

REVIEW OF HYDROGEN ACCIDENTS AND INCIDENTS IN NASA OPERATIONS

by Paul M. Ordin

Lewis Research Center

ABSTRACT

The report reviews a number of the accidents/incidents with hydrogen in NASA operations. The cause factors for the mishaps are reviewed and show that although few accidents occurred, the number could have been further reduced if the established NASA rules and regulations had been followed. Requirements for effective safety codes and areas of study for hydrogen safety information are included. The report concludes with a compilation of 96 hydrogen mishaps; a description of the accidents and their causes.

INTRODUCTION

The national concern over the growing energy crisis and environmental pollution has resulted in the consideration of hydrogen as a suitable fuel for future use. Hydrogen is readily produced from water by electrolysis, and designs have been proposed in which nuclear and solar power systems would provide the energy for producing the hydrogen efficiently. One advantage of using hydrogen is increased efficiencies in energy conversion devices over those obtained with hydrocarbon fuels.

Studies have shown that it is possible to produce liquid hydrogen at costs that would be competitive with those of other fuels. However, the availability and economics of a large liquid hydrogen supply are still a very important factor in the overall concept of a hydrogen economy. The second major factor in the development of a hydrogen economy is safety. What are the safety problems in the production, handling, transportation, and use of liquid and gaseous hydrogen? The purpose of this paper is to provide information on the overall safety of hydrogen by reviewing records of accidents and incidents which have occurred in the development and operation of NASA's propulsion and power systems.

This compilation of 96 mishaps serves not only to provide a general concept of the possible hazards in the handling and use of hydrogen but identifies significant lessons learned from these experiences. The records reviewed were primarily from NASA centers. These records described the mishaps and their causes and in many instances included recommended preventive or corrective actions. A number were obtained from contractors involved in the development of the chemical and nuclear propulsion systems.

Areas of research and development are suggested for increased safety and for the development of techniques to reduce the consequences of any mishaps.

NASA OPERATIONS

Hydrogen is used principally as a propellant for propulsion. The Centaur stage and the second and third stages of the Saturn launch vehicle utilize the liquid hydrogen - liquid oxygen propellant combination. The fuel-tank capacity of the Centaur stage is 38 cubic meters (10 000 gal). The Saturn's first stage has a 1021 cubic meter (270 000 gal) capacity and the second stage a 276 cubic-meter (73 000 gal) capacity.

Large quantities of liquid hydrogen are stored and used at NASA and contractor facilities. Tanks with storage capacities of over 3213 cubic meters (850 000 gal) exist at the Kennedy Space Center (KSC). Approximately 7600 cubic meters (2 million gal) of liquid hydrogen storage was available at the nuclear rocket test facility. Liquid hydrogen is transported from the manufacturer to the various NASA and contractor facilities in over-the-road tanker trailers designed to contain from 11 to 61 cubic meters (3000 to 16 000 gal) and in railroad cars having a maximum capacity of 129 cubic meters (34 000 gal). Each tanker trailer for the transportation of liquid hydrogen requires a special permit from the Department of Transportation (DOT). The Code of Federal Regulations includes the detailed requirements for railroad transportation.

In the Apollo-Saturn program alone, the KSC tanker trailers hauled over 16 million gallons of liquid hydrogen. Liquid hydrogen was also transported by barge to the Mississippi Test Facility. These barges have a capacity of 950 cubic meters (250 000 gal) and use vacuum perlite insulation to keep the boiloff below 0.15 percent per day. Liquid hydrogen was transferred from the barges to the test vehicle tanks or storage tanks at rates of about 38 m³/min (10 000 gal/min) through 25.4-centimeter (10-in.) diameter vacuum-jacketed lines. The barge operations were conducted in special canals in which the level changes of a barge during loading and unloading were controlled, as well as in canals which were subjected to tidal conditions.

The experience with hydrogen in NASA and AEC operations has been extremely gratifying in that relatively few accidents have occurred. We attribute this to comprehensive cryogenic and hydrogen safety programs practiced at the various facilities. For the most part, mishaps occurred when the guidelines and prescribed procedures included in the safety programs were neglected.

CAUSES OF MISHAPS

The causal factors which contributed to the mishaps detailed in the appendix have been categorized as follow:

- (1) Procedural deficiencies: the failure to follow established procedures or to prepare proper procedures
- (2) Planning deficiencies: limited planning, such as failures to prepare test plans or to perform hazard studies

- (3) Materials failures: the failure of materials and components due to stresses which had been considered within the design limits
- (4) Design deficiencies: inadequate component or system designs, including failure to specify safety devices and omission of other essential information, failure to determine stress and fatigue, errors in material selection (such as clerical errors in drawings and specifications)
- (5) Operation and work area deficiencies: inadequate working conditions during installation, maintenance, fabrication, and cleaning and the lack of training and/or specific instructions
- (6) Malfunction: any anomaly, including components in the system which failed to function as intended
- (7) Materials incompatibility: incompatible materials either brought together by accident or designed into the system
- (8) Contamination: the use of contaminated material

The distribution of the mishaps according to these general categories of causal factors is shown in figure 1. The 96 mishaps listed in the appendix were used to establish the distribution shown in this and following figures. In a number of cases, more than one factor was considered as being responsible for the mishap.

The largest number of mishaps (26 percent) was considered to be caused by work area deficiencies. Procedural deficiencies accounted for 25 percent. Design deficiencies were responsible for 22 percent. Planning deficiencies followed next with 14 percent. These four categories, which are basic to an overview of safety requirements for any type of engineering system, were responsible for 87 percent of the mishaps reviewed. Malfunctions were involved in about 8 percent of the accidents, while problems concerned with materials failures and materials incompatibilities were each factors in about 3 percent of the mishaps.

An effort was made to identify the hardware, equipment, or specific action directly responsible for each accident. These results are shown in figure 2.

Valve malfunctions and/or valve leaks were considered as being responsible for 20 percent of the mishaps. These valve malfunctions and leaks, as well as a number of the other specific causes of mishaps, were due primarily to operational (work area), procedural, and design deficiencies. For example, valve malfunctions and valve leaks were caused by

- (1) Not following the established procedure in applying correct pressures
- (2) Not carrying out the purging procedures as prescribed in the operational requirements

- (3) Not opening or closing the proper valves in the system as indicated in the design specifications

On several occasions, the valve design or the materials used in construction caused the malfunction or leak. Leaking connections and/or fittings were identified as being separate from valve leaks and caused about 16 percent of the mishaps. Items such as loose flange connections caused shrinkage of the "O" rings and/or gaskets because of the low temperature and resulted in leaks that caused mishaps. Fittings not installed properly also resulted in leaks that caused accidents. To a large extent, not following established procedures, or the lack of specific instructions were responsible for the leaking connections.

Safety disk failures, materials failures, and high venting rates were each identified as responsible for about 11 percent of the mishaps. Safety disk failures in tank and piping installations and in over-the-road tanker trailers caused leaks which were responsible for some of the accidents. A number of the disk failures were considered as malfunctions; however, in several instances, improper installation and failure to follow established planning for the replacement of ruptured disks caused the failure. In most instances, the disk performed as designed and ruptured when the design pressure was attained. The rupture did, however, release hydrogen and, in some instances, caused an accident.

Liquid hydrogen can decrease the ductility and impact resistance of structural materials with which it comes in contact. The use of materials not compatible with hydrogen caused a number of mishaps. In some instances the design did not fully consider the wide range of coefficients of expansion of the materials used and the degree of confinement of these materials required to limit the development of high stresses. Hydrogen embrittlement of materials was also a factor in a number of the accidents.

High venting rates of hydrogen through venting systems were considered as being responsible for a number of the mishaps. The problem related to these high venting rates, which to a large extent were due to system design limitations, was the ignition of hydrogen-air mixtures. It appears that, with high venting rates, ignition tends to occur more frequently above the vent stack, around the vehicle stage platform area, or above the tank testing area. High venting rates during weather conditions which limited the dispersion of hydrogen appear to be responsible for providing easily ignitable hydrogen-air mixtures.

Cryopumping has been identified as being involved in about 10 percent of the mishaps. In a number of instances, the cooling of vessels and lines produced a reduced-pressure environment that resulted in air being sucked into the system. Air entered through leaks or faulty valves. Incomplete facility construction and unsatisfactory procedures also allowed air to enter the system. The air formed flammable mixtures with hydrogen and occasionally ignited or, in several instances, liquefied (or solidified) and formed flammable hydrogen-air mixtures during the warmup phase of the operations. The ignition of such mixtures under these con-

ditions usually resulted in explosions or detonations. Mishaps caused by the liquefaction of air were also included in the cryopumping category. Air liquefies and forms a running stream when directly exposed to tanks and piping containing liquid hydrogen. In a number of tests, the liquid air was not directed away from major pieces of equipment and caused some failures that resulted in hydrogen leaks and fires.

The mishaps attributed to air in the system caused about 5 percent of the accidents. These included mishaps in which work with hydrogen was initiated or repairs were performed in hydrogen systems without the system or equipment being properly purged. The flammable hydrogen-air mixtures within the system components, such as tanks and lines, usually exploded when an ignition source was available. In a number of such instances, drilling, cutting, or welding operations provided the ignition source. Also included in figure 2 are bellows failures, which usually occurred in liquid hydrogen lines. The release of hydrogen most frequently resulted in fires. System overpressurization and installation errors were responsible for a large number of the bellows ruptures, which resulted in 4 percent of the mishaps. Several of the accidents were caused by battery operations (about 4 percent) in which hydrogen-air mixtures formed and ignited. In general, the lack of purging or ventilation was responsible for the buildup of the flammable mixtures. Highway accidents accounted for about 4 percent of the total mishaps included in the appendix. The other identified causes, which each resulted in less than 3 percent of the mishaps, included tank and line ruptures and vacuum losses.

In a number of accidents, the released hydrogen did not ignite. Table I presents a summary of the results of the mishaps with respect to where the release occurred and whether the hydrogen-air mixtures ignited. A total of 80 (83 percent) of the mishaps involved a release of liquid and/or gaseous hydrogen. The hydrogen was considered as being released to the atmosphere or within an enclosure such as a tank or line. In general, when the hydrogen was released within an enclosure, the enclosure contained an air environment, and a hydrogen-air flammable mixture resulted immediately. About 69 percent of the mishaps (56) involved a release of hydrogen to the atmosphere, and 21 percent involved release to enclosures. In six mishaps, hydrogen was considered as being released to both locations.

When hydrogen was released to the atmosphere, ignition of the mixture occurred 62 percent of the time (41 mishaps); and for release to enclosures, ignition occurred each time (20 mishaps). The available accident reports were reviewed to determine the source of ignition, and the results are shown in figure 3. In 30 percent of the mishaps in which hydrogen was released and ignition occurred, the source of ignition was not known. Electric short circuits and sparking were considered to be responsible for 24 percent of the ignitions and static charges for about 17 percent. For about 7 percent of the releases, the source of ignition was believed to be the flare on the vent stack. Use of welding or cutting torches, metal fracture, and impingement of high-velocity gases were

each considered to be responsible for about 5 percent of the ignitions. Ignition of hydrogen-air mixtures attributed to metal fracture involved tensile testing mishaps in which the fracturing of the specimens provided the ignition source. Also included are mishaps in which the cause of ignition was considered to be burst safety disks or metal failures. The specific ignition source was probably the static charges or hot spots that developed during material rupture. Ignitions attributed to impact include those considered to be caused by high-velocity fragments.

The importance of satisfactorily purging a system before any operations with hydrogen is demonstrated by the data presented in table II. The mishaps were reviewed with respect to the release of hydrogen, the ignition of the hydrogen-air mixture, and the role of possible purging problems. Of the total number of mishaps (96) 25 percent were associated with a purging problem; that is, the system was not purged as prescribed nor was the exit gas analyzed to ensure the removal of air. Such purging problems resulted in the release of hydrogen to the atmosphere (14 accidents (58 percent)) and in release within the system (10 accidents (42 percent)). Of those mishaps involving a release of hydrogen to the atmosphere, 93 percent resulted in ignition. Ignition occurred for all those mishaps in which hydrogen was released into the system. Various purging procedures are recommended and operational methods defined, but it appears that more positive means must be made available to ensure compliance with the requirements.

The causes of hydrogen tanker trailer mishaps are summarized in figure 4. Seventeen tanker trailer mishaps were included in the study with 71 percent (12) associated with off-loading operations (usually at the test facility) and 29 percent (5) occurring on the highway. In about 92 percent of the off-loading accidents (11), hydrogen was released, but in only 27 percent (3) did ignition take place. With respect to highway mishaps, 60 percent (3) involved a release of hydrogen, but no ignitions occurred. For both the off-loading and highway mishaps, disk rupture was the principal cause; other causes included open or leaking safety valves (18 percent), loose couplings, vacuum failures, and vent valve leaks. In several instances, positioning the trailer in preparation for connecting lines resulted in the driver hitting parts of the facility.

The safety record of over-the-road transportation of liquid hydrogen is quite evident in that only five tanker trailer highway accidents are included. These reports involved NASA operations. In three of these accidents the tractor was heavily damaged, but the trailer remained substantially sound. There was no damage in the other two highway accidents. In only one case was liquid hydrogen spilled on the ground, and there was no ignition of the hydrogen-air mixture.

The results of this review indicate relatively few accidents involving hydrogen during the development and operation of the NASA propulsion systems. This number could have been reduced considerably if the established rules and regulations had been carefully followed. Comprehensive hydrogen safety programs, including detailed safety codes, must be

evolved for each system. As with the NASA guidelines, these safety and operational codes must be based on the following factors:

- (1) Knowledge of the potential hazards of hydrogen
- (2) System engineering to preclude hazards
- (3) Personnel education in both the potential hazards and technical knowledge of the system
- (4) Assurance that specific safety procedures exist and are followed for each operation

These factors demand that, to be effective, safety codes must be based on knowledge of the properties of both the fluids (liquid gases and mixtures) and the materials used to confine them. The systems safety concept requires a technical management discipline covering conceptual and design studies, engineering, testing, fabrication, and operation of each system. At least one level of fail-safe redundancy should be provided for all subsystems and components judged to be critical or catastrophic. It is important that all supervisory and technical personnel working on a system have an intimate knowledge of the equipment arrangement, facilities, and system operations. Strict discipline must be maintained throughout all phases of testing, and procedures regulating each step of the operation are mandatory.

CONCLUDING REMARKS

Since many of the accident reports on which this review was based did not contain sufficiently detailed technical descriptions of the mishaps or were not specific as to the hardware and/or operating procedures involved, efforts are underway to modify the reporting procedures to include such information. The records do, however, indicate a very high level of safety with hydrogen. The solution to many of the problems can positively be prescribed, but further research and development would be required for answers to others. Some of those areas in which studies should be performed include the following:

- (1) Means to ensure positive removal of air during purging
- (2) Studies of maximum possible disposal rates and how these rates would be modified by the existing weather conditions
- (3) Development of easy and rapid means of detecting any initiation of cryopumping which could promote hydrogen-air mixture
- (4) Development of standards and specifications for liquid hydrogen valves, fittings, and connections with respect to leakage requirements

- (5) An improved understanding of the possible sources of ignition of the hydrogen-air mixture and means for eliminating them
- (6) The development of highway driving guidelines with respect to road and environmental conditions
- (7) Means of limiting flammable mixtures such as restricting vent points, adequate ventilation, inerting systems, and installing monitoring devices around suspected leak points

TABLE I. - SUMMARY OF MISHAPS INVOLVING
RELEASE OF HYDROGEN
[Total number of mishaps, 96.]

	No.	Percent of total mishaps	Percent of total releases
Mishaps involving release of liquid and/or gaseous hydrogen	80	83	--
Location of hydrogen release			
To atmosphere	a66	69	82
To enclosures (contain- ers, piping, etc.)	a20	21	25
Ignition of hydrogen releases			
To atmosphere	b41	62	51
To enclosures	20	21	25

^aIn six mishaps, hydrogen was released to both locations.

^bIn 25 mishaps, hydrogen that was released to the atmosphere did not ignite.

TABLE II. - IMPORTANCE OF PURGING
HYDROGEN SYSTEMS
[Total number of mishaps, 96.]

	No.	Percent of mishaps due to purging
Mishaps identified with purging problem	a24	25
Effects of mishaps due to purging problem		
Release into atmosphere	14	58
Release into system contain- ers	10	42
Effects of release into atmosphere		
Ignition	13	93
Nonignition	1	7
Effect of release into system contain- ers		
Ignition	10	42

^a25 percent of total mishaps.

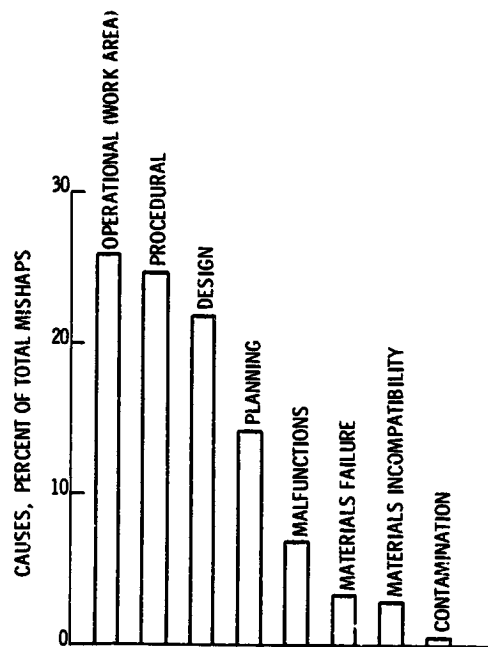


Figure 1. - General distribution of causes of mishaps with hydrogen - (more than one cause factor is involved with most mishaps).

DETAIL BREAKDOWN OF MISHAP CAUSES

- A VALVE MALFUNCTIONS AND/OR VALVE LEAKS
- B LEAKING CONNECTIONS
- C SAFETY DISK FAILURES
- D UNSATISFACTORY MATERIALS, EMBRITTELEMENT
- E HIGH VENTING RATES
- F CRYOPUMPING
- G AIR IN SYSTEM
- H BELLOWS FAILURE
- I BATTERY-RESTRICTED VENTILATION
- J TANK RUPTURE
- K HIGHWAY-TRAFFIC ACCIDENTS
- L VACUUM LOSS
- M LINE RUPTURE

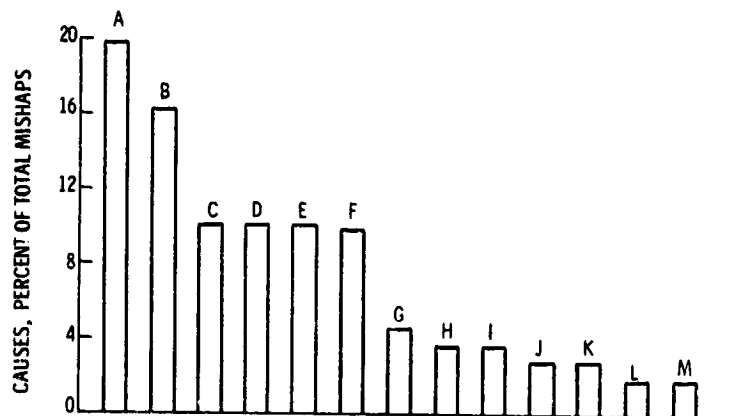


Figure 2. - Detail distribution of causes of mishaps in which hydrogen was released (more than one cause factor is involved with some mishaps).

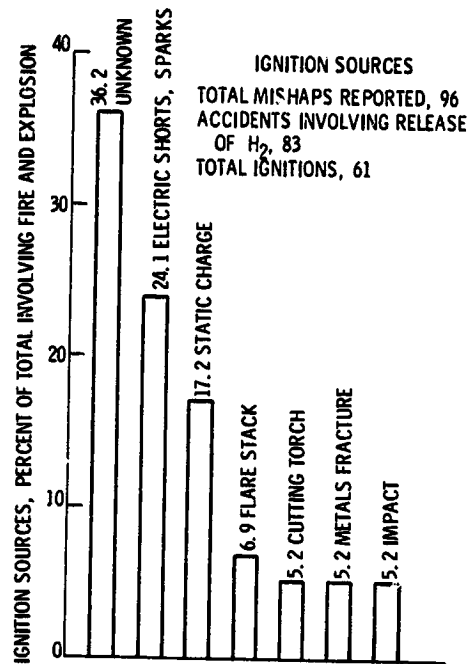


Figure 3. - Ignition sources - mishaps involving release of hydrogen.

LIQUID HYDROGEN TRAILER ACCIDENTS
TOTAL NUMBER, 17
OFF LOADING LOCATION, 12 (71 PERCENT)
ACCIDENTS IN WHICH H₂ WAS RELEASED:
OFF LOADING, 11 (92 PERCENT); HIGHWAY, 3 (60)
ACCIDENTS IN WHICH H₂ IGNITED:
OFF LOADING, 3 (27 PERCENT); HIGHWAY, 0

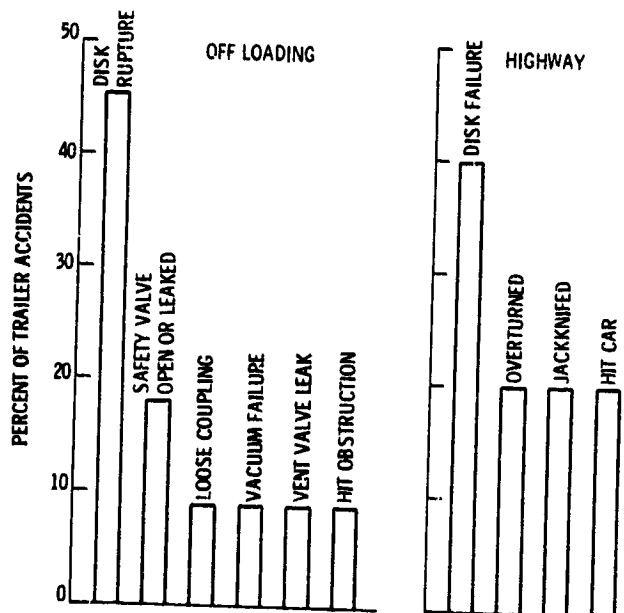


Figure 4. - Liquid hydrogen trailer accidents.

APPENDIX - HYDROGEN SYSTEMS MISHAPS

Mishap

1. During preparation for transfer of liquid hydrogen from trailer to storage facility, the safety valve opened and gas ignited. The pressure buildup was initiated by opening the liquid hydrogen valve to the build up coil when the mishap occurred. Flames filled the control cab. Fire appeared at three pipe connections to the vent line, all on the vent side of the relief valve. The fires were terminated after all the valves were closed, however, a leak continued through the high pressure relief valve. The fire was put out by terminating the supply to all the leaks. It was allowed to burn out and also slowed by using helium in the gas phase.

2. LH₂ tractor-trailer accident on highway with trailer containing CH₂. In going into curve, truck and trailer started to weave and pushed to side of road. Truck and trailer rolled about 40 feet downhill; the trailer rolled over 1½ times and tractor once, ending in upright position with driver still in seat. The tractor was a complete loss but little damage was incurred by the trailer. Trailer shell was satisfactory with normal venting through the stack. The rear cabinet doors were warped shut.

Cause

1. The tank pressure was considered to be at a relatively high value due to an incorrect pressure buildup. Opening the valve to blow down probably caused a pressure rise in the vent line manifold into which all the relief and vent lines were connected. A half-inch line in the vent side of the relief valve was broken and a large amount of high velocity gas was vented through the crack. Liquid hydrogen may also have been forced into the heat exchange loop too rapidly causing a pressure rise sufficient to open the relief valve and permit gas to escape through the cracked line. The gas was ignited most likely by static charges. Hydrogen leaks and fires existed at the threaded sections and at the ruptured pipe nipple. The relief valve was kept open by a piece of metal permitting leakage of hydrogen into the vent system. Road vibrations and limited support caused blockage at the threaded sections and rupture of the pipe nipple.

2. Accident occurred on bad road; steep with many sharp curves. The driver was going too fast for road conditions and type of trailer being pulled.

Mishap

3. Continuous venting of H₂ from LH₂ trailer occurred during highway transportation. Trailer delivered at test site and vacuum pressure checked to be less than 1 micron. The tank pressure was 50 psig. Attempts were made to stop the venting by thawing the manual vent valve; also, the burst disk was nearly frosted. The LH₂ was transferred and the external piping warmed with water. The rupture disk was replaced.
4. Accident occurred on highway with loaded LH₂ tractor trailer. Trailer started to jack-knife after driver applied brakes; trailer swung around 180° and continued to slide into shoulder. Trailer separated from tractor, turned over in ditch and continued to travel about 80 feet on its side. The king-pin flange tore loose from the trailer; trailer remained upright and did not suffer any damage. Sometime after accident, safety disks functioned and liquid load was dumped into snow and mud.
5. During transfer of LH₂ from commercial tank-trailer to receiving vessel, a leak developed in bayonet fitting at trailer/facility connection. Leak produced H₂ spray which enveloped rear of truck where hand-operated shutoff valve was located. Emergency trained personnel, wearing protective clothing, except for proper shoes, entered area and shut off flow control valve. Reentry personnel suffered frost-bite of their feet when shoes became frozen to water-wetted rear deck of truck.

Cause

3. The rupture disk had a number of holes but was not completely blown out. The H₂ leak probably existed throughout the entire trip; the loss was about 3886 gallons.
4. Driver noted car in lane traveling at slow speed; he started to apply the brakes, causing the trailer to jackknife. He applied power and the trailer swung 180° to the right side leading the tractor. He hit the bank and the king-pin flange tore loose; trailer turned over. The LH₂ was emptied about 1 hr after the disks ruptured. Light snow was falling and the road was wet. There was a strong wind, no chain warning, and the driver stated he was not speeding.
5. A loose hose flange connection allowed leakage of cold fluid through the hydrocarbon lubricated bayonet seal. This allowed cold fluid to contact and shrink the "O" ring seal (made of Buna-N rubber), thus permitting liquid hydrogen leakage to the atmosphere - all tank trailers should have a safely accessible auxiliary shut off valve in case of spills.

Mishap

Cause

6. Venting rate became extremely high during transit of 10 000 gallons LH₂ transport vessel. The annular vacuum appeared to be lost showing large patches of condensed water at the lower half of the outer vessel shell. It was necessary to stop many times to manually vent. In addition, a number of times the safety valve with an opening pressure of 55 psig was relieved. The trailer had only 3000 gallons remaining which was transferred to the storage tank. Crack was found in lowest portion of carbon steel jacket.
 7. Tractor-trailer returning from LH₂ delivery was hit by truck. Tank contained gaseous hydrogen. Tractor was demolished. LH₂ trailer did not suffer any leaks and vacuum was not broken.
 8. Safety disk failed during unloading from LH₂ trailer. The release of H₂ resulted in fracturing of a section of the vent pipe. The vent piping was carbon steel.
 9. A fully loaded LH₂ trailer parked off highway to permit drivers to eat and switch seats. While at site, high pressure caused safety devices to function. No fire or damage.
 10. Safety disk ruptured on LH₂ trailer during delivery of load. The supply was refused due to possible contamination.
6. Outer jacket cracked due to concentration of solid then liquid air in bottom of outer jacket. Air entered vacuum space due to crycpumping of LH₂. The air remained as a solid until the liquid H₂ transfer was completed, after which, the air melted. The crack was most likely caused by the thawing of solid air.
 7. A truck was racing with an auto and attempted to pass but spun into lane in front of tractor. Tractor traveling about 50 to 55 mph; it was raining at time of collision.
 8. Malfunction - premature failure of disk. The proper technique was not used in unloading the trailer due to operational problems. Fracture of the vent pipe was due to thermal shock caused by the cold liquid hitting the pipe.
 9. Disk malfunction, although outer vacuum appeared to be deteriorating. A new disk was installed and the trip continued.
 10. Malfunction - disk failed to function as intended. The disk was replaced and trailer put back in service.

Mishap

11. While disconnecting liquid H₂ fill line from LH₂ trailer, LH₂ escaped burning second man who was holding the hose; man was burned on hands and stomach.
12. During an LH₂ transfer from a tanker, the burst disk ruptured at 50 psi. Pressure limit for the operation was 30 psi.
13. During transfer operations of LH₂ from trailer, venting resulted in detection of a H₂ concentration in an adjacent building. The normal procedures could not be used because of difficulties in the self-pressurizing system and helium gas was used to pressurize the tank. The trailer was vented through the gas phase valve since the normal vent valve was inoperative.
14. While pressurizing LH₂ trailer for liquid transfer, the rupture disk burst. The trailer pressure was 22 psig. The relief valve was set at 27 to 29 psig. The trailer was moved to remote location and the disk replaced under loaded conditions. The liquid transfer was continued; however, during the operation, there was a leak through the vent valve.

Cause

11. The LH₂ shut off valve was partially open but both men assumed it was closed. Prescribed clothing was being worn.
12. The operator turned on the pressure valve and left it unattended, permitting pressure buildup past the allowed 30 psi.
13. Venting through the gas phase line directed the flow towards the wall of the adjacent building that had a duct at its base. The duct (1'x10') contained fill station piping. Ventilation action of an overhead fan in the room created a draft sufficient for the H₂ gas to enter and actuate the H₂ sensor.
14. The relief valve did not operate and the pressure may have increased sufficiently to cause the burst disk to fail. Leakage through the vent valve was attributed to water entering the system during repair to replace the burst disk.

Mishap

15. During a gas trailer filling operation, a burst disk relieved causing gas to escape. The gas flow caused the vent pipe to separate at the flared tube fitting and a fire resulted. The fire caused three additional tubes in the gas trailer to relieve increasing the intensity of the fire.
16. During preparations for offloading of a commercial tanker, the trailer experienced an overpressure causing the 50 psig relief valve to open and also rupture the 70 psig burst disk. Hydrogen was vented through the vent valve and disk. A vapor cloud of about 25 feet in diameter resulted. Examination later also showed cracks in the carbon steel vent line.
17. During LH₂ trailer-pump operations, the vent valve was opened rapidly and gas in atmosphere above the vent stack detonated. The rapid valve opening was aimed at initiating good pumping in the LH₂ pump-vaporizer system. The vent valve was closed but the stack continued to flow hydrogen which burned. The trailer pressure was 16 psig.
18. At offsite LH₂ fill station, LH₂ trailer hit GH₂ purge shut-off valve handle. Tuling attached to purge valve was bent on both ends but did not leak.
- Cause
15. No reason was given for the burst disk failure. The pulling away of the tube from under the SAE flared fitting indicated faulty assembly. Causes of faulty assembly include: (1) flare on tube too short (short flare is squeezed, then due to smaller area, tube is loosened), (2) nut too loose, (3) tube end not squarely cut, (4) foreign material in joint when tightened, (5) split flare.
16. The liquid phase valve into the trailer transfer buildup coil was opened prior to opening the gas pressurization valve. Opening the pressurization valve resulted in unrestricted large flows into the tank causing excessive pressures which opened the relief valve and ruptured the burst disk. Vibrations during transit may have caused the liquid phase valve to open. The trailer was almost completely full of liquid hydrogen which contributed to the accident. The flow of cold fluid caused the cracks in the carbon steel vent line.
17. Ignition occurred in rapid opening of vent valve. The fire continued because the flap valve on the vent did not make a tight seal. The Teflon gasket was found scorched. The vent stack was not purged allowing for a H₂-air mixture in the stack.
18. Driver was not sufficiently careful in approaching LH₂ system fill point. Should eliminate backing into position and install pipe barriers.

Mishap

19. While LH₂ barge was being disconnected from dock, a flash occurred in the vent stack. No damage occurred but potential existed for major damage.
20. During J-2 engine testing program, the engine start tank was pressurized and pegged up scale in excess of 1500 psi. The venting of the tank was attempted but pressure remained pegged. Assumption was made that pressure instrumentation had failed and blowdown was initiated through engine. The start tank ruptured and fire engulfed test stand area. Rupture of tank caused damage to engine and test stand facility.
21. During a test of an 8 foot scale tank loaded with LH₂, the tank burst at 77 psi destroying the test installation. No fire or explosion occurred and area control was successfully recovered within 24 hours.
22. During development test of a booster, a 3000 psig relief valve actuated at normal line pressure releasing GH₂. The GH₂ combined with air resulting in an explosion which damaged the test facility.
23. Explosion occurred during calibration of engine. The equipment was covered by shed and when the valve was operated allowing H₂ gas to flow through the engine, the gas ignited. Explosion caused damage to shed and injuries to personnel. The suggested overpressure was over 10 psi.

Cause

19. The LH₂ burst disk was found to have a series of pin holes which permitted GH₂ to enter the land vent line. An explosive mixture was formed when air entered the disconnected line.
20. Pressure increased in tank and was probably about 2900 psi at the time of failure. Water was present in the vent manifold where the start tank vent line ties into the manifold. It was believed that ice blockage prevented the venting as any relief action by the vent or relief valve.
21. A material failure in the tank. The test was programmed for 79 psi maximum and the tank burst at 77 psi. Contributing to potential hazards was the lack of an emergency recovery plan for such an emergency.
22. Improper setting of relief valve and inadequate inspection resulting in setting relief valve to open at line pressure. Contributing cause was poor design of the venting system which was installed in a horizontal position causing inadequate venting and buildup of static electricity.
23. A hydrogen valve leaked allowing a concentration of H₂ to build in propellant header. When valve was operated, H₂ gas was propelled through engine and collected under shed. The ignition source is unknown.

Mishap

24. LH₂ tank pressurization line on nozzle skirt ruptured at welded section. Two tests were underway at the same time; one required a pressure test up to 1850 psi in the GH₂ circuit and for the second, an equipment installation and leak check. The LH₂ pressurization line was capped.

25. A liquid hydrogen system exploded and burned during fill operations due to inadequate purging after the previous operation.

26. With completion of H₂ tensile tests, cryostat top was removed. In order to increase vaporization rate, the cryostat was warmed with conventional hair dryer, at which time an explosion occurred.

27. During rocket engine firing test, a fire occurred in several sections of the insulation covering the LH₂ supply line. The location of the fire was at the bottom of a supply line riser pipe. The insulation was Fiberglas with 8 percent organic fibers. The purpose of the insulation was to prevent cascading of run-off liquid air on bare liquid H₂ lines.

Cause

24. Line ruptured due to high pressures caused by leakage through a control valve between the GH₂ and LH₂ systems. The fuel pressurization system reached 1300 to 1400 psi while the burst pressure was 1250 psi.

25. Purging had been accomplished with gaseous nitrogen but had not been repeated with gaseous helium or hydrogen and air was still in the system.

26. Removing lid of cryostat resulted in cryopumping of air and formation of H₂-air mixture. Ignition was probably by sparks from dryer.

27. The vertical section of insulated pipe was considered as making an air fractionating column. As the liquid air runs down the pipe, oxygen enriched air could collect at the bottom. Cause of ignition not clear; could have been due to vibration or hot spot from flame.

Mishap

28. Ignition occurred when H₂ was flowed through nozzle. Fire was observed at nozzle inlet followed by large fireball. The explosions took place as the flow was being reduced from 120 pounds per second. No pressure wave developed and it appeared that damage was done by the negative phase of the shock wave. The amplitude of this phase was close to the design limit for venting to relieve gas/air explosions. The overpressure was about 0.5 pounds per square inch. Extensive damage to buildings was incurred.

Cause

28. Ignition may have been caused by (1) electrification of gas due to large flow; this would probably require some contamination, (2) electrification of particles; this would require dirt or scale in system, (3) incandescence; the exit velocities were over 4000 feet per second and metal particles may have hit a rod across the nozzle erect or (4) rupture of metal rod. The total height of the cloud was about 150 ft; explosion appeared to be concentrated below the top of the test cell building. This could suggest that cloud, equipment, and face of test cell provided partial confinement and reinforced the explosion.

29. An explosion occurred during nozzle flow tests to determine closed loop feedback control characteristics using LH₂ and LN₂ (in place of O₂). The fuel run vessel pressurization valve was opened rupturing the fuel tank rupture disk. The H₂ release ruptured the bellows joint in the vent line and H₂ ignited. The water deluge was turned on. Several fires were present. A survey of the facility was being made while the gaseous H₂ locked in the manifold was being vented through the tank pressure relief valve. During this time, a second explosion occurred causing additional fires and further damage to the stand.

29. The reference transducer which closes the control loop of the LH₂ tank pressurization flow control valve was disconnected. The lack of pressure feedback from the vessel caused the pressure flow control to open fully and resulted in the overpressure condition. The installation originally employed one transducer to provide feedback to the flow control valve and was also provided with a vent valve. The vent valve was removed and a second transducer installed, but was not connected.

Mishap

Cause

30. Explosion occurred at or near top of vent stack after termination of an H₂ fuel pump test. There was damage to stack segment, vent systems, ducting, and valves. The top section of vent stack was missing - a covering "hat" section (15 ft length) was on top of vent stack and housed a double reversing turning vane assembly.
30. Explosion resulted when large volume of CH₂ was vented off the newly formed "hat" section of the vent stack. (Structural failures were observed prior to this incident.) The system had slightly higher than normal catch tank pressures due to partial restriction of the vent stack outlet. Internal failures prior to incident were responsible for the reduction. Ignition was by static electricity or burning gas in vicinity of stack outlet.
31. After completing testing of LH₂ tank, the liquid was removed and tank purged with helium gas for about 4½ hours. A flange was then removed to allow for insertion of smaller tank, at which time an explosion occurred.
31. Hydrogen gas was present after the 4½ hours of purging. An explosive H₂-air mixture formed when second tank was inserted. The outer tank was still cold and air could enter the chamber by cryopumping. The ignition source was probably a hot wire level sensor; A platinum wire, heated to above the ignition temperature of the mixture.
32. Large hydrogen gas leak from dewar resulted when bolts holding fitting to top of tank was loosened. The fitting contained instruments. On loosening third bolt, H₂ gas exited from opening around seal. The Viton or neoprene O-ring was blown out of its groove and was immediately frozen making it impossible to reseal the fitting cover. The area was evacuated, dewar vented and gasket replaced. The ullage space was not purged with helium gas during the gasket replacement which may have been responsible for small leaks which developed during the transfer.
32. The fitting which contained the instruments was mounted on a flange, which in turn, was secured to another flange. A set of long bolts and short bolts were used to retain the components. The bolt heads were identical and not identified, hence, the error in loosening the wrong bolts. Leaks after gasket replacement probably due to condensation of moisture on related vent valve components.

Mishap

Cause

33. After filling LH₂ vessel with perlite insulation, inspection indicated the nozzle bellows sections were distorted. This suggested a shifting of the inner tank. Further inspection indicated four of the vertical supporting rods were damaged. A pressure change of 0.915 psig was necessary to cause the shifting of inner vessel and to fail the supporting rods.
34. During pressure testing of LH₂ pump discharge system, a failure occurred at the weld joint of an internally tied bellows. The weld failed at 1100 psi while the test pressure planned was 2000 psi. Rupture of the line released large amounts of liquid hydrogen. Explosion heard from 10 000 ft distance but little evidence of scorching. The piping (part of a triple gimbal) had been hydrostatically tested to 2400 psia and with helium gas to 2000 psia several days before the failure. Explosion equivalent to about 5 lb TNT; based on damage to equipment and buildings.
35. Explosion occurred in dewar used for metals tensile testing at liquid hydrogen temperatures. Container consisted of vacuum insulated bottom and cylindrical shaped polyurethane foam top. The venting of hydrogen was through a 2 inch diameter hole in the side of the foam insulation. The boil-off of liquid hydrogen was being accelerated by the use of two electric heaters on the bottom of the dewar. Explosion equivalent to about 0.25 lb TNT is considered to have taken place. This was followed by the dispersion of hydrogen which resulted in further hydrogen-air explosions.
33. Cause of shifting of the inner vessel (13/16") was an unequal distribution of insulation when the vacuum was relieved. The insulation was compacted opposite the relieving port and loosely packed directly below the entering port. This could have caused a restriction of flow and established a pressure difference around the inner vessel.
34. The improper design of the gimbal and the material selection were considered the most likely reasons for failure. The design resulted in serious weaknesses and the material used (17-4PH) undergoes ductile to brittle transition near -100° F. The steel was also notch sensitive and could not withstand the nonaxial loading at cryogenic temperatures. The ignition source was considered to be due to the energy from the tearing and moving of metal.
35. Air is believed to have backed into dewar through vent hole in polyurethane top. It was also considered possible that air could have been cryopumped due to the high porosity of the foam. Ignition believed to be caused by high surface temperature of heaters.

Mishap

Cause

36. During testing of LH₂ pump; with air turbine pump drive initiated and cooldown of pump loop underway, an explosion occurred. The speed had increased to design condition and stabilized. The H₂ alarms were actuated and panel power in the control room turned off. The explosion was felt from 700 to 1000 feet away, and a fireball centered on the test cell. A fire at the vents was extinguished after 50 minutes. The vent piping between dewar and cell was found distorted; severe damage to the cell and nearby building was incurred by the fire and explosion. Two fractures were found in the discharge section of the pump loop; the pump discharge nozzle was separated from the pump scroll and the female bayonet was broken within 1 inch of the valve disk. A leak was found at the vent connection of the top dewar. Based on damage, the explosion was equivalent to 2 to 3 lb TNT.
36. The fractures were due to the use of incorrect materials. The bayonet material was magnetic ferritic similar to 442 rather than 304 and the metal in the scroll, welds and nozzle were magnetic martensite 17-4P21 which are brittle at LH₂ temperatures. The pump case, flux joint, and vent piping were unjacketed and increase the flow of liquid air falling on the top and under the turbine pump base. Oil stains were found on the floor under the turbine-pump bedplate and with air could have been responsible for the initial explosion. Explosion probably caused fracture of vent line. Explosion due to ignition of H₂-air caused subsequent fractures at pump discharge nozzle and bayonet connection, adding H₂ to fireball. It was also considered possible that the dewar bayonet fractured prior to the explosion due to the brittle material. The fractured fitting could impart sufficient force to fracture the stressed brittle pump nozzle.
37. While a hot air dryer was being used to free a coupling in a hydrogen cryostat, a flash fire occurred. The H₂ cryostat was being dismantled.
37. The temperature at the center of the cryostat was sufficiently low to liquefy air. The prescribed requirements for purging and bringing cryostat to room temperature was circumvented. The H₂-air mixture was formed and ignition was assumed by a spark from an open filament of the dryer.

Mishap

38. While attempting to replace a rupture disk in a LH₂ vessel, H₂ gas was released and ignited. In fighting the fire, LN₂ was sprayed onto a second LH₂ vessel located nearby. This resulted in the cracking of the outer mild steel vacuum jacket. The loss of the vacuum caused a rapid increase in pressure and rupture of the burst disk of the second vessel. H₂ boiled off and was burned in the fire.

39. During cryoradiation testing a fire occurred when a dewar failed or leaked hydrogen into the atmosphere. The dewars were nitrogen walled liquid H₂ vessels to contain metal samples for testing. In the vessel, the hydrogen space was surrounded with vacuum, liquid nitrogen and an external vacuum space. The explosion damaged the dewar with hydrogen gas burning in vicinity of upper part of dewar.

40. An unscheduled venting of stage LH₂ tank occurred, creating a hazardous condition for personnel and creating a potential explosion/fire.

41. During prelaunch checkout, inadvertent LH₂ venting occurred when a check valve failed in the "open" position, causing an unscheduled checkout and replacement of components.

Cause

38. The rupture disk was being replaced with a load of LH₂ in the vessel and no separating inerting gas. The H₂-air mixture was probably ignited by static discharges. Rupture of the second vessel burst disk was caused by the low temperature exposure of the mild steel vacuum jacket.

39. The hydrogen compartment of the dewar failed and leaked liquid hydrogen into the vacuum space between the hydrogen and nitrogen. Cooling of the nitrogen compartment which was open to the atmosphere could have resulted in cryopumping of air into the vent. The wall between the nitrogen compartment and vacuum space (now filled with liquid hydrogen) failed, allowing air to mix with hydrogen. No ignition sources evident.

40. After previous venting operation of the LH₂ tank, the flex hose from a gas bottle was left connected to the LH₂ vent valve control valve. Seepage through the regulator probably occurred and the regulator control or gas bottle control valve may have been inadvertently opened.

41. An error in an installation drawing occurred in which a wrong part number was called out resulting in system contamination and valve failure.

42. An explosion occurred during tensile tests of metals in a liquid hydrogen vessel. Efforts were made to prevent air from entering by using a flexible top skirt designed to allow for movement of the tensile machine. A purge was also applied at each testing cycle.

43. During final stages of accelerator bubble chamber facility cooldown and loading with LH₂, a pressure release and fire occurred causing extensive damage to facility and related equipment. The initial fire with H₂ was believed to be short and the major damages caused by the secondary fires. The initial explosion and fire caused overpressures of about 1.5 psi. The explosion pressure was relieved by the lifting of the facility roof.

44. During initial testing at a liquid hydrogen bubble chamber facility, an explosion occurred shortly after opening a high pressure hydrogen line. The explosion was assumed to have taken place in the liquefier. Piping, transfer lines and dewar were ruptured. Hydrogen escaped and burned in a large cloud.

Cause

42. Air was considered to have condensed in the system due to leaks. The air that continued to enter was most likely solidified and collected in the bottom of the vessel. Purging after each test did not warm the vessel sufficiently to remove the air. Fracturing of the specimen probably provided sufficient energy for ignition.

43. The bubble chamber body and vacuum box were equipped with beamport windows made of beryllium. Most probable cause was failure of first inner and then outer beryllium ports which sealed the LH₂ from the chamber insulating vacuum and the vacuum from atmosphere. Failure of outer window was due to impact of inner window fragments and sudden temperature shock from LH₂. The material fractured in the brittle mode due to stresses induced by differential thermal contraction forces as well as by the internal pressure. Surface imperfections due to machine tool fabrication operations produced stress risers high enough to cause ultimate failure.

44. The liquid hydrogen was considered to be impure, containing about 2 percent contaminants, mostly oxygen. The single deoxo unit was too small. The ignition source was attributed to an electric charge which accumulated on solid oxygen as an insulator. The flow of high velocity gas produced the electric charge. With the layer of solid oxygen as an insulator having an electric charge, a voltage across the insulator would be sufficient to break it down and cause a spark to occur. The spark was most likely the ignition source.

Mishap

45. During filling a cyclotron beam target with LH₂, problems indicated a plug in the fill line. The exhaust valve was closed trapping liquid H₂ between plug and target flask. Exhaust valve was then opened and the flask heater turned on to melt plug. The target exploded two hours after the operation started.

46. During preparations for static firing tests of LO₂-LH₂ S-IVB stage, an explosion occurred prior to the lift off command. All systems indicated normal. Extensive damage was received by the test stand and stage. Sides of the stage and liquid hydrogen tankage were fragmented. Many small fires around stand. Estimated fire ball diameter was about 300 feet. Propellant mixing resulted in a detonation estimated to be 1 percent of the TNT equivalent.

47. S-II stage liquid hydrogen tank ruptured while undergoing tank pressurization tests with helium. No H₂ was on board. The LH₂ tank pressure was between 22.6 and 23.5 psig at time of rupture. Extensive damage was done to the test stand and the stage was demolished above the lower LOX tank bulkhead. Considerable fragmentation of the LH₂ tankage and forward skirt took place.

Cause

45. Ignition was considered to be caused by generation of static charge from flow of gas over Mylar in target.

46. Explosion caused by failure of high pressure titanium spheres used to store gaseous helium. The tanks, located below the thrust ring, failed due to the use of incorrect and out of specification filler wire in the fabrication. Results of incorrect wire were to lower the ultimate strength and introduce hydrogen embrittlement. Subsequent explosives were considered effects rather than causes.

47. The pressure at which the rupture occurred was well below the design allowed pressure of 38 psig. The failure was considered to be caused by the stress induced by the poor fit of the facility LH₂ fill-and-drain line in conjunction with the pressure applied during the test. A 5-inch gap had existed between the fill-and-drain line and the stage mating attachment. Hydraulic jacks were used to close the gap. Such a preload condition could create about 28 000 to 35 000 psi hoop stress in the tank wall. Considering the 12 000 psi stress present from the 23 psig differential pressure in the tank, the total stress in the hoop direction would be from 40 000 to 47 000 psi, well above the design value.

Mishap

48. Leak at LH₂ run vessel fill valve. Area was cleared and vessel emptied by remote controls. Tank pressure was about 100 psi when initial leak was noticed.

49. While a H₂ sample was being prepared for an analysis, one of two cryogenic sample bottle disks ruptured and the gas ignited.

50. During a welding operation on the LH₂ fill line it was discovered that LH₂ was still in the tanks although it was supposedly drained. Vacuum purge was not effective and a potential for a major explosion existed.

51. During pressure testing of tank for investigation of quick release manhole cover, tank burst at a pressure between 60-67 psig. Flow regulators indicated peak pressure of 67 psig.

52. During preparation for transfer of LH₂ from a test pad, a workman was removing a steel dust plug from the LH₂ line when the plug blew out and struck him.

Cause

48. Leak caused by valve stem packing failure.

49. A material deficiency in that the disk was extensively corroded and failed under working gas pressure. Contributing causes were inadequate quality control which failed to detect the corroded disk, and a test set-up which aimed the disk end of the bottle toward technicians.

50. A deviation from procedures when the purge was continued without 400 cycle power to the tank sensing probes in the LH₂ tank. When GN₂ purge was introduced, it liquefied and blocked the system.

51. Tank was overpressurized. Mistake was made interpreting blueprint in believing tank was designed to withstand 150 psig. Actual design limit was 50.7 psig.

52. The plug blew out because of pressure between the plug and the main manifold cutoff valve. Vent and drain provisions in the isolated section of the line between the main valve and the plug were not provided. Contributing cause was apparently a leaking helium purge line which allowed pressure buildup in the line.

Mishap

53. During transfer of water from a storage tank, using H₂ at 25 psi as a pressure source, a H₂ fire occurred when a line was loosened.

54. A LH₂ tank exploded causing injury and damage when hot wire sensors were used in tank after purging.

55. During test in which GH₂ was driving gas, an explosion occurred in the test section. The drive chamber was pressurized to 3500 psi. The test section failed; windows designed for pressure release failed and the walls, which were covered with wall board, ignited causing more damage.

56. Following loading of propellant run tanks, the insulation jacket (filled with perlite) on the common vent and pressurization line for the LH₂ storage tank burst.

Cause

53. The technician was wearing a nylon jacket and was using an unsafe method of relieving H₂ pressure. When H₂ escaped, it was ignited by a static charge. There was no supervisory or safety verification prior to start of hazardous tests and work control procedures were inadequate. The test installation was not properly grounded nor was the operator using grounding devices.

54. The tank had not been properly purged and the residual vapors formed an explosive mixture with air. The air entered when a cover was removed. The hot wire sensors provided the ignition source.

55. Window in test section failed due to excessive pressures. A higher pressure was obtained than calculated due to choked flow conditions in the tube.

56. The pressure in the jacket increased due to cryopumping of air and expanding liquid. The burst disk on the jacket failed to relieve due to ice formation.

Mishap

Cause

57. During a leak check of a flash point material testing chamber, the chamber was inadvertently overpressurized with GH_2 and the glass port in the door burst, causing damage to the chamber and to the facility.
57. Design deficiencies in the test chamber and installation. The pressure source was 150 psig and the chamber working pressure was 16.5 psia. There was no pressure regulator on the source and no pressure relief valve on the chamber. The pressure gage was installed between two chambers with shutoff valves to each, thus allowing erroneous pressure readings under dynamic pressure conditions. Contributing was failure to follow procedures in the leak checking.
58. Test facility H_2 vent line exploded destroying about 150 feet of line. The flare stack was on at the time.
58. The line had not been properly purged after removing and installing a vent valve in the system. Ignition of the H_2 -air mixture occurred either from flare stack or from static charge.
59. During preparation of a spacecraft LH_2 tank in an environmental test chamber, a LH_2 fire occurred in the chamber. The tank was being "topped off" at the time. Damage was caused to the facility and test system.
59. Ignition occurred as a result of bare wires in the heater access hole. A protective insulation grommet had inadvertently been omitted. The discrepancy had not been identified by inspection. Air entered system through vent line quick disconnects.
60. H_2 compressor had been shut down for repairs and was being put back into service when the explosion occurred. Damage resulted. Compressor was equipped with interchangeable intake and outlet valves.
60. Discharge valve was installed in intake position causing cylinder head to blow off and release H_2 to the atmosphere. Source of ignition not indicated.

Cause

Mishap

61. H₂-air explosion occurred near H₂ compressor (outside). CH₂ was released from the vent stack when a relief valve was actuated. Considerable damage caused by fire and explosion. Following explosion, the shut-off valves were closed and system vented.
61. Two relief valves were located in the 3000 psig system downstream of a 5000/3000 regulator. The relief valves were sized to handle substantially different flows. (One was designed for another program.) The relief valve was believed to have opened when the pressure setting was being increased from 2700 to 2900 psig. The accuracy of the 5000 psig gage used to control the dome of the 5000/3000 regulator control combined with the tolerance of the relief valve settings (± 3 percent) was sufficient to open the relief valve. Large flows were vented due to the large relief valve. In addition, the vent stack cap was designed so that the vented gases were released in a horizontal rather than vertical direction.
62. Leak of LH₂ was noticed from crack in plastic body of vacuum jacket shut-off valve. Attempts to stop flow of LH₂ transfer were not successful because increasing pressure caused the vacuum valve to rupture.
62. Leak through connections into vacuum system developed over a period of time. The leak was not detected by pressure check or soap bubble test. Air leaked into system during LH₂ flow. The LH₂ transfer was underway 20 hours prior to mishap. The pressure relief valve, designed for 18 psig, became coated with ice and prevented any relieving action. The pressure in the annulus increased air intake and increased temperature.
63. Fire erupted from 3000 psi CH₂ line. Line was in the vicinity of an electrical junction box. Fire extinguishing system was turned on and hand valves in bottle bank feeding CH₂ header to cell were closed. About 15 minutes required to bleed line and header to ambient pressure and extinguish flame.
63. Fire caused by either a short circuit in the electrical junction box or by the ignition of a hydrogen leak from a fitting. The short circuit caused the wires to burn and heat was sufficient to rupture bourdon tube in nearby gage. The tube probably ruptured, releasing hydrogen. Black smoke was noticed rising from junction box prior to larger CH₂ fed fire.

Cause

Mishap

64. During sampling tests on a facility LH₂ dock transfer system, the system was pressurized to 15 psig when an expansion joint ruptured. Technicians proceeded with the pressure cycle with the main valve closed instead of in open position as required. Damage to LH₂ transfer system.
65. While welding cable suspended over stainless steel H₂ instrument line, two holes were burned through tubing. Hissing sound was heard and operator closed valve. In feeling for gas leak which had been ignited, the operator's hand was burned.
66. During temperature shock tests of a booster LH₂ check valve, flashback from the vent stack fire occurred causing an explosion and fire damage to equipment. An electric heater blanket was used as a heat source.
67. During development tests, a CH₂ test tank was overpressurized and ruptured. The tank dome was destroyed.
68. Bourdon tube ruptured in pressure gage after 528 hours of operation in liquid H₂. The alarm sounded, the system was isolated and then vented.
64. The sampling was performed without checking the main valve which was closed and should have been open. Contributing factors were that personnel performing system repair had closed the main valve without tagging a critical valve.
65. A short during welding caused the pinholes in the tubing containing the GH₂.
66. Inadequate instrumentation of the heater blanket to detect hot spots and leaking packing on the LH₂ test valve stem. Heating of the valve caused excessive release of GH₂ and flash back. Contributing was lack of a preoperations hazard analysis and safety approval.
67. The pressure relief valves were set too high. In addition, the tank was not depressurized while being worked on. Safe distances, as required by the procedures for personnel safety, were not followed.
68. The tube was 403 SS which is subject to hydrogen embrittlement. It was requested that all gages that have bourdon tubes be replaced with 303 SS.

Mishap

69. During operation of a gaseous hydrogen purifier system, an explosion occurred when the valves were actuated to admit hydrogen. The purifier consisted of a precooler coil immersed in liquid nitrogen.

70. Explosion occurred in purifier system of H₂ expansion unit. Cryogenic purifier was used to remove traces of oil, water, O₂, and N₂ from H₂ prior to its use as the expanding medium. The precooler and adsorber were immersed in a LN₂ dewar. The explosion took place when the main H₂ flow was initiated through the purifier. The LH₂ contents in the chamber were dumped to the atmosphere through the safety vent system. Copper piping which was part of the purifier preceding the stainless steel section was split open.

Cause

69. Complete purging of the system was not accomplished because a valve in the system was not opened. The valve did not appear on the control panel schematic. Source of ignition not indicated but was considered to be related to the high gas velocity at the inlet to the adsorber coil.
70. Believed that H₂-air explosion occurred due to trapping of air by purifier. The purging was considered to be ineffective since the low flows of purge gas used were inadequate to offset the delta pressure from the LH₂ cooldown. The pressure was probably below atmosphere permitting leaks of air into the system.

Mishap

Cause

71. During general repair and equipment replacement on a LO₂-LH₂ Saturn test facility, a section of the 24-inch CH₂ vent line ruptured. An explosion occurred causing extensive damage. The H₂ vent system from the stage included the vent valve (being removed) which was connected through two flexible lines to the facility vent system. The facility system included a 20-inch vacuum jacketed line from the stage which connected to the 24-inch line leading to a catch tank. From the catch tank, a 36-inch line lead to the flare stack. The LH₂ tank was pressurized to about 4 psig with helium.

71. Most probable cause of explosion was mixture of H₂ + air which was concentrated at the particular location in the duct. H₂ accumulated in the system due to a number of pressurization and vent cycles with insufficient purging or from leakage of gaseous hydrogen system on stand (2500 psig). The vent system was not purged with high velocity gas and the periodic incremental purge with helium would not necessarily have removed the hydrogen. Air could have entered the system when the stage vent valve was removed and from an open valve at the base of the catch tank. Ignition was most likely caused by the flare stack. The combustible mixture was considered to have reached the flare stack and ignited. The flame propagated through the catch tank into the 24-inch diameter vent line and upstream until a mixture and pressure were attained which resulted in a detonation.

72. During welding of pipe to existing header vent system, hydrogen gas was ignited. The adjacent vessels and lines were inerted with helium and a hydrogen detection check indicated no H₂. The cutting was started again and hole made in header. The area was then cleared to permit a test to be conducted in a separate facility after which work on the header was continued. In striking an arc for welding, ignition of H₂ gas exiting from the hole in the header resulted.

72. A common H₂ vent system was used and an upstream hand operated shut off valve was malfunctioning. The H₂ continued to leak through the valve into the header. Ignition caused by welding arc.

Mishap

73. A violent explosion occurred above a test cell while some men were working in an adjacent cell. Explosion caused major shock damage to surrounding buildings. The bellows in an overpressurized H₂ system was severely damaged.

74. After cooldown of LH₂ system, operator noticed cold gas issuing from a small opening in a flexible section of the vent line. Examination indicated a deflagration had taken place in the vent line and there was a small hole in one of the folds of the flexible section. Two folds had been attached by a blob of solder. The vent cap showed signs of fire and was stuck in the open position.

75. After test of LH₂ vessel, a hydrogen leak into the atmosphere became evident during the warmup phase of the operation. The plans were to dispose the hydrogen through the vent system.

76. During loading of LH₂ into storage tank, the vent valve on the tank was opened and ignition occurred. Ignition, which took place at or near the instant of the valve reaching full open, was followed by a light pressure wave. The cloud contained about 125 lb H₂ gas at ignition. Water was used to cool the area, after which, inspection showed that a leak inside the vent valve body was still burning. The tank pressure was below 4 psig.

Cause

73. Liquid H₂ was admitted into suction line during checkout of the system. Liquid H₂ vaporized in warm section creating high pressure in bellows section of line. The bellows ruptured expelling H₂ gas to the atmosphere which resulted in an unconfined H₂-air explosion. No ignition source identified.

74. The hydrogen-air mixture may have been formed when the line warmed and sucked air back into the line around the seal of the vent cap or the cap may have stuck open and air diffused into the line. No source of ignition was determined.

75. The leak into the atmosphere was caused by an open line from the vessel vent system. A blind flange was removed and an incorrect valve opened permitting the leak.

76. A temporary venting system was being used with an unsatisfactory vent valve. Both the venting and leakage resulted in large concentration of H₂ gas which ignited without a detonation. Static discharge was assumed as the ignition source.

Mishap

77. A fire occurred on top of vent stack attached to liquid hydrogen vessel. Flame was extinguished by purging vent with helium.
78. Hydrogen vapors were being discharged from dewar vent when an electrical buzzer, being used as a vibrator, ignited the H₂ vapors.
79. During a thermal oscillator test an inadvertent H₂ leak and fire occurred while dumping from 75 to 50 percent of the LH₂. Fire was extinguished with minor damage to valves and lines.

80. During simultaneous hydrogen venting operations of two H₂ trailers adjacent to one another, hydrogen was ignited at one and then ignited hydrogen venting at the other.

81. After completion of process using hydrogen, an explosion occurred in the vicinity of the H₂ gas vent stack.

Cause

77. Unknown but electrical storms in the vicinity may have been responsible.

78. The buzzer was suspended over the small open-mouth dewar and ignited the vapors.

79. LH₂ was dumped through the Control Console rather than bypassing the Console to the roof vent. Dumping through the console resulted in freezing of valves and resultant leaks. Fire and damage was minimized by safety shutoff valves previously installed which permitted shutoff of the leak.

80. Air in vent line. Ignition of the CH₂-air mixture was by static charge or impact from contaminants in the vent line. Possible contributing cause to the ignition was an inadequately grounded vent flapper and contaminated or unclean fuel trailers. Also contributing to this incident was the simultaneous hydrogen venting from two adjacent trailers which permitted spread of the explosion.

81. During the normal process, cold H₂ gas is vented through the stack into the atmosphere. The process and venting continues for about 45 minutes. During this particular test, the weather was unusually calm and the gas probably accumulated around the vent stack and ignited.

Mishap

Cause

82. Low order detonations were observed from around the vent stack used to vent H₂ storage vessels. The vent valves on the dewars were closed but the explosions continued. Oxygen concentrations measured in the vent system peaked about 6% at which time an explosion would occur. The oxygen concentration dropped to zero after the explosion. These events continued until the hand valves in series with the rupture disks, which were damaged, were closed. The central vent was purged, the flange replaced and upon inspection, it was noticed that the rupture disks were blown in backwards, probably by the initial explosion.
82. A common vent system was used to connect the vent lines from each vessel to the vent stack. A flange covering a part in the vent system was removed which resulted in the aspiration of air into the stack. A chimney effect was in existence since the vent was filled with low density hydrogen. Air mixed with the hydrogen, producing a combustible mixture which was ignited by the flare (the flare stack was lit). Although the vent valves were closed, the explosions continued due to the buildup of H₂ + air mixtures in the venting system; the hydrogen leaked through the rupture disks which had failed.
83. Open air explosion occurred in vicinity of H₂ vent stack at engine test stand facility after large quantities of GH₂ were vented to atmosphere. Caused damage to test area.
83. Large quantity of hydrogen vented into atmosphere during prechill operations. Normal precooling time was about 45 minutes; however, for this test, due to troubleshooting an electrical problem, the precooling period was about 80 minutes. The LH₂ tank was pressurized and vented a number of times releasing additional quantities of H₂ into the atmosphere. During this testing period, it was noticed that no wind was present and therefore the H₂ gas failed to dispose as quickly as normal. The gas accumulated and was ignited; source of ignition unknown.

Mishap

84. During transfer of LH₂ from 200 000 gallon storage vessel to over-the-road trailer; the vacuum alarm in the outer jacket of the storage container was automatically energized at 50 microns. A 10 inch crack was located in the outer vessel (hairline crack), below an elbow of the 6 inch pressurizing line. The LH₂ was transferred and the inner vessel purged with hot N₂ gas; also positive and vacuum pressures were applied. The annular space was brought up to atmospheric pressure and filled with N₂ gas. The crack was then repaired.

85. Fire was noted in platform area on top of LH₂ tank. The LH₂ tank vents were closed and vent stack purge initiated. After about 3 minutes of purging, smoke was no longer evident. Examination of the area indicated discoloration of deck supports where the vent manifold was attached; the flange connecting the vent manifold to the vent stack was hot and discoloration indicated flowing of polyurethane foam insulation. Fire was evident inside the vent manifold piping.

Cause

84. Probable cause of crack formation was liquid air dripping on outer vessel. During transfer of 150,000 gallon of LH₂, liquid air could have been dripping from the pressurization line. Liquid air formed in vertical run of pipe next to elbow dripped off the elbow onto the vessel. The vertical runs did not have drip trays to collect liquid air and the crack formed where liquid air dropped.

85. The procedure prior to running required evacuation of the fuel duct by means of vacuum pumping. It was noticed that a vacuum could not be pulled on the fuel line; pressure purging was then attempted but the pressure could not be maintained. At this time, smoke was noted. It was believed that the fuel tank vent valve was open and when the vacuum was started, and vacuum pump shut-off valve opened, a vacuum was being pulled in the stack through the partially open GH₂ manifold shut-off valve. Opening the fuel tank vent valve resulted in a mixture of H₂ and air being pulled into the vent manifold. The LH₂ vent stack was lit and the GH₂ manifold vent not properly sealed. The mixture burned in the stack until the fire was extinguished by a GN₂ purge. The GH₂ manifold valve operating cylinder was found rusted and the piston seal brittle and warped.

Mishap

Cause

86. During routine maintenance of an automatic charger battery system, 6 of 27 nickel-cadmium batteries being reinstalled exploded.
87. During warmup of a large LH₂ sphere, the annular space was overpressurized and perlite insulation was expelled through the evacuation nozzle and the burst diaphragm. Air leaking into the vacuum annular space had apparently solidified. During tank warmup, the air vaporized causing a pressure buildup. The vessel sustained minor damage.
88. Hydrogen explosion occurred at emergency battery container used to transfer fuel elements. The container had 5 emergency power batteries. The explosion caused damages.
89. Seventeen of 27 nickel-cadmium batteries in an unattended emergency lighting cabinet in a facility mechanical equipment room were ruptured. This was due to internal overpressure or to an externally ignited hydrogen-air explosion. An explosion of considerable magnitude had occurred without smoke or soot deposits.
86. Inadequate work procedures in that a probable cause was ignition of accumulated hydrogen gas by a spark generated during the replacement work, and inadequate ventilation of the battery area; a second probable cause was stopped up vent caps, resulting from contaminated electrolyte, which permitted hydrogen pressure build-up to an explosive force in the 6 batteries.
87. Lack of design considerations for monitoring/evaluating the tank conditions during warmup. The hazards involved in making temporary repairs in the evacuation system were not identified. Leak points had been found and sealed approximately six weeks prior to this accident.
88. The H₂ concentration in the container increased because the battery charger had been left on charge. In addition, the container was placed in an unventilated airlock. Ignition of the H₂-air mixture was believed to be caused by the relays and microswitches activated when the airlock door was opened.
89. The exact cause of the explosion is unknown. Probable cause was inadequate maintenance procedures/techniques which allowed a contaminated electrolyte chemical reaction to plug battery vent caps, permitting a hydrogen pressure buildup. Another possible cause was deficient operating procedures which failed to recognize the possibility of an accumulation of hydrogen gas in a confined area which could be ignited by a spark.

Mishap

90. During shipping preparation operations, out-gassed hydrogen/oxygen from a recently discharged silver/zinc battery in a hermetically sealed drum was ignited. Ignition was caused by a spark generated by the scraping of the battery against the side of the drum. An explosion occurred, blowing the lid from the drum, charring desiccant bags within the drum, and causing other damage.
91. H₂ leak was detected in room adjacent to LH₂ pump vaporizer facility. A valve was removed from H₂ system leaving high pressure room vent line open to atmosphere. Liquid H₂ was being vaporized and pumped into gas bottles. The lines were being purged with He past the section where the valve was removed.
92. During flow of LH₂ from vessel to vaporization coils, a leak was noticed at fill line flange connection. The vessel was about 60 percent full and pressurized to 50 psig. The vaporizer was closed, area cleared, and system vented. Helium gas was sent through section of line and valves closed providing cut-off from other systems. The section was sprayed with water which temporarily stopped the leak. Transfer was initiated but venting continued.
93. Leak was noticed from bayonet connection area during operation of LH₂ dewar vaporization system. Frost was observed which is a good indication of a LH₂ leak.
- Cause
90. Inadequate handling/transportation/storage techniques in that the battery was placed in the drum too soon after discharge; (it is characteristic of silver/zinc batteries to outgas both hydrogen and oxygen for several hours after discharge). Also, the battery was not secured inside the container.
91. Hydrogen entered the room through the line at the point the valve was removed - the fans running in compressor room aided in creating increased draft for the gas to enter and actuate the H₂ sensor.
92. Kel-F ring which maintained gas trap between bayonet end and flange "O" ring was cracked. The leak caused the bayonet to distort permitting the liquid to contact the BUNA N "O" ring. This caused shrinkage, resulting in initially a gas leak which was followed by a liquid leak.
93. The Kel-F O-ring in the bayonet flange was cracked which caused leak.

Mishap

Cause

94. When the start button was initiated on a vaporizer conversion unit (LH₂ to CH₂) a hydrogen explosion occurred. This was a result of a pin hole leak in a stainless steel heating coil in the purge cabinet. Minor damage occurred.
94. Arcing from thermocouple wires touching the heating coil resulting in the pin hole leak and accumulation of an explosive mixture in the purge cabinet. The severity of the explosion was minimized by the GN₂ purge. When power was applied to the vaporizer, arcing ignited the gaseous mixture in the confined purge space of the coil housing.
95. While preparations were being made for a LH₂ turbopump test, an explosion occurred above the test cell. Major damage was caused throughout the test facility. A short duration fire caused minor damage. At time of explosion, a check was being made of the run and catch tank valves. The run tank valve was opened allowing LH₂ to enter the run header. The run and return headers were at ambient temperature and the vent valves were closed. LH₂ was also being transferred to the gas generator tank which required pressurization of the LH₂ run tank. Based on the estimated damage, with blast pressures of 2-3 psi, 10 pounds TNT equivalent was detonated initially and followed by a second detonation equivalent to about 20 pounds TNT.
95. Explosion due to overpressurization of bellows assembly in suction duct and subsequent release of about 60 pounds of H₂. Ignition was probably by static charge produced by torn edges of burst disk. Forcing the liquid H₂ from the run tank into the warm header caused flashing of the liquid and buildup of high pressures sufficient to rupture bellows. The relief valves were not large enough to handle the gases evolved. The bellows failure produced two separate clouds of H₂ gas joined by a flammable cloud zone which allowed common ignition. A large amount of H₂ was considered in the second cloud as being released from the run header.
96. Simultaneous pressurizing of both LOX and fuel systems was being performed in violation of procedures. Contributing causes were failure to transfer information at shift change and inadequate design of the pressure relief valve to handle maximum pressures.
96. During pressurization of stage fuel tanks prior to static firing, the LH₂ fill ducting line was overpressurized causing damage to the line, upstream bellows and the LOX tank. Overpressurization occurred when a worker inadvertently closed the fill and rain line allowing purge gas to enter the LH₂ system.

Cause

Complete closure of the pressure regulator by test personnel was not performed as required and an out-of-sequence step was conducted. There were no positioning or directional markings on the valve box to indicate the direction the screw adjustable pressure regulator should be turned to increase/decrease pressure.

Mishap

During pressurization retest of a vehicle H₂ tank following replacement of a transducer, the tank was pressurized to 196 psig with personnel still in the chamber. Serious injury to personnel was averted by quick action on the part of Control Room Console personnel, who stopped tank pressurization and vented the tank.