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# SAFETY GUIDELINES FOR ACCELERATOR INSTALLATIONS

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## Summary

The most difficult safety task is to identify a potential hazard or admit that it exists. Corollaries to existence are the magnitude of the potential accidents, and the probability of their occurrence. Once the hazards are identified there appears to be no shortage of guidelines and rules. But collecting rules is not the total answer to safety either. There must be a reasonable correspondence between the rules and the practice while the hazard exists.

AEC safety guidelines for high-energy accelerator facilities are reviewed, and a bibliography of applicable codes is given in the Appendix. Several current safety problems are discussed. Liquid hydrogen distance tables seem to be fixed now. The forced ventilation of buildings containing liquid hydrogen has not afforded any protection against the two major fires resulting from large hydrogen spills. The possibility of spark-induced explosions in hydrogen purifiers or liquefiers is calculated to be very high and emphasizes the need for a low-temperature helium-gas purge.

## Safety Guidelines for Accelerator Installations

### Introduction

The United States Atomic Energy Commission provides two reports that contain safety guidelines that pertain particularly to accelerator installations. Both of these reports, described below, attempt to point out the hazards that may be found at accelerator installations, but leave the solutions up to the laboratories.

### Safety Guidelines for High-Energy Accelerator Facilities

Atomic Energy Commission Report TID 23992, "Safety Guidelines for High-Energy Accelerator Facilities, 1967" was written by a national committee composed of representatives of major AEC research facilities and AEC Headquarters and field office staffs.[1,2] The guidelines include four major sections:

I. Management Safety Guidelines
II. Buildings and Facilities Guidelines
III. Experimental Equipment
IV. Operating Procedures.

The purpose of these guidelines, as stated in TID 23992, is "...to provide a guide for the organization and review of safety programs in accelerator laboratories. The various laboratories differ significantly in size, location, and scope of their activities. Therefore, safety at each installation can best be served by the individual laboratory developing its own detailed safety-program standards, procedures, and specifications. This document presents guidelines that may be considered by management for development of its policies and standards."

In other words, this document (a) guides the director in setting up a laboratory safety organization to formulate, advise on, and implement safety policy; (b) asks that local safety rules be written by the laboratory; and (c) provides a checklist of guidelines that should be considered in the assembling of the local safety manual.

The importance of the guideline approach is that each laboratory must establish its own safety program to fit its own needs. It was the committee's intent to emphasize that each laboratory is different and has its own style of operation. Keep in mind also that these guidelines are directed to high-energy accelerator facilities only. They are not directed to or tested for their applicability to other areas such as chemistry laboratories or computer installations,[3] nor do they consider the design and operation of the accelerator itself. Radiation and electrical safety are treated only in a peripheral manner; other documents treat these subjects in greater detail.

The introduction to TID 23992 recognizes that the laboratory in its mission of supporting high-energy physics is involved continuously in operation of accelerators and experimental devices; in design and construction of buildings, facilities, and experimental equipment; in installation and removal of experimental setups and beam-transport arrays; and in assembly and disassembly of experiments.

These guidelines go on to recognize the problem of: (a) the simultaneous use of many pieces of hazardous equipment; (b) the

*Work performed under auspices of U. S. Atomic Energy Commission.

consequences to the surroundings of the failure of a piece of equipment; (c) the diverse activities and interests of those present; (d) how to maximize the use of equipment while minimizing the hazard.

Electrical Safety Guides for Research

Parallel with the effort on the accelerator facility guidelines, the AEC established an Electrical Guides Committee with representation from several of the major laboratories to prepare "Electrical Safety Guides for Research," Technical Bulletin 13, December 1967.[4]

The basic purposes of the Electrical Safety Guides are: (1) to provide general criteria for laboratory administration of electrical safety programs for research activities, and (2) to provide safety exhibits (capacitors, inductors, etc.) for those categories of electrical equipment generally used in the research programs; with each exhibit containing a brief description of the equipment, associated hazards, and safety considerations.

The electrical problem facing the laboratory is described in Technical Bulletin 13 as follows:

"AEC laboratories engage in a wide variety of research activities for which the nationally-recognized and local electrical codes and standards do not provide satisfactory coverage. The many combinations of electrical parameters used in research activities require that special efforts be expended to assure that adequate safety measures are developed and followed in the design, development, construction, operation, and maintenance of research equipment and facilities.

"To better define the particular areas where additional emphasis on electrical safety may be needed, a survey was made of the electrical accidents that have occurred in research activities at the AEC laboratories encompassing the five-year period 1962 through 1966. . . . ."

The electrical guidelines consists of two parts and an appendix. Part I is a criteria for administration of electrical safety programs for research activities. Part II consists of equipment safety exhibits.

The administration and management sections of both TID 23992 and TB13 recommend that the laboratory director establish a safety committee. Both reports recommend safety reviews and the formulation of a safety manual.

In the Electrical Safety Guide the second section, Equipment Safety Exhibits, discusses the various basic types of electrical equipment. The electrical guide is arranged in a component format inasmuch as the same basic electrical components, such as capacitors, are used in all of the many kinds of research apparatus.

Other Guides

In addition to the AEC guidelines, there are many other industrial codes and guides that are applicable to the special equipment found at accelerator installations. Some of these guides are listed in the Appendix.

The code user should remind himself that codes represent the least acceptable practice. He should also ask himself, "Who wrote the code and how well does it apply to my problem?"[5] These codes, however, do provide a checklist of items to consider, and emphasize test procedures. The test pressures and procedures are extremely important. They must be realistic, but they must not be made more difficult simply to be "safe." One way to appreciate this limit is to realize that the pressurized cabin of the aircraft[19] that brought many of you here was tested to only 1.33 times the pressure relief-valve setting.

## Some Current Safety Problems

Hazard Identification

Identifying a hazard is always a safety problem in the sense that a hazard can be very obvious to one group because of their training or experience, but be very elusive to another. In addition we are constantly faced with new hazards created by new situations or new materials in which no one has had any experience. Some hazards are easily identified such as the "don't-fall-off" category. No technical expertise is required, but it does require attentiveness, which is extremely important, particularly around radiation hazards and high voltage.

An example of a subtle hazard is an explosion involving freon TF and barium that occurred last year in the space industry, killing two and injuring eleven people.[6] Even in oil-diffusion-pump vacuum systems there have been 74 explosions recorded in a field survey made for NASA.[7] Two of these explosions occurred when the diffusion pump was under steady-state high-vacuum conditions. The remaining 72 explosions occurred during the pressurization of a hot diffusion pump with either air or oxygen; or when the forepump was turned off. Some tests were then performed in which a number of low-pressure explosions were successfully initiated in a glass bell jar located above the pumps while operating at pressures above 100 microns and temperatures of 900°F. During one series of experiments with air and ozone, an explosion occurred with sufficient energy to break the glass bell jar while the bell jar was operating at a pressure in the $10^{-6}$-torr range. This test was later duplicated, and a second bell jar was broken by an explosion that occurred in the ozone-air contaminated vacuum system.[8]

How Safe Is Safe?

After many years, how safe is safe is still a vexing problem. Even though we have identified the hazard and have decided to work at preventing accidents, we still must decide on safety standards. We must be safe enough to prevent accidents that can cause death and serious injury. We should also think more about reliability[5] because it indirectly affects the safety of personnel.

An approach used by the Lockheed Georgia Company[9] to select the reliability requirements for all-weather landing equipment is the use of a risk-probability chart of the type shown on Fig. 1. The procedure is to attempt to estimate the probability of having an accident severe enough to cause a death, then to compare this risk with some of the hazards of day-to-day living.

To apply this procedure to our work, we see that the hourly probability of death in the atomic energy industry which includes all causes of accidental death in construction, production, research, and service has been $2.4 \times 10^{-8}$ for the past few years and was $1.2 \times 10^{-8}$ in 1968. This is about an order of magnitude better than U. S. industry,[10, 11] and five times better than the national all-cause accidental death rate.

If it is permissible to base probability on a single data point, then a liquid-hydrogen bubble chamber operator in the U. S. during the time he is on duty at a filled liquid-hydrogen bubble chamber has about a 1.0 to $1.5 \times 10^{-6}$ probability of death. The bubble chamber risk is about that of riding in an automobile or an airplane.[9, 11] Another way to say it is that it is as risky as living in your 50's.[12]

The bubble chamber probability is based on one death and the estimated operation time of 15 different liquid-hydrogen bubble chambers in the United States since 1956.[13] Small chambers (6 in.) were assumed to have a two-man crew

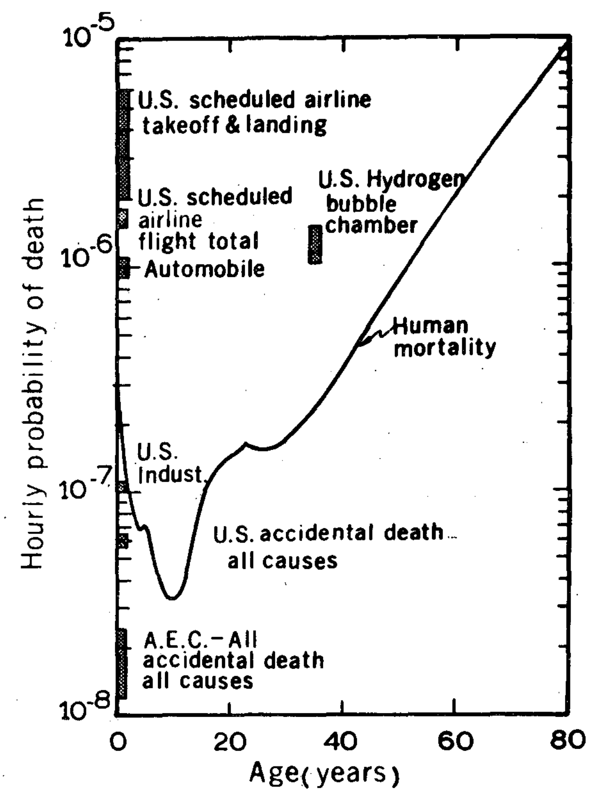


Fig. 1. Risk probability chart. The bubble chamber data are based on a single death and for the estimated operation of 15 U. S. bubble chambers since 1956.

exposed to the hazard, medium 10 to 20 in. chambers three men, and large chambers four men. The chambers were assumed to be filled 1/3 to 1/2 of their lifetime.

Distance Tables

The storage of liquid hydrogen involves two kinds of distance-quantity tables; one relates to thermal radiation, the other to explosive forces and missile affects. In the past, there have been many distance tables, some were the result of liquid-hydrogen spill tests, and others were selected by different groups for use as their guidelines. The distance-quantity data give recommended distances between inhabited buildings and liquid-hydrogen storage tanks of various capacities. The data that I believe to be most current are shown on Fig. 2 and in the form shown originally by T. Ehrenkranz and R. Reider of Los Alamos in 1964.

The thermal-radiation data were obtained from a Bureau of Mines report[14] and an Arthur D. Little report.[15] The Bureau of Mines thermal-radiation data are shown for 0, 1, and 2% water vapor and are the distances at which the heat flux is approximately 2 calories/cm$^2$. This is roughly the radiant flux required to produce flesh burn and ignite certain combustible material in short exposure times. The Arthur D. Little distances are based on the thermal radiation energy required to give unprotected personnel second-degree burns when exposed for 30 sec.

Recommended distances for protection from explosive forces is also shown in Fig. 2. The difference between the high and the low data is a measure of the disagreement among the agencies generating these tables. The distance tables have not converged since the 1950's and now seem to be polarized along the lines shown. Which table you choose as your guide will depend upon your hazards and the consequences of your accident.

The Compressed Gas Association, which represents commercial interests or the seller, recommends minimum distances. This is one of the weaknesses of self-imposed industry codes that Admiral Rickover[16] spoke of at the Materials Engineering Congress in Detroit last year. These distances, however, were adopted by the National Fire Protection Association as NFPA 50B[17] and are shown as the lower curve in Fig. 2. The Defense Department, who represents the user or purchaser, requires the greatest distances; and these are specified in DOD Instruction 4145-21.[18] The Defense Department has reduced the number of distance tables by collecting many of their agencies tables into DOD 4145-21.

Also shown on Fig. 2 is the Defense Department's recommended distances to protected inhabited buildings. Their distance table is a stepwise approximation of the Bureau of Mines 1% water-vapor thermal-radiation curve, The distance tables apply only to fixed storage, and not to moving storage. In California the practice for trucks carrying liquid hydrogen in urban streets is to keep the truck moving with the traffic and to escort it along a prescribed route. The escort offers protection from automobile accidents, especially at intersections, and can summon aid quickly in an emergency.

## Safety Uniformity

Maintaining safety uniformity spacially and in time is another problem. Ideally we would like to believe that all the different experimental areas in our laboratories have been installed and operate safely according to prescribed uniform rules. However, it is not possible in this

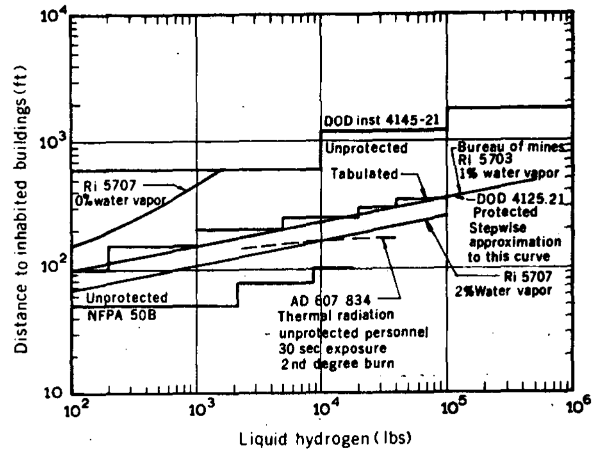


Fig. 2. Distance table: National Fire Protection Association 50B adapted from Compressed Gas Association Pamphlet G-5.2T Tentative Standard for Liquefied-Hydrogen Systems at Consumer Sites. Distance tables of this form were first shown by T. Ehrenkranz and R. Reider, Los Alamos, 1964.

imperfect world to reach a uniform acceptance of the safety rules by all of the individuals involved and, even when the rules are accepted in principle, it is difficult to assure that all experimental areas within the laboratory are working to acceptable standards.

A safety system must be a "least-energy" system in order to work effectively. That is, any operation must not only be safe, but also be easy to perform. Ideally, a system should be set up so that people fail into a safe situation.

Any system will decay with time and a letdown in safety practice is to be expected. A safety review used to reestablish the safety standards is best when it is initiated by the group. A better way to maintain the safety level is to have people who are educated and trained in the technical aspects of their work and who are kept interested and attentive.

## Building Forced-Air Emergency Ventilation

Does it do any good? At CEA and Saclay it didn't help. Perhaps forced-air ventilation in buildings containing flammable-fluid apparatus need only be sufficient to prevent flammable gas mixtures from accumulating. Looking specifically at liquid hydrogen, it now seems clear that we must assume that any large amounts of hydrogen released suddenly into the air will ignite spontaneously. Consequently it is even more important to emphasize the design philosophy of containment and put less emphasis on emergency ventilation.

## Water Sprinkler Systems

Water sprinkler systems and their detection devices are one of the most widely used safety devices we have, but least accepted by researchers. The sprinkler interface problem is very difficult; consider the problem in bringing together management, who must comply with a fire code; plant engineers, who must install the system; the building owner, who may be responsible for the maintenance; and the experimentalist, who risks having his equipment accidentally showered. Water sprinkler systems, especially around computers and electronic equipment, would be accepted by more people if they firmly believed that water would come on only during a fire.

Water sprinkler systems should have more versatility or imagination in their design. It is one thing to design a system for a generally used office building where the occupants are far removed from sprinkler-system problems. It is a completely different situation if unnecessary water damage can cause a costly delay in your experimental program. Unfortunately sprinkler systems do go off accidentally, mostly because the components are not adequately tested by the installers or because all variations in the environment were not considered. More dry testing should be performed by the installers together with the people who are going to use the area, so that more people understand the limits of the system.

Fire detection should especially be installed in research equipment trailers of the kind now in use in accelerator experimental halls. These trailers are difficult to enter and often have excessive wood paneling.

There has been much concern over water damage to electronic equipment, but it has been shown that most electronic equipment is easily dried out and not damaged by water.[3] An electrical shock hazard caused by water can occur in some locations and, of course, must be guarded against. But also remember that dry, burned-up equipment, is not of much use either.

## Spark-Induced Explosions in Hydrogen Purifiers or Liquefiers*

Ignition Energy. Early studies of gas-stream Van de Graaff generators have shown that a high-velocity dirty gas stream can produce an electrical charge. If there is an insulator to accumulate this charge, such as a layer of frozen oxygen, then a spark discharge can occur when the voltage across the insulator is sufficient to break down the dielectric. The spark is the ignition source, the hydrogen exists, and frozen oxygen particles are the dirt flowing through the system as impurity in the hydrogen. In liquid-hydrogen bubble chambers, for example, the impurity is seen as easily moved fine powder on the bottom of the chamber. All the requirements for an explosion are satisfied.

The spark discharge necessary to ignite a hydrogen-oxygen mixture must satisfy three requirements: (a) The spark must contain sufficient energy to ignite the mixture. (b) The dielectric layer of insulation must be thick enough to hold the required voltage before discharging. (c) The charged particles in the gas stream must have enough energy to force their way through the potential field of the charged insulator surface.

Ignition energy is often defined as the amount of energy stored in a capacitor and discharged through a prescribed pair of electrodes and surrounded by a combustible mixture such as hydrogen-oxygen. However, the important criteria is that the gas mixture be raised to the ignition temperature in the vicinity of the spark, and the mixture be held above the ignition temperature for a sufficient time.

Spark ignition then is mainly a heat-transfer problem where the temperature-time dependence is determined by the rate that a capacitor supplies energy to the arc and the rate of heat transfer away from the arc area. So far solutions to this problem have been obtained experimentally because of the complex relationships between the combustion chemistry, ionization, geometry, and spark-gap breakdown.

A hydrogen-oxygen stoichiometric mixture under atmospheric temperature and pressure can be ignited with an energy as small as 7 μJ discharged across a gap. The effective volume of STP hydrogen-oxygen stoichiometric mixture that can be raised to the ignition temperature 577°C, by 7 μJ is a spherical volume having a diameter of 0.010 in. This was calculated by using the specific heat expression $Q = mc_p\Delta T$, which gives $5.2 \times 10^{-9}$ g.

*Many of the thoughts and ideas in this section on spark-induced explosions were worked out in discussions with R. Watt of SLAC.

Energy to Heat Liquid Hydrogen and Frozen Oxygen to the Ignition Temperature. Consider a liquid-hydrogen circuit operating at 25°K and 5 atm pressure. How much energy is required to convert the required amount of liquid hydrogen and frozen oxygen to gas and heat it to the ignition temperature? In this discussion we assume that about the same mass of mixture must be raised to the gaseous ignition-temperature state whether starting from the gaseous condition or solid and liquid conditions.

In the previous section we found that $5.2 \times 10^{-9}$ g of $H_2$-$O_2$ mixture is the minimum mass required for ignition. We can calculate that an energy of 5.48 µJ is required to boil $0.57 \times 10^{-9}$ g of hydrogen (the fraction of hydrogen in a stoichiometric mixture of $H_2$-$O_2$) and raise it to the ignition temperature.[20] It requires about 4.25 µJ more to melt $4.6 \times 10^{-9}$ g of frozen oxygen, raise it to the boiling point, boil it, and then raise it to the ignition temperature. A total energy of 9.7 µJ is thus required when starting with liquid hydrogen and frozen oxygen instead of the 7 µJ required when starting from ambient conditions--hardly any difference at all!

Capacitive Energy Storage and Voltage. Assume that a layer of oxygen has been frozen on the inside of a metal tube transferring liquid hydrogen. Liquid hydrogen flowing over the frozen oxygen will electrically charge and store energy in the frozen oxygen which now behaves as a coaxial capacitor. The dielectric strength of frozen oxygen is assumed to be about like that of nitrogen or argon, say 3500 kV/in.[21]

Consider 1-in.-long coaxial capacitors of various diameters and dielectric thickness as shown on Fig. 3. When the capacitor (frozen oxygen) is charged to more than its dielectric strength, it will break down and spark. If this were a capacitor of two coaxial metal tubes then all of the energy stored would appear in the spark discharge. In this study the inner surface is frozen oxygen which is a poor conductor and may discharge only that energy which is stored in the vicinity of the spark. Assume arbitrarily that about 9000 µJ must be stored, or about a thousand times more energy than the 9.7 µJ found in the previous section. This increase is required to account for the inefficiencies, because of the local discharge of the capacitor, because the mixture is seldom stoichiometric, and because the spark length (the thickness of the frozen oxygen) is less than the quenching distance of about 0.02 in.[20,22] From Fig. 3 we see that the potentially explosive geometries are very reasonable even with a 9000-µJ storage requirement in the frozen oxygen. The energy of combustion of these small amounts of oxygen combined stoichiometrically with hydrogen is sufficient to burst standard tubing in these sizes.

The voltage required to break down the frozen oxygen is calculated to be in the range of 3 to 80 kV (Fig. 3). Evidence of voltages in this range have been seen as dendritic trails in insulators, made by sparks. Such trails were made in the SLAC 40-in.-diam liquid-hydrogen bubble chamber, and were observed as carbonized paths left in the epoxy base of the Scotchlite light reflector. To make similar trails in Lucite-type plastics has required voltages of about 100 kV.

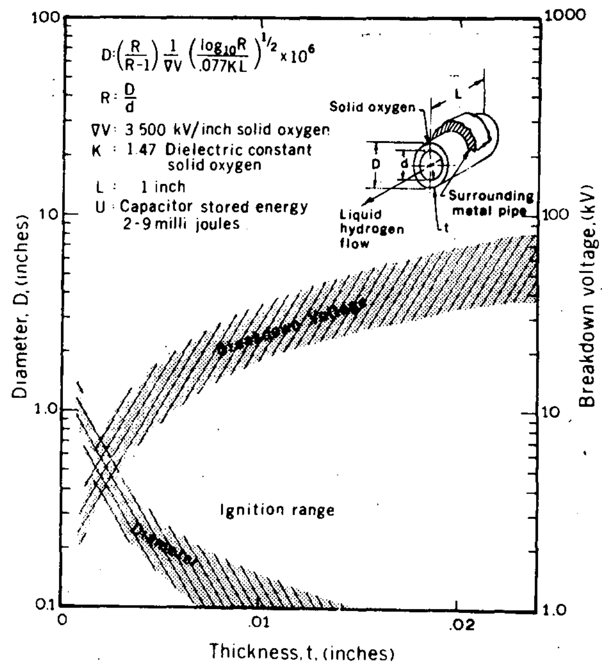


Fig. 3. Spark-induced potentially explosive range in a mixture of frozen oxygen and liquid hydrogen. Calculated potentially explosive range for various size frozen-oxygen cylinders capacitively charged by flowing liquid hydrogen. This figure shows the small volume of oxygen needed to store 2 to 9 mJ, which is a about 1000 times the 7 µJ needed for ignition.

At this time, the mechanism described above is unproven, and experimental evidence is needed to establish its correctness. However, the petroleum industry solved a problem involving a similar mechanism several decades ago. The suggested mechanism makes clear the importance of keeping oxygen out of hydrogen systems by careful attention to hydrogen purity and procedures. It is very important to purge liquid-hydrogen circuits with gaseous helium before starting the warmup cycle, so that all hydrogen is removed from the system before any frozen oxygen melts. Liquefiers and purifiers might be designed as though they were high-voltage electrical apparatus, with thought given to minimizing parameters such as voltage gradients, providing arrangements that will drain electric charge rapidly, and minimizing hydrogen stream velocities.

## Conclusion

There now exist two principal safety guidelines that relate to USAEC accelerator installations. These guidelines identify hazards, but leave the solution to the individual laboratories.

Attentiveness and education are still important safety factors. Many of the same problems exist for liquid hydrogen, but some different approaches to their solution are offered such as the risk-probability chart used to compare levels of safety.

Distance tables that give recommended distances between buildings and liquid-hydrogen storage tanks of various capacities are becoming fixed and accepted. In my opinion, buildings containing flammable fluid apparatus need only sufficient forced ventilation to prevent flammable mixtures from accumulating. Containment of flammable fluids, however, remains the first line of fire protection.

The possibility that explosions in liquid-hydrogen liquefiers and purifiers can be caused by a spark discharge through a capacitor of frozen oxygen has been introduced. The risk appears real enough that liquid hydrogen piping circuits should be designed to reduce the probability of electrical discharge, and should be purged with helium gas before warmup and before any frozen oxygen melts.

## Appendix. Bibliography of Standard Codes

General guidelines for equipment can be found in the following codes:

1. ASME Nuclear Vessels, Section III.
2. ASME Unfired Pressure Vessels, Section VIII.
3. American Standard Code for Pressure Piping, ASA B31.1 and ASA B31.3.
4. Interstate Commerce Commission Regulations, Tariff No. 19.
5. Safe Handling of Compressed Gases, Pamphlet P-1, Compressed Gas Association.
6. Compressed Gases, Safe Practices Pamphlet No. 95, National Safety Council.
7. National Fire Protection Association, Vol. 1, Flammable Liquids, Vol. 2, Gases.
8. National Fire Protection Association National Electrical Code, Article 500, Hazardous Locations.
9. American Petroleum Institute, API RP-500. API recommended practice for classification of areas for electrical installations in petroleum refineries.
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11. Instrument Society of America RP-12.2. Intrinsically safe and nonincendive electrical instruments.
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13. National Fire Protection Association Technical Committee Report 1967 NFPA No. 496, Proposed Standard for Purged Enclosures for Electrical Equipment in Hazardous Locations.

    NFPA No. 493-PT, Intrinsically Safe Process Control Equipment for Use in Hazardous Locations.

    NFPA No. 50B, Liquefied Hydrogen Systems at Consumer Sites.

    NFPA No. 68, Guide for Explosive Venting.
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18. Quantity-Distance Standards for Liquid Propellants (applied to military departments and defense agencies), DOD Instruction 4145.21, January 27, 1967.

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