is <u>not</u> gas-tight. It is flame-tight. Flame-tight means that the enclosure is strong enough to contain the pressure produced by ignition of a flammable mixture inside; and that the joints and threads are tight and long enough to prevent issuance of any flames or any gases that are hot enough to ignite a surrounding flammable mixture.

(2) <u>Equipment</u>

(a) All electrical sources of ignition shall be prohibited in classified areas, including open electrical arcing devices and heaters or other equipment which operates at elevated temperatures. This means using approved explosion-proof equipment, Class 1 Group B Division 1, or selecting non-arcing equipment approved for Division 2. NEC Articles 500 and 501 cover the equipment application and installation methods for Class 1 locations.

(b) When properly classified equipment is not available, general purpose equipment in general purpose housing may be used when continuously pressure-purged with clean air or nitrogen. Positive indication of continued purge shall be provided.

(c) In any installation, the cost of equipment and installation will be reduced if those items which might become ignition sources are located outside the hazardous area.

(d) Also, systems installed in the hazardous area but not required during hazardous periods may be built with general purpose equipment, with provision to disconnect them before the hazardous period begins. The conduits for such systems must be sealed in accordance with NEC requirements wherever they leave the hazardous area. Seals must be checked to verify that they are effective.

(3) <u>Grounding</u>

(a) All equipment and connections, fixed or movable, shall be grounded.

(b) NEC Article 100 defines the term "grounded," and Table 250-94

(b) Further, with hydrogen, the energy required for ignition is so small that the so-called "spark-proof" tools reduce the hazard ineffectively and give a false feeling of security.

(c) "Spark-proof" tools are not required.

(d) However, all tools shall be used with caution to prevent slipping, glancing blows, or dropping, all of which would cause sparks.

(4) Spark-Proof and Conductive Floors

These are not required as the same comments apply as for "Spark-proof" Tools. However, if such floors are used, care should be exercised not to destroy the safety properties by cutting the floor, painting with non-conductive paint, or allowing it to get dirty.

(5) Hot Objects, Flames, Smoking

(a) Exclusion areas shall be established around hydrogen facilities and clearly marked. Barricades, signs, and warning lights should be used, as appropriate.

(b) The larger or more hazardous the facility, the larger the exclusion area should be. Boundaries should be set with the concurrence of the appropriate safety authority. A minimum radius of 50 feet is recommended.

(c) Inside the exclusion area, smoking shall be prohibited.

(d) Except as they occur normally during tests, flames and objects above 80% of the ignition temperature shall also be prohibited. Welding and cutting will not be performed when hydrogen is present.

(6) Flame Arrestors

(a) Flame arrestors rely on the fact that a flame will be quenched if sufficient heat can be removed from the gas by the arrestor. The quenching distance is the spacing between parallel walls which will just permit a flame to pass. Quenching distance for hydrogen is on the order of 1/4 that of other fuels. As the pressure increases, the quenching distance decreases.

(b) Flame arrestors designed for hydrocarbon flames will not stop hydrogen flames.

(c) Sintered bronze flame arrestors are effective in stopping hydrogen flames. Porosity, area, thickness, duration of flame, mixture, pressure, and mass flow are factors that must be considered. Sintered stainless steel is not as effective as sintered bronze.

(Reference: Fourth Symposium on Combustion (1953), page 689)

(d) Flame arrestors made of metal screen can also be effective against hydrogen, if properly constructed and assembled.

(e) Use only flame arrestors that are specifically designated for hydrogen applications, and follow installation directions carefully.

(f) Arrestors that are effective against hydrogen-air flames will not necessarily stop hydrogen-oxygen flames.

5. <u>PROTECTION OF PERSONNEL AND EQUIPMENT</u>

a. <u>Presence of Personnel In Test Rooms</u>

(1) Despite the provision for safety equipment and the experienced judgment of the project engineer, every entrance into an operating test cell must be considered dangerous. It is, therefore, recommended that reasonable steps be taken to avoid the need for entering.

(2) Entrance into operating test cells shall only be made by authorized personnel after the severity of operating conditions has been reduced, (pressure, speed and temperature) and only if the project engineer and personnel entering deem such entrance to be <u>both safe and necessary</u>.

(3) Cells in which combustible mixtures are present shall not be entered under any condition.

(4) The presence of personnel in an operating test cell shall be known to personnel outside the test cell.

b. <u>Personnel Shelters</u>

Shelters for personnel should be self-sufficient so that there is no reason to evacuate the shelter during an emergency. Telephone and air lines to the shelter shall be protected from damage. Air supply lines shall be provided with filters to remove oil vapor.

(1) Ventilation for Shelters

Particular attention shall be paid to the ventilation or source of air for shelters that may, in case of emergency, be enveloped in combustible or the products of combustion.

(2) Release of Inert Gas Inside Shelters

Inert gases under pressure should not be piped into tightly sealed shelters if there is a possiblity of accidental release and suffocation from lack of oxygen.

(3) Fuel in Shelters and Control Rooms

Fuel shall not be piped into shelters or control rooms.

(4) Visual Observation

Any window opening into a test cell where excessive pressures or ricocheting fragments could be present must be considered a hazard. If a window is required, it should be made as small as practical and should be of bullet-proof glass or the equivalent. A mirror system or a movable steel panel can be used to advantage in some cases.

c. Barricades

(1) Need for Barricades

Barricades are often needed in hydrogen test areas to shield personnel, dewars, and adjoining areas from blast waves and/or fragments. Barricades may also be needed to isolate liquid hydrogen storage areas from public property to which they might otherwise be too close (see Section 6). The purpose of barricades here is two-fold.

(a) To protect uncontrolled areas from the possible rupture and fragmentation of a storage dewar. This is a rather remote possibility, but such accidents have happened.

(b) To protect the dewars from malicious or thoughtless gunfire.

(2) Confinement

Barricades must not cause excessive confinement, which might lead to detonation rather than simple burning of escaped hydrogen. For example, liquid hydrogen spill tests conducted inside an open-ended (U-shaped) bunker, without a roof, produced detonation of the hydrogen-air mixture.

(a) Whether or not this would happen in a given case would depend on the relative height, length, and spacing of the walls. However, there are no guiding rules, and it is therefore best to avoid wrapping barricades around hydrogen areas. Sometimes this can be accomplished by placing a barricade closer to the thing to be protected, instead of closer to the source of spilled hydrogen.

(b) Straight or gently curving barricades are acceptable.

(3) Height of Barricades

The proper height and length of a barricade may be determined as follows:

Any straight line drawn from the top boundary of the area in which blast or fragments will originate, to any part of a building, dewar, etc., that is to be protected or to any point 12 feet or less above the center of that portion of a highway which would be too close without a barricade, must pass through the barricade.

6. STORAGE AND TEST LOCATIONS AND BLAST EFFECTS

a. Quantity-Distance Concept

Quantity-distance criteria are based on the obvious fact that the effects of fire, explosion, and detonation can be reduced to tolerable levels if the source of hazard is kept far enough from people and facilities. Tests and experience are employed to determine how the effects of an accident are related to the quantity of material involved in the accident. In the case of hydrogen, these effects are blast waves, fragments, andinfra-red radiation. Other tests and physical laws show how these effects diminish with increasing distance from the source. Finally, from a knowledge of the tolerance levels of people and structures, safe distances are determined. These distances, therefore, are based entirely on the estimated damage that could result from an incident, without considering probabilities or frequency of occurrence.

b. Policy

(1) The quantity-distance relations are intended as a basic guide in the choice of sites and separation distances. The distances given are based on the total quantity of propellants present. This may be unrealistic because proper design can sometimes guarantee that only part of the propellants will be involved in an accident. If safety authorities are satisfied that such positive safeguards exist, appropriate lesser distances may be used.

(2) Safety authorities may also waive separation distance requirements where small quantities of liquid hydrogen are used in well-controlled laboratory experiments.

c. Quantity-Distance Tables

(1) The Armed Services Explosives Safety Board, in consultation with the Armed Services and NASA, has developed quantity-distance tables for liquid hydrogen. These are published as Department of Defense Instruction 4145.21, January 27, 1967. The tables given in this Part are adapted from Instruction 4145.21.

(2) Two different situations are considered. One is the storage of liquid hydrogen, where the main hazards are pressure rupture and gas-phase burning of hydrogen in air. The other is the use of liquid hydrogen in propulsion systems together with liquid oxidizers, where the main hazard is detonation of liquid hydrogen-solid oxidizer mixtures.

(a) Storage

1. Applicability - It is assumed that the liquid hydrogen storage area is unconfined and that suitable dikes or run-off paths are provided. A storage area is one in which the only activity is associated with retaining and transferring liquid hydrogen into and out of dewars at nominal transfer pressures. A supply dewar associated with a specific test facility will not necessarily qualify as a storage area with respect to fixing the separation distances for the facility, even though the tests may not involve liquid oxidizers.

2. Definitions

a. Incompatible Storage - Strong oxidizers and explosives must be stored a suitable distance from hydrogen. The oxidizers include oxygen, fluorine, concentrated nitric acid, nitrogen tetroxide, chlorine trifluoride, and hydrogen peroxide. Explosives include blasting materials, ordnance, and unstable chemicals such as pentaborane.

b. Protected - The term "protected" means shielded from fragments.

c. Quantity - The quantity of liquid hydrogen refers to the weight in pounds in a given container, if separated from another container with a lesser quantity by the distances given in Table A, column 5. If containers are not separated by the appropriate distances, the quantity shall be the total in all of them.

(b) Use With Liquid Oxidizers

1. Applicability - Where liquid hydrogen is used in conjunction with liquid oxidizers such as oxygen or fluorine, as in engine static test or lauch operations, the quantity-distance criteria are based on blast hazards. The total amount of propellants (fuel plus oxidizer) that could be involved in accidental release must be related to an equivalent amount of TNT or similar high explosive that would produce the same blast wave overpressure.

2. Determination of Explosive Equivalent - A given total quantity of liquid hydrogen plus oxidizer, accidentally released, can be expected to produce a blast wave characteristic of some smaller amount of high explosive. To determine the equivalent amount of explosive, multiply the amount of propellants by the following factors, and then enter Table B with the results to determine the separation distance.

Propellant Combination	Explosive Equivalent Factor: Static Tests Stands	Explosive Equivalent Factor: Range Launch Pads
LH_2 - LO_2	0.60	0.60
LH_2 + RP-1 - LO_2	Sum of 0.60 for LH_2-LO_2, 0.10 for RP-1-LO_2	Sum of 0.60 for LH_2-LO_2, 0.20 for RP-1-LO_2
LH_2 - LF_2	0.05 *	-

* Arbitrarily taken to be the same as the equivalent established for another hypergolic combination, N_2O_4 - Aerozine-50, in Department of Defense Instruction 4145.21. Toxic hazards not considered may be overriding.

(c) Use Without Liquid Oxidizers

No quantity-distance relations have been established for operations involving liquid hydrogen alone, such as pump or heat-transfer tests. The work and the conditions under which it is carried out are so variable that no hard-and-fast rules can be set down. Each test setup must be considered separately to determine the possible results of accidents, keeping in mind the likelihood of contamination by liquid air and the danger of detonation if gaseous hydrogen-air mixtures are formed in confined spaces.

d. Blast-Wave Characteristics

When an explosive material detonates near the ground, a hemispherically-expanding shock, or blast wave, is generated. The strength of the wave decreases as it moves outward from the site of detonation; and, of course, the strength at any given distance is related to the amount of material detonated.

(1) The term "strength" refers to several characteristics of a blast wave which relate to the wave's potential for causing damage:

(a) Peak Overpressure - The static pressure (often called "side-on" pressure) is greatest at the wave front. This is the peak overpressure, generally reported as psi above atmospheric pressure.

(b) Duration - After the wave front passes, the static pressure falls and actually drops slightly below atmospheric pressure.

However, it is the duration of the positive phase - the time required to drop from the peak overpressure to atmospheric pressure - which is of greatest significance in causing damage.

(c) Blast-Wind Velocity - Behind the front of the blast wave, the air moves at considerable speed in the same direction as the wave. For example, if the peak overpressure is 5 psi, it will be accompanied by a 160 mph wind.

(d) Dynamic Overpressure - The pressure rise produced when the blast-wind is brought to rest is called the dynamic overpressure.

(e) Peak Reflected Overpressure - If a blast wave strikes a surface (such as a wall) at normal incidence, the air flow will be stopped and a shock wave will reflect backward from the surface. Behind the reflected shock, the surface will briefly be subjected to the peak reflected overpressure; this is sometimes called the "face-on" overpressure. It is considerably larger than the stagnation overpressure, which is the sum of the peak and dynamic overpressures.

(2) The most frequently quoted property of blast waves is the peak overpressure. Figure 6-1 shows curves of peak overpressure versus distance for various weights of TNT. However, it is not necessary to present a separate curve for each amount of explosive. Peak overpressure is subject to what is called "cube-root scaling." That is, the distance at which a given peak overpressure occurs is proportional to the cube root of the weight of explosive. Consequently, all of the curves in Figure 6-1 could be superimposed on the curve for one pound of explosive if, instead of distance, the distance divided by the cube root of the weight were plotted against overpressure. This correlating parameter, $(FT/LBS^{1/3})$, is called scaled distance," and it will be used in order to simplify the presentation of the remaining blast-wave characteristics.

(3) The material in Figures 6-1 to 6-5 was adapted from Naval Ordnance Laboratory figures which were prepared for Volume I, Propellant Hazards Manual, currently being written under the auspices of the Interagency Chemical Rocket Propulsion Group. In all cases, the data are for TNT blast waves. Tests now underway indicate that the waves produced by detonation of the liquid hydrogen - liquid oxygen combination do not have precisely the same properties. Nevertheless, Figures 6-1 to 6-5 may be used to get an overall view of propellant blast effects, and for estimation purposes.

e. Effects Of Blast Waves On Structures

When a blast wave strikes a large building, it will exert forces tending to translate the building and to crush it. The crushing effect occurs because the pressure outside is greater than the atmospheric pressure inside. The translating effect occurs because of the pressure difference which exists while the wave is traversing the structure, and because of the dynamic pressure of the blast-wind. Objects which are subject to such combinations of forces in a blast are called diffraction structures.

(1) On the other hand, smaller objects such as utility poles, chimneys, and small buildings which do not extend very far in the direction of blast-wave motion, will not be subjected to appreciable static-pressure differentials. Almost all of the blast effect on such objects is due to the drag which they present to the blast-wind. Therefore, they are called drag structures.

(2) There is not always a hard-and-fast line between the two kinds of structures. For instance, a building whose walls are mostly glass may be more a drag structure than a diffracting structure; this could happen if the windows quickly broke, equalizing the internal and external pressure and exposing the structural supports to the blast wind. It can be seen that there will also be intermediate cases, in which the initial impact of the blast only partially opens the building, so that it is subject to both diffraction and drag effects.

(3) In principle, it is possible to calculate blast effects from a knowledge of blast-wave properties, the strength of materials, and the structural load-response. In practice, such calculations are very difficult because of the complex effects described in the preceding paragraphs. It is generally easier to be guided by prior experience, which has established the ranges of overpressure that will cause either severe[1] or moderate[2] damage to different types of construction. Considerable information of this kind exists, but it will not be given in detail here; instead, it will be considered in relation to the quantity-distance table (Table B).

[1] Building not usable without almost complete reconstruction

[2] Major repairs required to load-bearing members.

f. Effects of Blast Waves At Separation Distances Specified in Table B

Comparison of the quantity-distance requirements of Table B with the data of Figures 6-1 and 6-4 shows that the Table is designed to place inhabited buildings at an unbarricaded distance such that they will experience a peak overpressure of about 0.5 psi and a dynamic overpressure of about 0.01 psi.

(1) If the source of the blast is barricaded, the Table permits shorter separation distances. Perhaps because of this, it is common misconception that barricades reduce the overpressures experienced at large distances. This is not the case. After the blast wave passes the barricade, it will re-form with almost the same strength as it would have if no obstacle were in the way. Thus, overpressures at the barricaded distances will be approximately twice as great as those cited in the previous paragraph. The barricade only serves to stop fragments.

(a) Effects on Buildings

Blast-damage data show that, of the most common types of construction, wood-framed and masonry buildings are the most vulnerable. Wood-framed buildings will sustain moderate-to-severe damage at peak overpressures of 2.4 to 3.3 psi. Masonry buildings will sustain moderate-to-severe damage at peak overpressures of 4.0 to 4.7 psi.

1. Most other types of construction are more sensitive to dynamic overpressure than to peak overpressure. However, even the most vulnerable buildings in this group will not suffer moderate damage unless the dynamic overpressure exceeds 0.15 psi.

2. Other sources of information suggest that the distances in Table B are not great enough to prevent plaster damage, but are great enough to prevent deformation of window frames. It is not possible to be explicit about the level of damage that would be sustained by other structural components, but indications are that it would be minor with the following exception.

(b) Effects on Glass

The exception referred to above is window glass. The damage threshold varies widely, depending on the area, thickness, and mounting of the glass. However, at a peak overpressure of 1 psi, a large fraction of all windows will break; and at 0.5 psi, a significant amount of breakage can still be expected. Thin or poorly-mounted windows break at overpressures as low as 0.15 psi in laboratory tests. In the field, breakage has often occurred at distances where the overpressure should have been only 0.03 psi. These cases are probably due to the fact that blast waves can be channeled and focused by winds and by atmospheric temperature variations when they travel long distances. Even if such cases are neglected, there is still a large range of overpressures, from 0.15 to 1 psi, which may break glass. Figure 6-1 shows that there is a corresponding factor-of-ten uncertainty in the distances at which broken windows may be expected. In short, the separation distances specified in Table B will not prevent glass damage.

(c) Effects on Humans

Humans are sensitive to two characteristics of blast waves: peak overpressure and dynamic overpressure.

1. Peak overpressure can rupture eardrums at the 5 psi level. At considerably higher levels, direct internal damage will result. There is approximately a one percent chance of fatal injury at overpressures of 35 to 45 psi, and a 99 percent chance at 55 to 65 psi.

2. The dynamic overpressure exerted by the blast-wind can cause secondary injuries by picking people up and throwing them. A standing man will be moved by the wind accompanying a blast wave in which the peak overpressure is 3 psi; if he is lying down, stronger blasts will be required to move him.

3. Thus, humans in buildings located according to Table B will not suffer any direct internal damage, nor will they be thrown about.

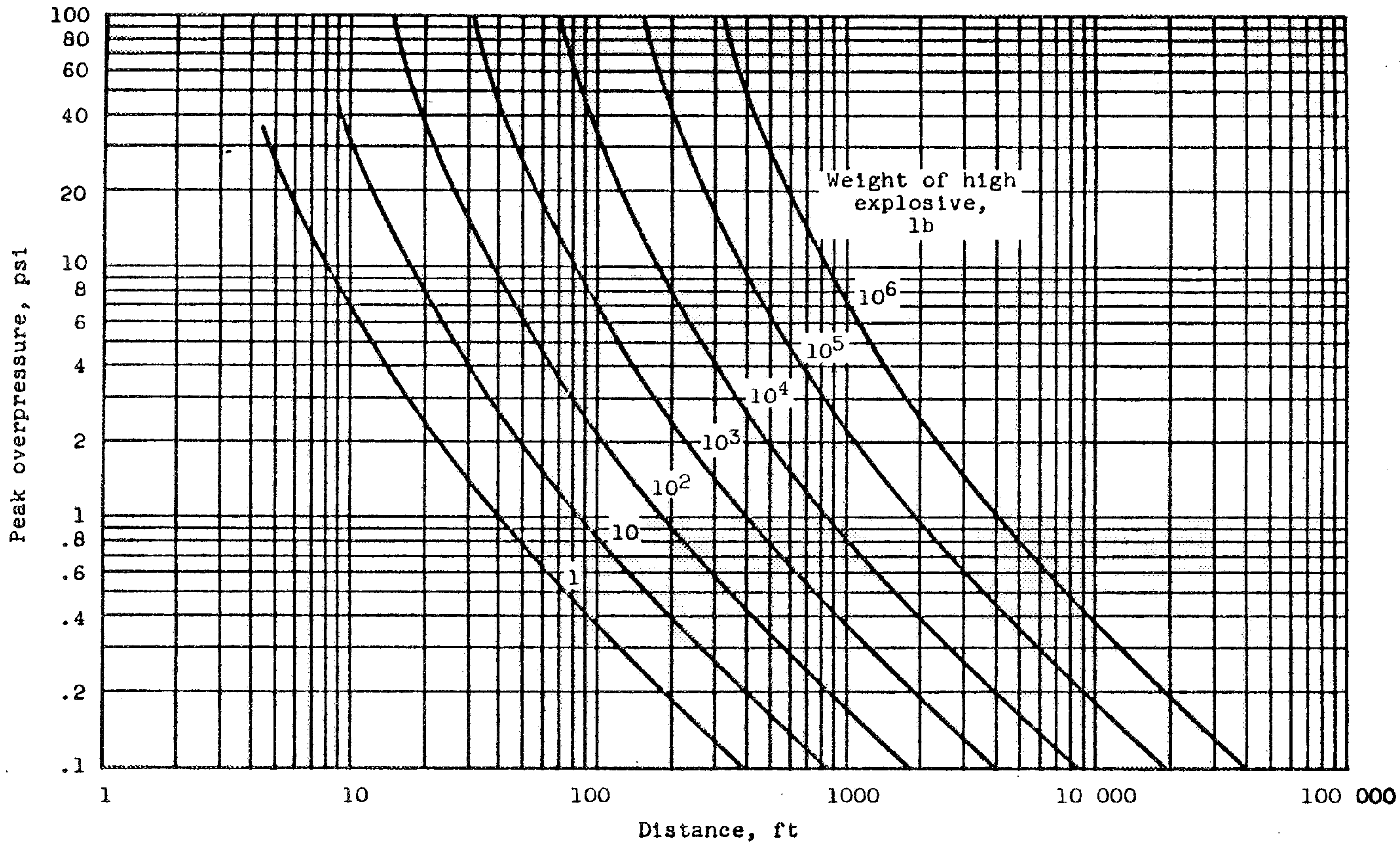


Fig. 6-1. - Variation of peak overpressure with distance from detonation.

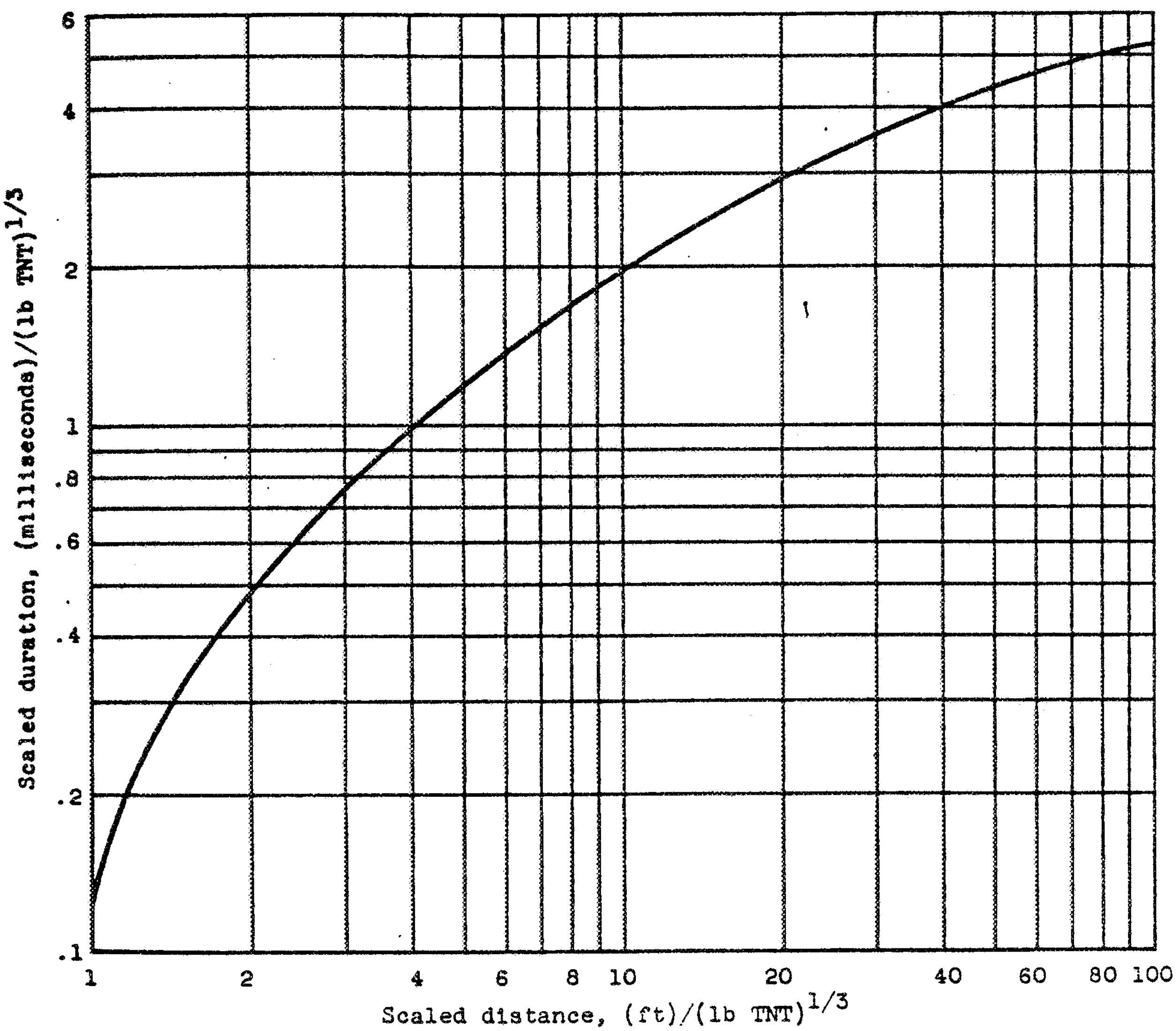


Fig. 6-2. - Duration of positive phase.

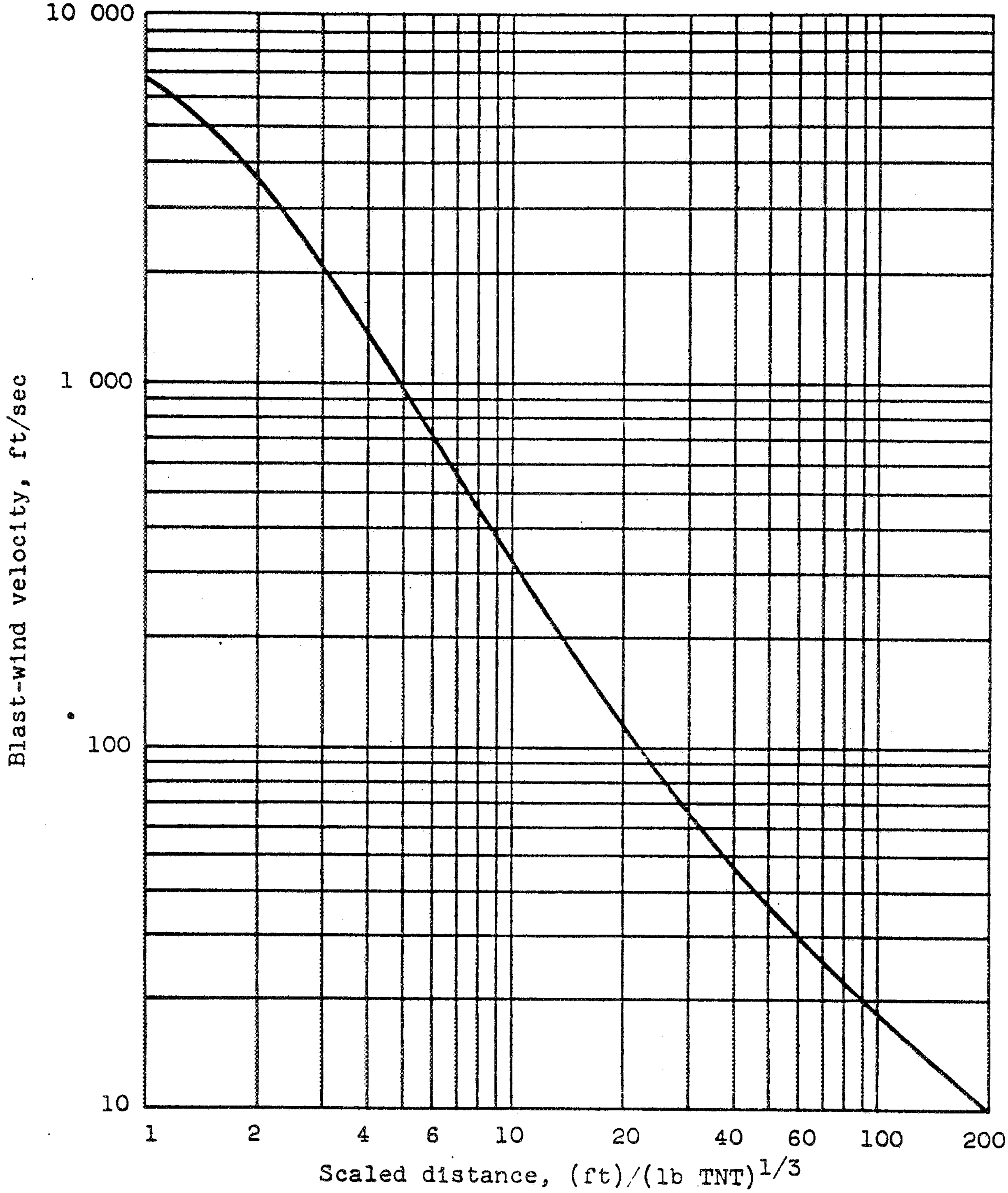


Fig. 6-3. - Variation of blast-wind velocity with scaled distance for 70° F air.

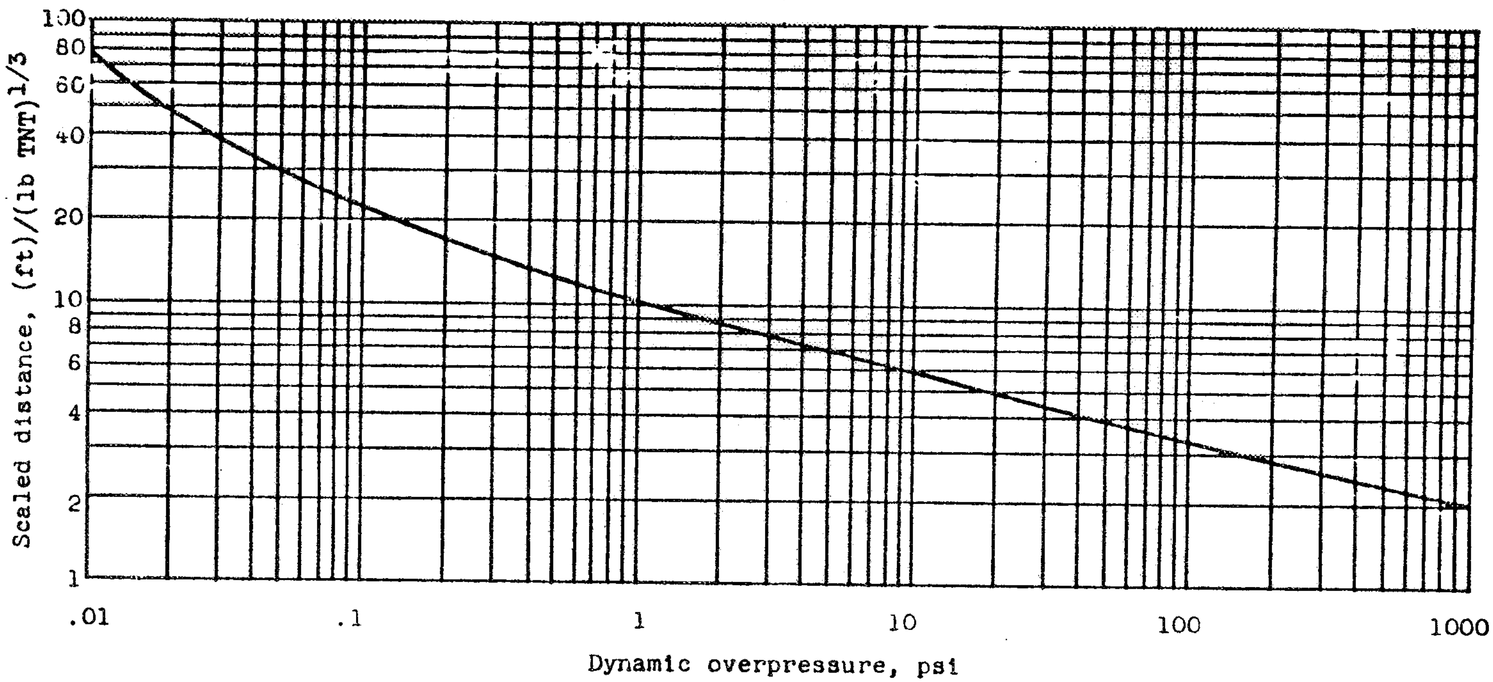


Fig. 6-4. - Variation of dynamic overpressure with scaled distance.

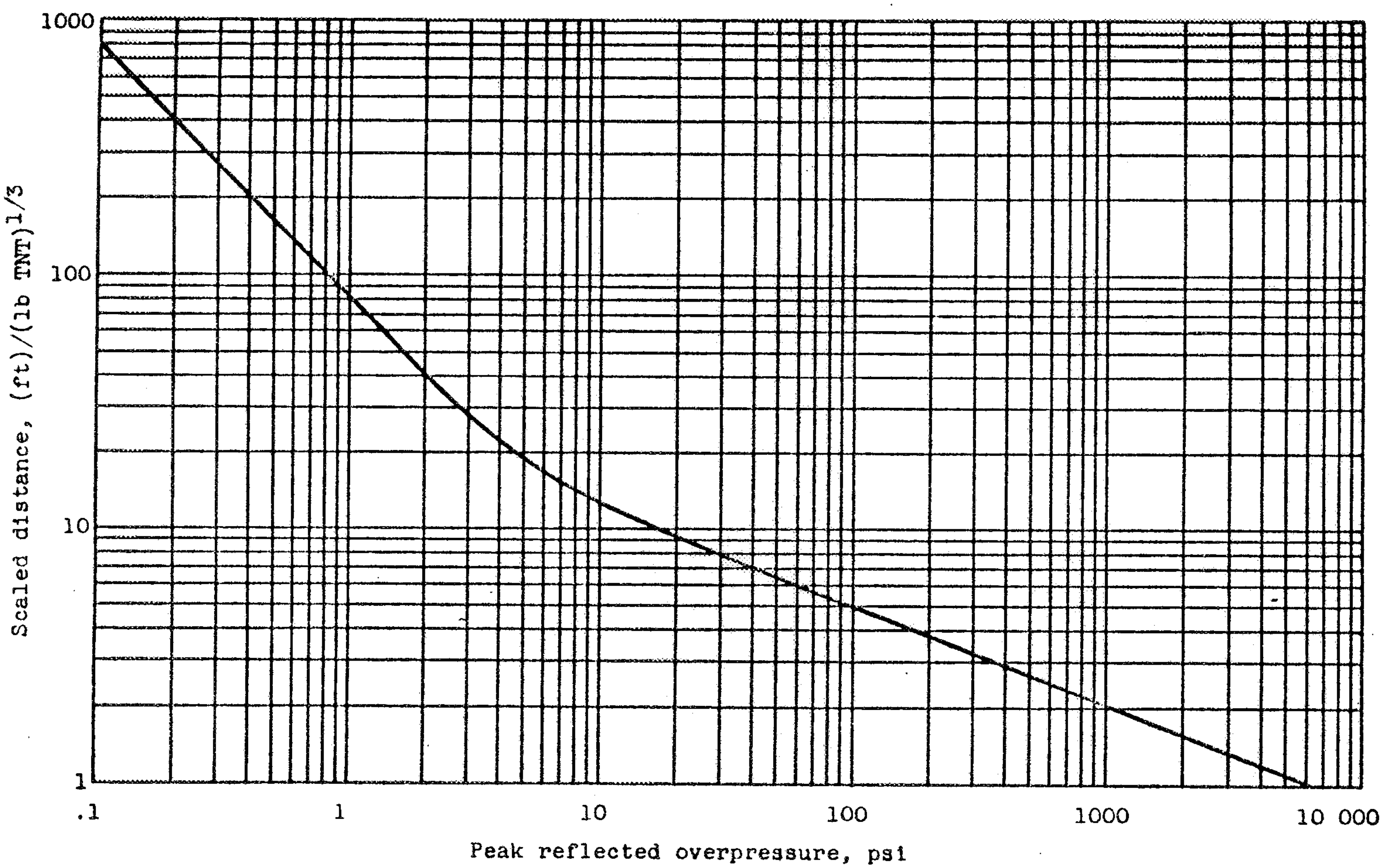


Fig. 6-5. - Variation of peak reflected overpressure with scaled distance.

TABLE A - LIQUID HYDROGEN STORAGE

Pounds of LH_2		Inhabited buildings, highways railroads, & incompatible storage		Another LH_2 storage
Over	Not Over	Distance in feet		Distance in feet
		Unprotected	Protected	
Column 1	Column 2	Column 3	Column 4	Column 5
	100	600	80	30
100	500	600	130	50
500	1000	600	150	60
1000	10,000	600	240	90
10,000	50,000	1200	320	120
50,000	100,000	1200	365	135
100,000	300,000	1800	440	165
300,000	500,000	1800	485	180
500,000	1,000,000	1800	550	205

Basis for Table A:

<u>Column 3</u> - distances necessary for protection from fragments of tanks or equipment

<u>Column 4</u> - distances sufficient to prevent excessive heating by infrared radiation; Bureau of Mines Rept. 5707 (1961)

<u>Column 5</u> - reduced from column 4 to take into account the type of construction used in LH_2 storage areas

TABLE 8 - LIQUID HYDROGEN IN CONJUNCTION WITH LIQUID OXIDIZERS

Equivalent weight of explosive, pounds	Distance in feet from explosive hazard			
	To Inhabited Buildings		To Public Highways and Railroads	
Not over	Barricaded	Unbarricaded	Barricaded	Unbarricaded
100	190	380	115	230
200	235	470	140	280
300	270	540	160	320
400	295	590	175	350
500	320	640	190	380
600	340	680	205	410
700	355	710	215	430
800	375	750	225	450
900	390	780	235	470
1,000	400	800	240	480
1,500	460	920	275	550
2,000	505	1010	305	610
3,000	580	1160	350	700
4,000	635	1270	380	760
5,000	685	1370	410	820
6,000	730	1460	440	880
7,000	770	1540	460	920
8,000	800	1600	480	960
9,000	835	1670	500	1000

(continued) TABLE B - LIQUID HYDROGEN IN CONJUNCTION WITH LIQUID OXIDIZERS

Equivalent weight of explosive, pounds	Distance in feet from explosive hazard			
	To Inhabited Buildings		To Public Highways and Railroads	
Not over	Barricaded	Unbarricaded	Barricaded	Unbarricaded
10,000	865	1730	520	1040
15,000	990	1780	595	1070
20,000	1090	1950	655	1170
25,000	1170	2110	700	1265
30,000	1245	2260	745	1355
35,000	1310	2410	785	1445
40,000	1370	2550	820	1530
45,000	1425	2680	835	1610
50,000	1470	2800	880	1680
55,000	1520	2920	910	1750
60,000	1570	3030	940	1820
65,000	1610	3130	965	1880
70,000	1650	3220	990	1930
75,000	1690	3310	1015	1985
80,000	1725	3390	1035	2035
85,000	1760	3460	1055	2075
90,000	1790	3520	1075	2110
95,000	1825	3580	1095	2150
100,000	1855	3630	1115	2180

(concluded) TABLE B - LIQUID HYDROGEN IN CONJUNCTION WITH LIQUID OXIDIZERS

Equivalent weight of explosive, pounds	Distance in feet from explosive hazard			
	To Inhabited Buildings		To Public Highways and Railroads	
Not over	Barricaded	Unbarricaded	Barricaded	Unbarricaded
125,000	2115	3670	1270	2200
150,000	2350	3800	1410	2280
175,000	2565	3930	1540	2360
200,000	2770	4060	1660	2435
225,000	2965	4190	1780	2515
250,000	3150	4310	1890	2585

Basis for Table B:

Department of Defense Instruction 4145.21, January 27, 1967

7. OPERATING PROCEDURES

a. Policy

Safety is achieved, in working with hydrogen, by adherence to the following:

(1) hydrogen leaks must be prevented, but

(2) a constant watch must be kept to detect immediately any accidental leaks and proper action must be taken,

(3) accumulations of leaked hydrogen must be prevented by plentiful ventilation.

(4) likely ignition sources must be eliminated but unknown ignition sources must be suspected as being present.

b. Personnel

(1) Qualified Operators

(a) There are two prime objectives in requiring qualified operators. The first objective is to secure safe operations. The second objective is to permit reliance on dependable manual controls rather than on complex automatic controls. Automatic controls are expensive to buy and install, and experience has shown them to take valuable research test time for adjustment and maintenance.

(b) Qualifications required for operation of hydrogen systems shall be based on the engineers or mechanics having:

1. Physical, mental, and emotional fitness, especially to act properly in emergencies.

2. Knowledge of the properties and characteristics of hydrogen, both liquid and gaseous.

3. Knowledge of the equipment and installation to be operated.

4. Training and experience in operation under the instruction of a qualified operator.

5. Operators of manufactured equipment, such as compressors, must be familiar with manufacturers' manuals.

(c) Although the policy requiring qualified operators applies more directly to research test operations, safety requires that the same policy apply to hydrogen handling other than research.

(2) Number of Personnel Required

The "buddy" system must be followed; at least two qualified personnel must be present. However, no more than a necessary minimum of personnel shall be present in a hazard area.

(3) Personnel Protection

(a) Personnel shall wear protective face shields, goggles, and suitable clothing.

(b) Synthetic clothing, such as nylon, shall not be worn because it produces charges of static electricity that can cause ignition of flammable gas. See Section 4, d, (2). Gauntlet-type gloves or tight clothing which will hold liquid against the body must be avoided.

c. Storage

Liquid hydrogen shall be stored in carefully constructed and tested closed containers under at least 3 to 10 psig pressure to prevent air from entering. The containers shall be vented through relief valves to the atmosphere and carefully grounded. Rules pertaining to flammable liquid or low-pressure gas storage are applicable. Dikes or their equivalents should be used. The use of excessively high barricades around storage areas is undesirable because they retard dissipation of any leaked hydrogen and may give conditions which could cause a detonation. (See Section 5, c) Do not store, transport, or load propellants together. (Refer to Section 6 for separation distance requirements.)

(1) Dewars

The dewar storage area shall be isolated by a 50-foot chained-off distance. Warning signs, "No smoking within 50 feet," are required.

(2) Electrical Grounding

Dewars shall be adequately grounded at all times. Transfer couplings should have bonding wires clamped across each joint.

(3) Typical Vacuum Values

(a) Dewar vacuum and vacuum jacketed plumbing

Microns	
Warm	Cold (static)
0 to 50	10^{-4}

(b) In the event of the uncontrollable loss of vacuum, the dewar contents will probably have to be transferred to another receiver and the dewar inerted preparatory for leak detection and repair.

(4) Safety Valves

Liquid hydrogen expands about 800 times when warmed to room temperature. If restrained, pressure of many thousand pounds per square inch will result and may cause rupture of equipment and hydrogen explosion or fire. Safety relief valves in dewars, in systems, and between shut-off valves shall be tested for proper operation periodically.

(5) Burst Discs

Replacement discs must be selected to be accurate duplicates of the original and installed with extreme care. Burst disc assemblies fitted by the supplier with the pressure and vacuum supports are preferred.

(6) Contamination

(a) Contamination must be prevented. When liquid hydrogen is exposed to air or other gases of higher boiling point, the hydrogen will be contaminated by either liquefied or solidified gases. Containers suspected of contamination must be removed from service immediately to avoid further complications. The container shall be tagged or otherwise identified as unfit for service. Arrangements shall be made for special handling as soon as possible.

(b) Contamination might occur from interconnected systems, e.g.

oxygen or impure-nitrogen systems connected to hydrogen systems. Therefore, check valves shall not be relied upon to prevent contamination.

(c) When solid oxygen particles are formed, localized concentrations approaching and reaching flammable range can occur. Often, though, the quantity of oxygen with respect to toal volume is still below the 1 ppm level. Since the vaporization rate of liquid hydrogen increases tremendously in transfer operations, the rate of oxygen accumulation will also increase, for example, from impurities in the pressurizing hydrogen gas. Where liquid is withdrawn from vessels frequently, accumulation is less likely; but where liquid is stored, not used, and tanks occasionally "topped" to make up evaporation losses, accumulation of higher boiling impurities (everything but helium) will take place. The approach is to eliminate all oxidants from the hydrogen system

(d) The following precautions should be observed:

1. Hydrogen liquid should be stored under pressure (3-10 psig) to aid in preventing external contaminants from entering the system.

2. Pressuring hydrogen gas must be free as possible of impurities, at least 99.6 percent pure. The levels of impurities, especially oxygen, should be known to assure that it is a satisfactory pressurant.

3. All transfer or handling equipment, for both gas or liquid, must be clean and dry and purged.

4. Hydrogen should not be re-circulated if contamination would be dangerous and cannot be prevented.

(7) Decontamination

Periodic decontamination of a tank or dewar is to be done by draining the contents and letting the product container warm-up to permit removal of all contaminants. Roadable dewars, which may frequently be connected to improperly cleaned and purged transfer systems, are likely to become contaminated. Large fixed dewars, which are not filled and emptied often, do not require decontamination unless they have been inadvertently subjected to a contaminating condition.

A decision to act then depends upon the degree of contamination and becomes a matter of engineering judgment.

(a) To insure decontamination, the container shall be vacuum purged - if strong enough to withstand a vacuum - to one centimeter of mercury. If the dewar is not strong enough, a warming or pressure purge will be necessary.

(8) <u>Hazards of Substituting Dewars</u>

(a) Structural weakness of vessel. Liquid hydrogen and helium dewars, as ordinarily constructed, are not strong enough to hold liquid oxygen, air or nitrogen.

(b) Contamination danger.

(c) Although <u>not recommended</u>, hydrogen and helium equipment can be used interchangeably; <u>no other substitutions are permitted</u> without approval by the cognizant safety authorities. Even with interchange of hydrogen and helium equipment, purging must be complete. Contents of dewar must be accurately marked on dewar.

d. <u>Transportation</u>

(1) <u>ICC Requirements</u>

(a) Dewars for the highway or rail transportation of liquid hydrogen must have the required special permit of the Interstate Commerce Commission.

(b) Transport dewars are to be marked in accordance to ICC regulations with both of the following legends: FLAMMABLE GAS and LIQUID HYDROGEN.

(c) ICC special permits prohibit venting of hydrogen gas on the highways. The pressure in the sealed dewar must be monitored. If it shows signs of approaching the relief-valve setting, the truck must be driven to a safe place off the highway and the pressure reduced through the manual blowdown valve.

(2) <u>Normal Venting</u>

(a) <u>Choice of Location</u>. Although properly maintained modern transport dewars are well-enough insulated to cross the country without excessive pressure rise, there may be occasions when the pressure slowly approaches the relief-valve setting. Drive to an open area off the road, clear of power lines, buildings, and people. Consider wind direction so that vented gas will be carried away safely.

(b) Time of Venting. By observing the rate of pressure rise, try to plan the manual venting operation for the daylight hours. In any event, the operation must be carried out well before the automatic relief devices function.

(3) Emergency Procedures

(a) General. The first concern should be to prevent death or injury. In event of accident or emergency, get the dewar off the road if possible, preferably to an open location. Shut off the tractor-trailer electrical system. Post warning lights and signs and keep people at least 500 feet away.

(b) Vent or Other Minor Fire. Attempt to shut off the supply of hydrogen. Do not try to put out a hydrogen fire while it is still being supplied with hydrogen. If water hose is available, it should be used to keep metal parts cool until the fire burns itself out. A fire extinguisher should be used to put out engine, tire, or electrical fires that are not fed by hydrogen.

(c) Cold Leaks. If there is no fire, "fog" will be visible in the vicinity of a liquid hydrogen leak. Stop or minimize the leak if it can be done safely. Remove all ignition sources. There is flammable mixture wherever fog is visible and sometimes beyond the visible cloud. Do not deliberately flare hydrogen leaks.

(d) Major Accident

1. In event of a major accident that makes it impossible to move the dewar off the road, post warnings and keep people away. Notify local authorities and then home base.

2. If there is a large hydrogen fire in which the source of hydrogen cannot be shut off, do not allow firemen to extinguish it. Have them use water streams to cool the container and surrounding equipment and to put out second-

ary fires.

3. If there has been major damage to the vacuum shell or vent system, pressure may build up. In that case, the liquid hydrogen container may rupture explosively. Keep people at least 500 feet away. If the surface of the inner vessel is exposed, do not apply water; this would only act as a heat source to the much colder hydrogen, and would aggravate the boil-off.

4. If frost spots appear on the outer jacket, it means that liquid hydrogen is contacting the carbon steel of which it is usually made. This metal becomes brittle when cold, and should not be struck or shocked lest it break.

(4) Personnel

The driver or an accompanying technician shall be familiar with the hazards of hydrogen and with emergency procedures. Personnel shall be fully trained and tested in the construction, operation, and safety features of the dewar.

e. System Preparation

(1) Cleaning

(a) All storage, transfer and system components must be completely clean before being placed in service.

(b) Liquid hydrogen systems must be clean of any surface film, oxidant, grease, or oil.

(c) Liquid hydrogen systems must be free of all matter that would jam or clog valves and flow passages; for example, rust, dirt, mill scale, weld spatter, and weld flux.

(d) Valve stem seals and seats must be carefully inspected and cleaned if necessary.

(e) The systems must be dry and free of water or any liquid of boiling point higher than that of liquid hydrogen.

(f) A recommended cleaning procedure is as follows:

1. For a warm system, all loose particles such as sand, grit, rust, weld spatter shall be removed by flushing the system

or component first with 1, 1, 1-trichloroethane to degrease and second with demineralized water.

2. The system shall be dried by evacuation and flowing dry nitrogen gas through it (if the system cannot withstand a vacuum (See 4 below) To break loose attached particles, the system shall be "cold-shocked" with liquid nitrogen. The particles then can be flushed out with liquid nitrogen into filters. The filters shall then be cleaned separately.

3. Such systems should be dried by three cycles of evacuation (see paragraph 7, f, (1) (a) on Purging) through a cold trap before filling with hydrogen gas. Usually three cycles will dry a system so that the cold trap shows no further collection.

4. If the system cannot withstand a vacuum, the system may be dried by flowing hot nitrogen gas through it. The nitrogen gas temperature should be well above the boiling temperature of water.

(g) Systems that have been cleaned shall have all openings closed in an airtight manner with metal covers and suitable gaskets. Good practice dictates similar treatment or the use of plastic containers for pipes and systems that are yet to receive a final cleaning.

(h) Experience indicates that factory-cleaned equipment is frequently contaminated.

(2) Cleaning Filters

(a) The frequency at which filters should be cleaned depends on the amount of use and impurities in the fluid. The operators must watch increases in pressure drops and clean filters as needed.

(b) Filters are cleaned by disconnecting, warming, draining, flushing (use 1, 1, 1-trichloroethane or ultrasonic cleaning) and drying thoroughly. Filters must not be cleaned by back-flushing through the system.

(3) Lubricants

(a) Combustible lubricants for valves, etc., must be avoided.

The best lubricant for valves and fittings is graphite. Find out which are approved lubricants and use them carefully. Any lubricant must be prevented from getting into liquid hydrogen.

(b) Silicone or Kel-F grease may be used (sparingly) on O-rings.

(4) <u>Leak Prevention</u>

(a) Seal materials suitable for low temperature and vacuum service are required. Natural rubber freezes, hardens, and loses its seal at low temperatures. Synthetic rubber, Teflon, Kel-F, copper, brass, and stainless steel, for example, may be used as low temperature seals. Also see Appendix 2.

(b) Avoid pipe threads because they are more subject to leaking. Use welded fittings or flanged connections of suitable design.

(c) Use proper size "O" rings.

(d) Systems must be mechanically tight.

(e) Check system for leaks while warm prior to activating system.

(f) Have adequate supports under temporary piping.

(g) Do not abuse equipment. Use proper tools.

(h) Do not overtighten valves.

(i) Do not attempt to tighten any fittings while cold, i. e. below zero Fahrenheit.

(j) Do not attempt to tighten any fittings while under pressure even if warm.

(k) Do not backseat valves unless they are designed for backseating.

(l) Do not overpressurize.

(m) Poor vacuum insulation in transfer lines will cause a warm seal to fail and liquid will squirt out.

(n) Be sure bayonet-type joints fit snugly.

(5) Pressure Tests

All hydrogen containers and systems must be pressure tested in accordance with applicable codes. Tests of the cryogenic portions must include cold-shocking with liquid nitrogen followed by additional pressure tests.

(6) Leak Detection

(a) After initial assembly or after alterations, check joints, etc. for leaks with portable detector.

(b) Use portable or fixed combustible gas probes for hydrogen operations. Be sure they are of a type approved for hydrogen.

(c) "Leak Tec" or equivalent for warm systems.

(d) Watch for frosty clouds or visible condensation on surfaces indicating leaks.

f. Purge Methods

(1) Vacuum Purging

In vacuum purging, the operator must be sure the container or system will not collapse when the vacuum is applied.

(a) Vacuum purge; air to vacuum to inert gas to hydrogen and conversely --

1. Initially the system is evacuated to 1 centimeter of mercury. Then the system is tested under static conditions to insure that it is tight by observing the rate of rise of pressure within the system. (One millimeter per minute rise for a five-minute period would indicate good vacuum holding ability.)

2. Next, nitrogen (or, if necessary, helium) is introduced to a positive pressure of 1 psig. Then the system re-evacuated to 1 centimeter of mercury. The system is repressurized with the inert gas to 1 psig and then re-evacuated to 1 centimeter of mercury. Now the system is ready for hydrogen gas. The advantage of a vacuum purge is that a minimum amount of helium purge gas would be used if helium is required.

(b) Vacuum purge; air to vacuum to hydrogen gas --

This method is similar to that stated above except the inert gas step is omitted. After initial evacuation to a few millimeters of mercury, the system is purged with hydrogen gas and evacuated for three complete cycles.

(2) Pressure Purging

Positive pressure purge; air to inert gas to hydrogen -- The principle of this method of purging is a progressive dilution of air to reduce the percentage of residual air to a safe limit.

(a) Hydrogen purge gases must be at least 99.6% pure.

(b) Air in the system is displaced with an inert gas, helium, to a positive pressure within the pressure range of the receiver. The mixture is vented to atmosphere. The system is repressurized with helium to the positive pressure. Then the mixture is again vented to atmosphere. The system is again pressurized with helium and vented to atmosphere being careful to leave a positive pressure in the receiver to prevent air migration. Hydrogen may now be introduced. A disadvantage of this method is that considerable quantities of helium purge-gases are required. A second disadvantage is that it is difficult to determine if all voids or dead-legs have been adequately purged.

(3) Purging Transfer Connections

In the event that neither of the foregoing purge methods can be adapted to a transfer line, the line shall be purged by flowing helium through special purge fittings that allow complete purging end-to-end. This method should only be used for short lines such as those used to connect roadable dewars to storage dewars.

g. Welding Procedure

(1) Purging and Inerting Hydrogen Tanks or Systems for Welding

Consult with personnel who are familiar with the equipment concerned and agree on the best method of purging and inerting. The general procedure is to remove all of the hydrogen to a safe location and fill the tank or system with inert gas before welding as follows:

(a) Transfer all possible liquid or gaseous hydrogen out of the tank or system to other containers or, if necessary, discharge safely to atmosphere.

(b) Isolate the tank or section of the system to be welded to further prevent return of any hydrogen. If possible, make certain of isolation by disconnecting. (If not possible to disconnect, vent and purge continuously with an inert gas as in paragraph 7, g, (1), (d), 3.

(c) Warm the entire tank or isolated section of the system to at least the critical temperature of liquid hydrogen, minus 400°F. This will evaporate all the liquid hydrogen. Stripping of insulation and preparation for welding can now be done safely.

(d) For purging and inerting

1. If the tank or system concerned is not leaking and is strong enough to withstand a vacuum (be sure of this, otherwise the tank or system will collapse).

   a. Evacuate to one centimeter of mercury absolute. Hold this condition--without the vacuum pump operating--for five minutes as an isolation, leak, and general information check.

   b. Fill the tank or system with gaseous nitrogen or argon to about 1 psig.

   c. Evacuate again as in (d), 1, a above.

   d. Fill again with gaseous nitrogen or argon to about 1 psig.

2. If the tank or system is strong enough to withstand a vacuum but has a known leak, seal the leak with tape, putty paints, grease, etc. to obtain the 1 centimeter of mercury, then proceed as for a non-leaking condition. (see (d), 1)

3. If the leak cannot be stopped, or its location is unknown, or if the tank or system is not strong enough to withstand a vacuum or if the section to be welded cannot be disconnected, then it is necessary to vent and purge continuously with nitrogen or argon gas flowing at about 1 psig.

(e) Sample and analyze the gas in the tank or system to be welded. After two cycles of purging, as in (d), 1, above, the percentage of hydrogen remaining should be less than two-tenths of one percent. Before welding the percentage of hydrogen must be less than 10 percent of the L.E.L. (Lower Explosive Limit) for hydrogen in air (less than 0.4 volume percent of hydrogen present.)

(f) Maintain a small pressure, about 1 psig, of inert gas in the tank or system, if the welding operation permits, to prevent inward migration of air.

(g) Perform welding as required.

h. System Cooling

(1) This optional method of preparing a warm vessel or system to receive liquid hydrogen uses liquid nitrogen for pre-cooling. The cooling process evaporates large amounts of the cooling liquid which, if it is hydrogen, may become a safety hazard. Steps to follow are:

(a) Evacuate the vessel or system to approximately 1 centimeter of mercury. (If this vacuum cannot be withstood safely, a warm inert gas pressure purge should be carefully planned.)

(b) Introduce the liquid nitrogen slowly into the vessel or system taking care to insure that there is no air migration which would cause contamination.

(c) Allow ample time to obtain all of the cooling possible from the liquid and cold gas.

(d) Drain off the remaining liquid nitrogen.

(e) Remove the nitrogen gas atmosphere by evacuating the vessel or system to 1 centimeter of mercury. (See (1), (a) above.)

(f) Now introduce the hydrogen purge gas slowly. Continue the flow until the vessel or system goes to a slight positive pressure.

(g) Now the liquid hydrogen may be admitted into the vessel or system

i. Ventilation

(1) Plenty of ventilation to avoid accumulation of leaked hydrogen gas is a great aid in achieving safety in operations. Natural ventilation, if adequate, is most reliable.

(2) Hydrogen diffuses rapidly if not confined. A spill of 500 gallons of liquid hydrogen will diffuse to non-explosive limits within one minute if out-of-doors. At "room" temperature, hydrogen is the lightest of all gases, only one-fourteenth as heavy as air; consequently, it rises. Therefore, inverted pockets will trap hydrogen gas.

(3) However, cold hydrogen at -418°F has the same density as air at "room" temperature and will not rise in air.

(4) Equipment containing hydrogen must not be covered so as to trap hydrogen.

j. Fuel Handling

(1) Receiving Dewars

Connect electrical ground. Inspect dewar generally for leaks or mechanical defects, etc. Check dewar pressure and vacuum.

(2) Connecting Lines

Clean connections. Purge all connecting lines and containers. See paragraph 7, (f) on "Purging." Avoid contamination.

(a) Watch for condensed water on surfaces for this indicates leaks. Make a check for leaks with a portable detector after each assembly or alteration. Use minimum grease on "O" rings. Use an approved vacuum grease such as Kel-F or Dow-Corning silicone.

(b) In the assembly of threaded pipe joints, the male portion shall be screwed into the female portion one-third the normal travel before applying a thread compound. The thread compound shall only be applied to the male thread. Teflon or Kel-F seal tapes may also be used with the same care.

(3) Pressurizing Liquid Hydrogen

(a) See checklist or operating instructions for particular equipment.

(b) Only minimum number of personnel shall be allowed in area. No personnel allowed around test installation.

(c) Do not use air or nitrogen (boiling point -320°F) to pressurize liquid hydrogen (boiling point -423°F). Contamination will result because air or nitrogen will freeze. Self-pressurizing or auxiliary hydrogen or helium gas required.

(d) Apply pressure slowly.

(e) Do not exceed system limitation.

(4) Liquid Hydrogen Transfers

All transfers shall be made in tightly closed systems. Liquid hydrogen should not be transferred into an open-mouthed dewar or be allowed to come into contact with air, for it can become contaminated with solid air in this manner. Ground wires shall be securely clamped across each coupling. These ground wires shall remain connected until after the coupling is separated. All fuel transfers shall be made against enough back pressure (about 3 psig) to prevent air migration.

(5) Disconnecting and Moving Hydrogen Supply Containers from Test Installations

Dewars and gas trailers should be disconnected from the test equipment after operation. Dewars and gas trailers should be moved from the test facility as soon as practical. In controlled areas, where large dewars are utilized and disconnection may constitute a hazard, the dewar(s) may remain connected between research operations at the discretion of the test conductor. Movements of dewars and tube trailers should be avoided during peak traffic hours.

k. Check-off Sheets

(1) Check-off sheets are substantial aids to safe operations and, therefore, are required for all but the simplest installations.

(2) In addition to the checklist of items pertaining to the specific equipment, there shall be a checklist of items concerned with safety of the test room and test area. There should be listed such items as combustible gas detection, ventilation, de-energizing electrical ignition sources, posting of warning signs, and notification to fire and guard forces.

l. Safety Signals

(1) Uniform audible and visible safety signals shall be used.

(2) Signal meanings shall be posted in all operation areas. All personnel must know and obey the signals.

m. System Identification

The preferred method of indicating the contents of a container or system is the printed word. Color codes are strictly secondary. If used, however, color codes should be uniform.

n. Amount of Hydrogen Leakage Permitted at Test Installations

(1) Every reasonable effort should continuously be made to eliminate leakage from hydrogen-using installations. In practice, however, complete elimination of leakage is sometimes very difficult to obtain. Therefore, operations may be done with some leakage if the test installation is entirely out-of-doors or in a well-ventilated expendable building. The following shall be used as a guide for determining the amount of leakage to be tolerated:

(2) Hydrogen leakage shall not exceed that causing an indication of 20 percent of the lower explosive limit at a distance of 2 feet above the leakage source (no wind) and shall only be permitted providing:

(a) The source of leakage is known and the leakage is stable. (For example, leakage from a crack may be unstable inasmuch as the crack may increase in size.)

(b) Plentiful ventilation is provided.

(c) The leakage is unconfined and free to diffuse rapidly

(d) Ignition sources are eliminated.

(e) Gas detection means are employed as stated above.

(f) Leakage is determined at test temperatures and pressures.

(g) Fully informed and experienced judgment approves.

(3) In the foregoing, the leakage may be determined by using helium in conjunction with a mass spectrometer and by converting the reading to the equivalent quantity of hydrogen.

o. Hydrogen Gas Cylinders

(1) Do not transport cylinders unless valve is covered with protective bonnet.

(2) Never handle cylinders roughly.

(3) Secure cylinders in an upright position with a chain, cable, or strap.

(4) Store cylinders in places where they are not subjected to physical damage and where they are protected from direct summer sunlight.

(5) Do not use leaky or damaged cylinders. Mark as defective and inform disposal personnel.

(6) Never alter, repair, change, or take apart a valve or safety disc on a cylinder.

(7) Use proper regulator on all cylinders. Tag regulator to indicate its use.

(8) Do not use a wrench to open a cylinder valve. If it can't be opened by hand, tag it as a bad valve and return it to the supplier.

(9) Cylinders used in laboratories should not be left unattended; they should be removed to a safe storage area when not in use.

(10) Never open the valve to "blow clear" before connecting a cylinder. There is danger of igniting the hydrogen.

p. Safety Approval Required Before Initial Operation

Before any test installation is operated with hydrogen, approval of operational safety shall be obtained from the proper safety authority.

q. Avoid "Last-Minute" Rushing

In the eagerness to commence test operations, especially in new installations, extreme care must be taken so that recklessness does not develop. It must be kept in mind that the starting of operations is a critical period. Unexpected and hazardous conditions may be discovered. Safety and operational check procedures shall be carefully and completely followed. Initial tests shall always be at conditions of lesser severity. The conditions of greater severity ultimately desired shall be applied only after the safety of operation at the conditions of lesser severity has been proven; for example, test at low speed before high speed, low pressure before high pressure, liquid nitrogen before liquid hydrogen. If possible, transitions between conditions should be gradual.

8. EMERGENCY PROCEDURES

a. Emergency Shutdown Switch

In setups equipped with an emergency shutdown system, whether automatic or manual, there shall always be a manual switch. In the event of uncontrolled leak, fire, over-speed, or other emergency, the operator shall notify the appropriate fire and damage-control forces immediately.

b. Presence of Combustible Gas Mixture

When an accumulation of combustible gas is known to be present in a test cell or area:

(1) Do not actuate electrical or other devices having questionable non-sparking characteristics. Telephones and radios usually fall in this category. Metal dampers, sash, doors, etc. may create sparks when opened.

(2) Shut off the gas and ventilate

(3) Evacuate the area. Personnel shall stay out of areas where there are combustible gases.

(4) Notify fire and guard forces immediately.

c. Use of Portable Hydrogen Detectors

(1) Portable detectors are used to determine whether dangerous amounts

of hydrogen have been released in areas not equipped with installed detectors, or to check areas where an accident has left the installed detectors inoperable.

(2) Only units approved for hydrogen are to be used. This approval means that the detector will not act as an ignition source. However, it does not eliminate other sources of danger.

(3) One danger results from the fact that detectors may give falsely low readings in the presence of high concentrations of hydrogen. Therefore, a sudden shift of wind or a rapid additional release of hydrogen might surround a man with a highly flammable mixture, even though the detector indicates less than 100% of the L.E.L. (Lower Explosive Limit).

(4) Another source of danger is that the detector may respond to the presence of various inert gases, such as helium or carbon dioxide. These will affect the readings because the instruments are calibrated with hydrogen-air mixtures. In some cases, negative readings result, which makes it impossible to detect small hydrogen concentrations.

(5) For these reasons, portable detectors must be used with great care. Always approach the suspected area slowly, proceeding in a direction with the wind. Leave the area immediately if the detector indicates 10% of the L.E.L., or if it begins to show negative readings. Watch the meter constantly; the instruments do not respond instantly to changes in hydrogen concentration, so any sign of "changing" readings is a signal to stop until the needle is steady.

d. Fire Fighting

(1) Typical Fire Involving Liquid Hydrogen

A typical fire-fighting problem will be described. Refer to paragraphs 2 a, 2 b, and 2 c for further discussion of the burning behavior of hydrogen.

(a) Assume rupture of a large liquid hydrogen container or supply piping system, such that a large amount of hydrogen is released in an unconfined area. Considerable liquid will immediately flash to vapor and mix rapidly with air. When ignited, this large volume of mixture will burn very quickly. The effects accompanying this initial phase are described below under paragraph (2); once ignition occurs, nothing can be done to counteract these effects. In the final phase of the fire, hydrogen will continue to burn at a rate governed by its vaporization rate, and there may be time to take action as described below under paragraph (3). Note, however, that in the case of multiple-wall vessels the insulating vacuum could be lost at any time. This would instantly aggravate the hazard by increasing the fuel flow to the fire.

(2) Initial Phase

(a) Flame effects. Flame will occupy the volume around the ruptured tank. Spills of a few hundred gallons may cause a "flash hot-gas ball" about 50 feet in radius. Wind may change the shape to an ellipsoid almost entirely downwind of the rupture. Flame temperature will be approximately 3600°F.

(b) Radiation effects. The hot gas ball will radiate but at less than the rate for a gasoline-air fire of the same size. Radiation effects on adjacent vessels and lines should not be severe, especially as reflective paint is normally used.

(c) Blast effects. Detonation of hydrogen-air mixtures in unconfined spaces is unlikely. However, the rapid burning of the initial cloud will produce pressure waves which are sometimes strong enough to damage structures and injure people.

(3) Final Phase

(a) Hydrogen fires are invisible; and since they radiate less than ordinary fires, and their radiation is strongly absorbed by normally-humid air, they usually give little warning of their presence either by sight or by feeling of warmth. Furthermore, the invisible flame may be many feet long and it shifts quickly with the slightest breeze. Therefore, personnel shall wear protective clothing when fighting fires involving hydrogen.

(b) The only positive way of handling a hydrogen fire is to let it burn under control until the flow of hydrogen can be stopped. If the hydrogen fire is extinguished and the flow of hydrogen is not stopped, a hazardous combustible mixture starts forming at once. Very probably the mixture will be ignited with an explosion to cause more damage and restart the fire.

(c) The block or isolation valves located close to the hydrogen container shall be closed by remote operation from a safe distance outside of the local hazard area.

(d) Although the hydrogen fire should not be extinguished until the flow of hydrogen can be stopped, water sprays, etc. should be used to extinguish any secondary fire and to prevent the spread of the fire. The hydrogen containing equipment should be kept cool by water sprays to decrease the rate of hydrogen leak and prevent further heat damage. (However, do not apply water directly to a cold wall that contains liquid hydrogen; the water will act as a heat source and will aggravate leakage.)

(e) It is permissible to use carbon dioxide (CO_2) in the presence of hydrogen fires. Although there may be some toxic carbon monoxide produced in the flame, it will not be a large amount. Anyone breathing the hot flame gases will die in any case, regardless of the presence of carbon monoxide. By the time the flame gases are diluted with fresh air to breathable temperatures, the carbon monoxide will be down to tolerable levels. However, confined spaces should be well ventilated before they are entered. Dry chemicals are better than CO_2 because they make the flames visible.

(f) Personnel should operate remotely controlled water-spray equipment if installed instead of hoses to cool equipment and to reduce the spread of the fire. If necessary to use hoses, those using the hoses should stay behind protective structures. Fire fighting or other emergency personnel shall confer and cooperate with personnel who are familiar with conditions in the area of the emergency. Any unusual conditions or materials shall be made known. Unexpected conditions may require special actions.

V-BAND COUPLINGS FOR LIQUID HYDROGEN LINES

1. V-band couplings, when properly applied, are approved for connecting vacuum jacketed liquid hydrogen lines. Suppliers offer a wide selection of couplings which range from light to heavy-duty and cover a number of flange angles and thicknesses. Visual inspection is often not adequate to distinguish between some of the similar types. It is therefore mandatory to use part numbers to insure proper application of the couplings. Table I lists some couplings suitable for use on two, six and eight inch lines.

2. Prior to applying applicable V-band couplings, it is important that male and female flanges mate properly. It is not expected that these couplings will correct any misalignment inherent due to fabrication, nor will they make a leak-free joint where flanges and/or O-rings have been damaged.

3. In applying and tightening the couplings, extreme care must be exercised to insure a leak-free joint.

4. Vacuum jacketed piping should not be subjected to excessive tension forces. For example: Extremely high tension forces can result from contraction of the piping due to cool-down and these must be avoided by proper design and installation. Flexible sections are often employed; however, to be effective, these sections must be connected with sufficient slack (or compression) when warm so that they will not be excessively stretched as the system is cooled to the operating temperature.

5. When trailer dewars are connected to the various test facilities, excessive tension loads can easily occur in the flexible transfer lines. The following procedure is set forth as an example of how the problem can be avoided: After completion of the hook-up and prior to operation, the dewar should be moved to compress the flexible hose an amount equivalent to the amount of contraction induced in the line when the system is brought to the operating temperature. If compression cannot be obtained, the flex hose should be permitted to loop sufficiently so that the line will straighten out on contraction. This operation will eliminate axial tension to which the coupling would otherwise be subjected when the line contracts. Stainless steel will contract at the rate of 0.0417"/ft from +70° to -425°F.

EXAMPLE: If the line between the dewar and the anchor point in the system is 30 feet long, the dewar movement required to either compress or loop the flex hose, should be 30 x .0417 or approximately $1\frac{1}{4}$ inches.

6. Care must be exercised in the handling of flanges and O-rings. When not in use, cover plates must be attached to protect both the male and female flanges and O-rings and to prevent contamination of the system.

APPENDIX I (contd)

TABLE I

V-BAND COUPLING INFORMATION

LINE SIZE (IPS)	RECOMMENDED V-BAND COUPLING	LATCHES NUMBER & TYPE	SEGMENTS (QUANTITY)	MANUFACTURER RECOMMENDED OPERATING PRESSURE (PSIG) BASED ON 4:1 SAFETY FACTOR	TEMPORARY SUBSTITUTES (SEE NOTE)
2"	Speciality Products Crop #4706-4-550 or Marman #4475-550-M	(2) Latches - One quick coupler and One T-bolt	2	150	Speciality Prod Crop #3406-8-550
6"	Marman #4170-1200-M	Same	4	165	Marman #4175-1200-D
8"	Marman #4170-1400-M	Same	4	135	Marman #4175-1400-D

NOTE: These V-band couplings do not have the features of the recommended type which provide more take-up and permit more equal distribution of band tension. It is recommended that these couplings be used only until the recommended coupling is available.

GASKET MATERIALS FOR CRYOGENIC SERVICE

1. The following materials have been laboratory and/or field tested and are approved for cryogenic service:

a. Glass-filled Teflon materials conforming to Martin Company Specification Control Drawing 55E 30. Approved materials and sources are:

(1) Fluorogold - manufactured by Fluorocarbon Corporation, 1754 Clementine Street, Anaheim, California

(2) Cryol-s and Cryol-m - manufactured by Johns-Manville, 2060 Bronx Street, Bronx 60, New York.

(3) Fluorogreen E-600 - manufactured by John L. Dore Co., P.O. Box 7772, Houston 7, Texas.

(4) Garlock Chemiseal 8573 - manufactured by U.S. Gasket Company, Plastics Division, Garlock, Inc., 610 N. 10th Street, Camden 1, New Jersey.

(5) Fluororay Blue Ceramic - manufactured by Raybestos - Manhattan, Inc., Bridgeport, Conn.

b. Teflon-encapsulated, metal-reinforced asbestos. Approved material and source is CG-12 - manufactured by Fluorocarbon Corporation.

c. Teflon-impregnated asbestos (Johns-Manville JM-91) with copper ferrules on inside and outside diameters, manufactured to

APPENDIX 2 (contd)

General Dynamics/Astronautics Part Number GD/A 83-67907 by Gasket Manufacturing Company, 319 West 17th Street, Los Angeles, California, or by Johns-Manville.

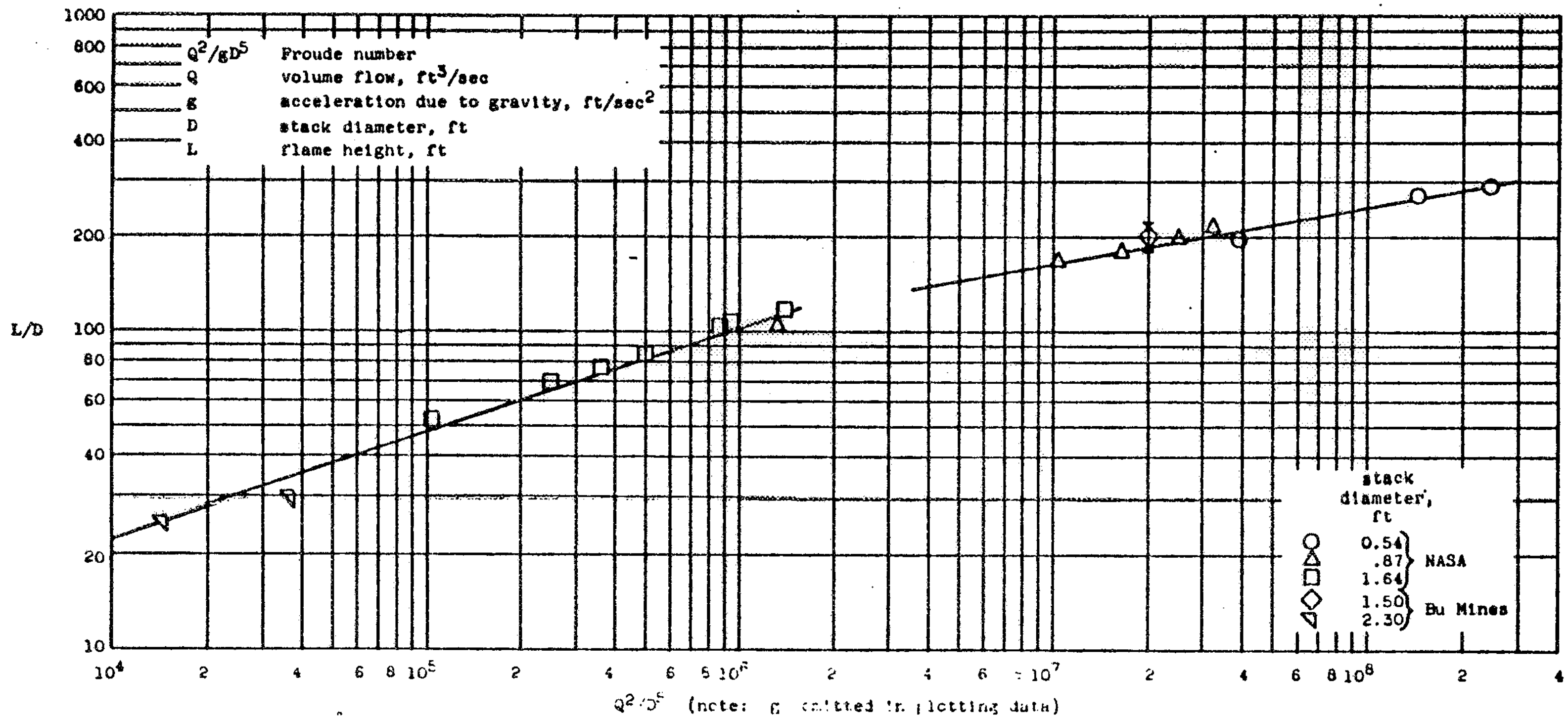
2. Gasket dimensions and tolerances shall conform to Appendix 3.

Reference: Memo of 17 December 1962 by Lt. Col. Norris E. Hartwell USAF, Chief, Engineering Division, Facilities Design Directorate, Ballistic Systems Division, Norton AFB, Calif.

STANDARD GASKET DIMENSIONS FOR BLS FLANGES
For Use With Welding Neck, Slip-On, Blind, Lap Joint or Socket Weld Flanges, Flat or Raised Face

Nominal Pipe Size or Tube O.D., inches	Gasket Inside Diameter inch*	Gasket Outside Diameter ** for ASA Flanges as Noted						
		150 lb ***	300 lb	400 lb	600 lb	900 lb	1500 lb	2500 lb
1/2	1	1 7/8	2 1/8	2 1/8	2 1/8	2 1/2	2 1/2	2 3/4
3/4	1 1/4	2 1/4	2 5/8	2 5/8	2 5/8	2 3/4	2 3/4	3
1	1 5/8	2 5/8	2 7/8	2 7/8	2 7/8	3 1/8	3 1/8	3 3/8
1 1/4	2	3	3 1/4	3 1/4	3 1/4	3 1/2	3 1/2	4 1/8
1 1/2	2 1/4	3 3/8	3 3/4	3 3/4	3 3/4	3 7/8	3 7/8	4 5/8
2	2 3/4	4 1/8	4 3/8	4 3/8	4 3/8	5 5/8	5 5/8	5 3/4
2 1/2	3 1/4	4 7/8	5 1/8	5 1/8	5 1/8	6 1/2	6 1/2	6 5/8
3	3 7/8	5 3/8	5 7/8	5 7/8	5 7/8	6 5/8	6 7/8	7 3/4
3 1/2	4 3/8	6 3/8	6 1/2	6 3/8	6 3/8			
4	4 7/8	6 7/8	7 1/8	7	7 5/8	8 1/8	8 1/4	9 1/4
5	6	7 3/4	8 1/2	8 3/8	9 1/2	9 3/4	10	11
6	7 1/8	8 3/4	9 7/8	9 3/4	10 1/2	11 3/8	11 1/8	12 1/2
8	9 1/8	11	12 1/8	12	12 5/8	14 1/8	13 7/8	15 1/4
10	11 1/4	13 3/8	14 1/4	14 1/8	15 3/4	17 1/8	17 1/8	18 3/4
12	13 1/4	16 1/8	16 5/8	16 1/2	18	19 5/8	20 1/2	21 5/8
14	14 5/8	17 3/4	19 1/8	19	19 3/8	20 1/2	22 3/4	
16	16 5/8	20 1/4	21 1/4	21 1/8	22 1/4	22 5/8	25 1/4	
18	18 5/8	21 5/8	23 1/2	23 3/8	24 1/8	25 1/8	27 3/4	
20	20 5/8	23 7/8	25 3/4	25 1/2	26 7/8	27 1/2	29 3/4	
24	24 3/4	28 1/4	30 1/2	30 1/4	31 1/8	33	35 1/2	

* Plus 1/32" minus 0, thru 10" size; plus 1/16" minus 0, from 12" thru 24"
** Plus or minus 1/32" thru 10" size; plus or minus 1/16" from 12" thru 24"
*** For use also with 150 lb MSS, IPS corrosion weight, or light-type tube flanges



Appendix 4. - Relation between hydrogen-burnoff flame height and modified Froude number of flow (data were determined for weight flows from 3 to 70 lb/sec).

FLAME HEIGHTS ON H_2 BURNOFFS

According to theory, the ratio of flame height to stack diameter should depend on Froude number raised to some power*:

$$L/D \text{ is proportional to } F^n$$

The Froude number expresses the ratio of the initial momentum of the gas to the buoyancy. A large Froude number means that the flame has the appearance of a directed jet; that is, it is long and does not spread very much. If the Froude number is smaller, the flame is buoyant. It grows much wider than the stack diameter and is readily tilted by the wind.

All this applies only if the flow is thoroughly turbulent as it leaves the stack.

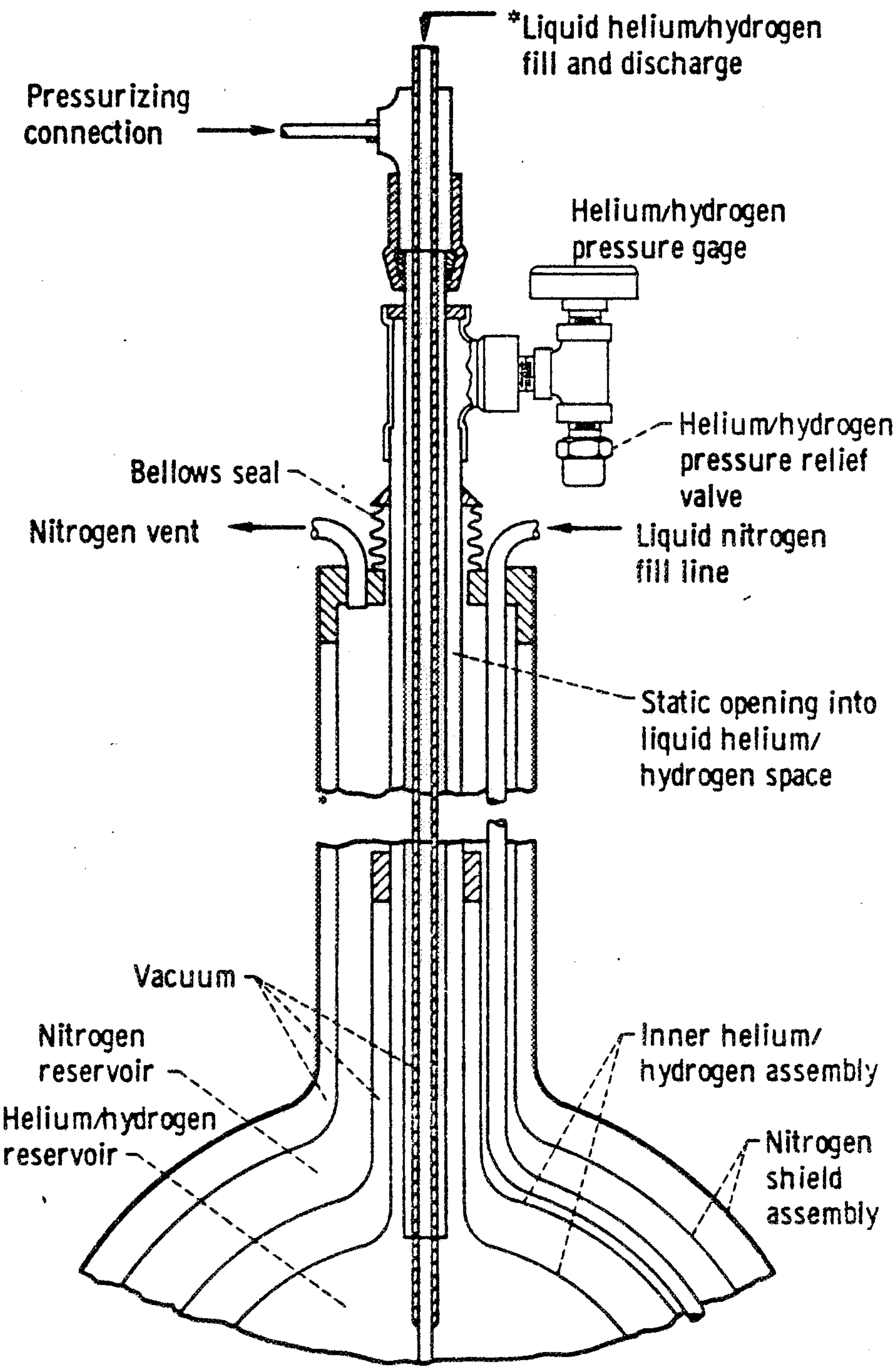
If the flame is buoyant, the mixing of fuel and air is assisted and the flame height is reduced. There is a power-law relation between L/D and air entrainment. The relation is such that the exponent on Froude number is 0.33 at low values of L/D. At higher values, the exponent drops to 0.20. Eventually, at very large Froude numbers, the flame is controlled entirely by momentum; presumably, the exponent would then become zero and L/D would become constant.

Appendix 4 shows that data obtained with large weight flows of hydrogen conform to theory, even though the theory is based on observations of laboratory flames involving very small weight flows. At the lower Froude numbers, the slope of the line is 0.32 (theory: 0.33), and it drops to 0.18 at higher Froude numbers (theory: 0.20).

Theory does not provide any way to guess the Froude-number range where the exponent would drop to 0.10 and then to zero. However, the data already cover a very wide range of Froude numbers, and Appendix 4 should therefore be helpful in predicting flame heights for most hydrogen burnoffs. The lower line segment can be extrapolated to lower Froude numbers with confidence. Extrapolation of the upper segment to higher Froude numbers will tend to overestimate the flame heights and so will yield conservative results.

In conclusion, attention is again drawn to the fact that buoyant flames are easily blown about by the wind. A burnoff must be located far enough from a facility so that an adverse wind will not carry the flame too close.

* P. H. Thomas: Ninth Combustion Symposium, pg. 844.



*Standard opening 5/8" O. D. by 0.020" wall
Larger neck opening available on special order

Appendix 6. - Dual entry laboratory Dewar.