NUREG-1364

Regulatory Analysis for the Resolution of Generic Safety Issue 106: Piping and the Use of Highly Combustible Gases in Vital Areas

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

C. C. Graves

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ABSTRACT

Highly combustible gases such as hydrogen, propane, and acetylene are used at all nuclear power plants. Hydrogen is of particular importance because it is stored in large quantities and is distributed and used continuously in buildings containing safety-related equipment. Large hydrogen releases at the hydrogen storage facilities or in these buildings could lead to fires or explosions that might result in loss of safety-related equipment. This report gives the regulatory analysis for the resolution of Generic Safety Issue 106, "Piping and the Use of Highly Combustible Gases in Vital Areas." Scoping analyses showed that the risk associated with the storage and distribution of hydrogen for cooling electric generators at boiling-water reactors (BWRs), the off-gas system at BWRs, the waste gas system at pressurized-water reactors (PWRs), and station battery rooms and portable bottles of combustible gas used for maintenance at PWRs and BWRs is small. On the basis of generic evaluations, the NRC staff has concluded that several possible methods to reduce risk could provide cost-effective safety benefits at some plants. However, in view of the observed large differences in plant-specific characteristics affecting the risk associated with the use of hydrogen, and the marginal generic safety benefit that can be achieved in a cost-effective manner, it is recommended that this generic issue be resolved simply by making these results available in a generic letter. This information may help licensees in their plant evaluations recommended by Generic Letter 88–20, Supplement 4, "Individual Plant Examination of External Events for Severe Accident Vulnerabilities," June 28, 1991.

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EXECUTIVE SUMMARY

This report gives a cost-benefit analysis and supporting information for U.S. Nuclear Regulatory Commission's (NRC's) resolution of Generic Safety Issue 106 (GSI-106), "Piping and the Use of Highly Combustible Gases in Vital Areas." The scope of GSI-106 includes hydrogen storage facilities and battery rooms at pressurized-water reactors (PWRs) and boiling-water reactors (BWRs); waste gas systems at PWRs; off-gas systems at BWRs; hydrogen distribution systems for electric generators at PWRs and BWRs and the volume control tank (VCT) in the chemical and volume control system at PWRs; and small, portable bottles of combustible gas such as hydrogen, propane, and acetylene. The scope does not include large amounts of liquified petroleum gas at PWRs and BWRs or the gaseous and liquid hydrogen storage and distribution systems for hydrogen water chemistry installations at BWRs covered under Licensing Issue 136.

Idaho National Engineering Laboratory (INEL) provided technical assistance for resolving this issue. Scoping and screening analyses by INEL indicated that the risk associated with the use of hydrogen for electric generators at BWRs, battery rooms, PWR waste gas systems, BWR off-gas systems, and portable bottles of combustible gases was small. Therefore, the more detailed risk and cost-benefit analyses by INEL were limited to the hydrogen storage facilities and to the hydrogen distribution systems for the VCT and generator at PWRs. These facilities and distribution systems are not categorized as safety related. However, because of the use of large quantities of hydrogen for these applications, there is a potential for damage to safety-related equipment because of hydrogen deflagrations or detonations. The basic regulatory requirement pertinent to GSI-106 is General Design Criterion 3 in Appendix A to Part 50 of Title 10 of the *Code of Federal Regulations.*

The hydrogen storage facilities and distribution lines to the VCT and generator are not near the primary coolant system or reactor pressure vessel. Hence, hydrogen deflagrations or detonations would not lead to pipe-break loss-of-coolant accidents (LOCAs), steam generator tube ruptures, or anticipated-transient-without-scram sequences. The remaining core damage events in the probabilistic risk analysis for this issue were divided into transients with failure of decay heat removal (DHR) systems (T/DHR) and transient-induced LOCAs (T/LOCAs). The T/DHR transients involve loss of all forms of core cooling and release of reactor coolant at high pressure from pressurizer power-operated relief valves (PORVs) or safety valves. The T/LOCA transients involve failure of reactor coolant system makeup or recirculation following a consequential reactor coolant pump seal failure (as a result of loss of seal cooling) or a PORV LOCA caused by a stuck-open PORV or safety valve. This transient includes such events as station blackout and loss of component cooling water or service water.

The failures considered for the storage facility were (1) a hydrogen tank rupture resulting in a detonation at the facility and blast damage to a nearby safety-related structure and (2) a pipe failure at the facility with a large release of unburned hydrogen and ingestion of a flammable hydrogen-air mixture at a safety-related air intake. Postulated failures of the hydrogen distribution systems in the auxiliary and turbine buildings were leaks or breaks with large hydrogen releases and subsequent deflagrations or detonations or smaller undetected leaks resulting in the buildup and subsequent detonation of large amounts of trapped hydrogen.

The alternatives considered to reduce a vulnerability in the storage area included (1) relocation of the storage area, (2) installation of a blast shield to prevent unacceptable blast damage, and (3) installation of shutters actuated by hydrogen detectors to prevent ingestion of flammable hydrogen-air mixtures at safety-related air intakes. For the turbine building, the alternatives were (1) use of excess flow valves and check valves or restricting orifices to limit flow from the storage facility and generator to a break in the hydrogen supply line, (2) use of a normally isolated hydrogen supply with periodic manual makeup and a check valve or restricting orifice to limit back flow to the break from the generator, and (3) modifications to protect safety-related equipment from the consequences of hydrogen deflagrations or detonations. For the auxiliary building, the alternatives considered were (1) use of excess flow valves or restricting orifices to limit the flow rate from large hydrogen supplies to the break, supplemented by hydrogen detectors, if needed; (2) use of limited hydrogen supplies; and (3) use of normally isolated hydrogen supplies. These alternatives include administrative controls and design features to prevent inadvertent bypass of the flow-limiting devices and limited supplies, to monitor for hydrogen leaks, and to isolate the hydrogen supply following loss of normal ventilation in the auxiliary building.

A number of hydrogen events have occurred and continue to occur in the turbine buildings at U.S nuclear power plants. In addition, several large fires involving hydrogen and oil have occurred in turbine buildings at foreign plants. Hydrogen events in the turbine building are not expected to be significant sources of risk for most U.S. plants because (1) vital equipment is not located in the building or (2) recovery operations for T/DHR transients can prevent core damage (e.g., feed-and-bleed operations and recovery of main feedwater). These plants could suffer significant economic losses because of damage to plant equipment and replacement power costs, but not core damage. However, some plants are considered susceptible to core damage resulting from hydrogen events in the turbine building that lead to T/DHR transients or T/LOCA transients (predominantly seal LOCAs).

There have been a number of leaks but no fires, explosions, or large hydrogen releases involving the hydrogen system supplying the VCT in the auxiliary building. The hydrogen events considered potentially significant are those causing loss of vital equipment and resulting in a seal LOCA. Licensees of a number of plants have provided corrective measures (e.g., normally isolated or limited supplies, flow-limiting devices, and leak detection equipment and procedures) to reduce the risk from this source. However, some plants are considered to be susceptible to core damage because of a large storage facility and the lack of protective features to prevent large hydrogen releases.

Since industry will continue to use appreciable amounts of hydrogen to cool the generators and for water chemistry control, the risk from hydrogen fires and explosions cannot be completely eliminated. However, a blend of accident-prevention and -mitigation capabilities may reduce the risk from these sources to acceptably low levels. Examples of preventive measures include the use of excess flow valves or restricting orifices to reduce the possibility of the release of large quantities of hydrogen following a piping leak or rupture and administrative controls or hydrogen detectors to detect leaks. In regard to mitigation, standard fire protection measures can go far to reduce the consequences of a hydrogen fire or explosion. Although the adequacy of fire protection measures is outside the scope of GSI–106, the staff notes that these measures can include accident-mitigation strategies for turbine building fires such as (1) early elimination of the hydrogen sources by isolating the storage facility and venting and purging the generator with carbon dioxide and (2) controlling the pumping of lubricating oil that could spread the fire.

For the hydrogen distribution systems in the auxiliary and turbine buildings, the generic estimates of the reduction in core damage frequency obtained with the alternatives for the distribution systems ranged up to 0.5E–5/reactor-year (RY) to 1E–5/RY. However, risk reductions at individual plants may be significantly larger than the generic values because of the proximity of the hydrogen distribution system to vital equipment. The estimated costs for several of the proposed alternatives are small. Hence, when considered individually, several of the alternatives analyzed for reducing the risk for this issue would be cost effective in meeting the $1000/person-rem guideline. The analyses for these alternatives indicate cost savings when onsite averted costs are included. However, in view of the observed large differences in plant-specific characteristics affecting the risk associated with the use of hydrogen, and the marginal generic safety benefit that can be achieved in a cost-effective manner, it is recommended that this generic issue be resolved simply by making these results available in a generic letter. This information may help licensees in their plant evaluations recommended by Generic Letter 88-20, Supplement 4, "Individual Plant Examination of External Events for Severe Accident Vulnerabilities," June 28, 1991.

1 STATEMENT OF PROBLEM

1.1 Introduction

Combustible gases such as hydrogen, acetylene, and propane are used at all nuclear power plants. Of these gases, hydrogen is of principal interest because it is stored in large quantities and is distributed and used in some safety-related buildings during normal plant operation. It is provided as a coolant for the main electric generators at both pressurized-water reactors (PWRs) and boiling-water reactors (BWRs). It is also fed to the volume control tank (VCT) in the chemical and volume control system of PWRs to reduce oxygen in the reactor coolant system. The hydrogen for these purposes is usually stored as a high-pressure gas [e.g., 1500 to 2400 pounds per square inch gage (psig)] in large storage facilities and is distributed to the auxiliary and turbine buildings through small-diameter field-run piping. Failure of the piping or bottles/cylinders at the storage area could result in flammable hydrogen-air mixtures at safety-related air intakes or fires or detonations that could damage safety-related structures. Hence, the storage area should be located at a safe separation distance from these structures and intakes. The distribution piping to the electric generators in the turbine building generally would not be near safety-related equipment. However, some plants have safety-related equipment such as motor control centers, cables, switchgear, and diesel generators in, or adjacent to, the turbine building. In PWRs, the auxiliary building, which contains the VCT, also contains most of the components of the safety-related systems at the plant. Hence, leaks or breaks in the piping or components of the hydrogen distribution system in the auxiliary building at PWRs or in the turbine buildings at some PWRs and BWRs could result in fires or explosions that represent a threat to plant safety because of potential damage to safety-related equipment. Capacities of individual hydrogen bottles or cylinders at the storage facilities range from about 200 to 10,000 standard cubic feet (scf) of hydrogen, while total amounts of hydrogen in the storage facility may be more than 100,000 scf. This represents a significant potential energy release. Hydrogen gas also represents, to a lesser degree, a potential threat to safety-related equipment because of its presence in PWR waste gas systems, BWR off-gas systems, station battery rooms, and small bottled supplies in plant buildings at PWRs and BWRs.

A number of events involving hydrogen have occurred at U.S. and foreign nuclear plants. These have ranged from detection of concentrations above the lower flammability limit in the waste gas system and leaks in the auxiliary building to explosions and very large fires in the turbine building. Although no safety-related equipment apparently has been lost to date in the United States because of a hydrogen event, the occurrence of these precursors requires an evaluation of the risk associated with the use of hydrogen in nuclear plants.

1.2 Existing Regulatory Requirements and Guidelines

1.2.1 General

Because the structures, systems, and components involved in the use of hydrogen at nuclear plants are not classified as safety related, they do not have to be seismic Category I, environmentally qualified, or redundant. However, hydrogen fires or explosions or the release of unburned hydrogen could result in damage to nearby safety-related equipment and should be considered in setting design and operational requirements.

1.2.2 Regulations and Regulatory Guides

The basic regulatory requirement dealing with the storage, distribution, and use of combustible gases at nuclear power plants is General Design Criterion (GDC) 3, "Fire Protection," in Appendix A to Part 50 of Title 10 of the *Code of Federal Regulations* (10 CFR Part 50). This criterion states, in part, that "structures, systems, and components important to safety shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions."

Section 50.48 of 10 CFR requires that every plant have a fire protection plan that satisfies GDC 3. The plan should include descriptions of special features needed to limit damage to structures, systems, and components important to safety so that the capability to safely shut down the plant is ensured.

Appendix R to 10 CFR Part 50 gives the fire protection program requirements to meet GDC 3. It includes new requirements and guidance dealing with fire protection measures to limit the damage to systems important to safe shutdown and the use of alternative or dedicated capability for areas where fire protection features cannot ensure safe shutdown, should a fire occur in that area. Appendix R applies to all plants licensed to operate before January 1, 1979, except to the extent described in 10 CFR 50.48. Revision 2 of Branch Technical Position CMEB 9.5-1 in Section 9.5.1, "Fire Protection Program," of NUREG-0800 contains revised guidelines, which include the acceptance criteria in Appendix R and 10 CFR 50.48, for implementing GDC 3 for later plants.

In accordance with 10 CFR 50.49, "Environmental Qualification of Electric Equipment Important to Safety for Nuclear Power Plants," non-safety-related electric equipment should be environmentally qualified if its failure under postulated environmental conditions could prevent safety-related equipment from accomplishing its safety function.

NRC Regulatory Guide 1.29, "Seismic Design Classification," states that parts of non-seismic Category I structures, systems, or components whose continued function is not required, but whose failure could reduce the functioning of seismic Category I structures, systems, or components to an unacceptable safety level or cause incapacitating injury to control room occupants, should be designed and constructed so that a safe shutdown earthquake would not cause such a failure.

1.2.3 Standard Format and Content (NUREG-75/094), Standard Review Plan (NUREG-0800), and Technical Specifications

1.2.3.1 Standard Format and Content (NUREG-75/094)

NUREG-75/094 does not have a separate section describing the hydrogen storage facilities and distribution systems. Hence, most final safety analysis reports (FSARs) do not give this information. However, the staff has provided some guidance on acceptable approaches for meeting GDC 3 with respect to the scope of Generic Safety Issue (GSI) 106 in Standard Review Plan (SRP) (NUREG-0800) Section 9.5.1, "Fire Protection Program," and in SRP Section 11.3, "Gaseous Waste Management Systems."

1.2.3.2 Standard Review Plan (NUREG-0800)

Branch Technical Position (BTP) CMEB 9.5-1, Revision 2, in SRP Section 9.5.1, Revision 2, contains some guidance concerning

- the use of excess flow valves and other protective features for the distribution of hydrogen in safety-related buildings
- alarms and annunciation for fire detection and loss of ventilation in safety-related battery rooms
- barrier design features and possible additional defense in depth in the turbine building to protect against fires in the turbine oil system or the generator hydrogen cooling system

The guidance on the hydrogen distribution systems includes the use of seismic Category I piping, sleeved piping with the outer pipe vented directly to the atmosphere, or excess flow check valves sized so that the hydrogen concentration in affected areas does not exceed 2 volume percent. Because these SRP revisions were published in July 1981, the staff did not use this guidance in its review of some plants.

SRP Section 11.3 (Revision 2) provides guidance on design features in gaseous waste management systems for both PWRs and BWRs to satisfy GDC 3 with respect to hydrogen explosions. For systems designed to withstand the effects of a hydrogen explosion, SRP Section 11.3 specifies analysis of the process gas stream for potentially explosive conditions and annunciation both locally and in the control room. For a system not designed to withstand the effects of the explosion, SRP Section 11.3 specifies two independent gas analyzers operating continuously to provide two independent measurements. The gas analyzers should annunciate alarms both locally and in the control room. Guidance also is given for systems with recombiners and for equipment testing intervals.

1.2.3.3 Technical Specifications

The technical specifications for most BWRs and PWRs are expected to include coverage of the explosive gas monitoring instrumentation for gaseous radioactive waste. NRC Generic Letter 89-01, which addresses the relocation of portions of the Radiological Effluent Technical Specifications to the Offsite Dose Calculation Manual, states that existing requirements for explosive gas monitoring instrumentation for waste gas systems will be retained in the technical specifications. It also provides model specifications for retaining existing requirements for explosive gas monitoring instrumentation that apply on a plant-specific basis.

1.2.4 Electric Power Research Institute Guidelines

The recent hydrogen water chemistry (HWC) installations for BWRs that were considered under Licensing Issue 136, "Storage and Use of Large Quantities of Cryogenic Combustibles on Site," involve the storage of larger quantities of hydrogen and higher average consumption rates than those encountered in typical applications for hydrogen supplied to the VCT in PWRs and the main generator in all plants. In 1987 (letter from J. Richardson dated July 13, 1987), the staff approved new guidelines by the Electric Power Research Institute (EPRI, 1987) for these HWC installations. The guidelines describe several system design features and procedures for the prevention or mitigation of the consequences of fires, explosions, or unburned leaks of hydrogen that are in addition to, or more restrictive than, those given in SRP Section 9.5.1, Revision 3, and BTP CMEB 9.5-1, Revision 2. They include

- new relations for separation distances between the hydrogen storage location and safety-related structures and air intakes that often give much larger separation distances than the values from the

National Fire Protection Association cited in SRP Section 9.5.1

- color-coded piping and warning signs (American National Standards Institute Standards A13.1 and Z35.1)
- excess flow check valves, system trips, and other design features (e.g., hydrogen detectors) to mitigate the consequences of leaks or breaks in hydrogen lines and to perform the intended design function with or without normal ventilation and, as a minimum, a system trouble alarm and/or annunciator in the main control room
- periodic testing of excess flow valves used to protect against breaks in hydrogen lines and components

In the letter of July 13, 1987, from J. Richardson, transmitting the safety evaluation report on the EPRI guidelines, the staff recommended that the guidelines be extended to include hydrogen systems supplying hydrogen to the VCT in PWRs and for cooling the main electric generators in PWRs and BWRs. Although EPRI has not done so, the staff used the separation distance criteria in EPRI's guidelines as an initial screening mechanism during plant surveys made in this study.

1.2.5 NRC Inspection Program

The NRC Light Water Reactor Inspection Program has several inspection requirements pertinent to GSI-106. Inspection Procedure 64704, "Fire Protection Program," which specifies an inspection frequency of once every other systematic assessment of licensee performance cycle, is required for all operating plants. This procedure includes reviews of control of combustible material, reduction of fire hazards, and fire control capabilities. Sites for storing combustible gas and hydrogen lines in safety-related areas are specifically identified in this inspection procedure. In addition to the plant and NRC inspections, this procedure covers three audits required under the technical specifications: (1) an annual audit by the offsite fire protection specialist, (2) a 2-year audit by the licensee's quality assurance organization, and (3) a 3-year audit by a consulting fire protection firm.

1.3 Scope

In 1981, the staff identified GSI-106 in NUREG-0705, "Identification of New Unresolved Issues in U.S. Commercial Nuclear Power Plants." The work on this issue was directed initially at the risk associated with the distribution of hydrogen to the VCT in the safety-related auxiliary building of PWRs. In 1986, the staff considered expanding the scope to include the new concerns associated with the storage of large quantities of liquid propane and the cryogenic storage of hydrogen and oxygen at reactor sites. Instead of expanding the scope of GSI-106, the staff included the new concerns in Licensing Issue 136, "Storage and Use of Large Quantities of Cryogenic Combustibles on Site" (NUREG-0933). Licensing Issue 136 addressed the use of large quantities of

- hydrogen and oxygen in permanent hydrogen water chemistry (HWC) installations being installed at BWRs to reduce oxygen in BWR piping to control intergranular stress corrosion cracking
- liquified propane in, for example, proposed systems for the incineration of radioactive waste

In 1987, the staff accepted licensing topical report EPRI NP-5283-SR-A (EPRI, 1987), which provided guidelines for these HWC installations. With the issuance of staff safety evaluation reports on both concerns, Licensing Issue 136 was closed in 1988 (see NUREG-0933).

A significant number of events involving combustible gases have occurred at nuclear plants and ranged from detection of flammable mixtures and unburned leaks to explosions and fires in turbine buildings. In April 1987, the staff issued Information Notice 87-20 to the licensees of all plants as the result of a reported leak in the hydrogen piping in the auxiliary building at the Vogtle nuclear plant; this leak was caused because a conventional globe valve was used instead of a valve designed specifically for hydrogen. Such notices are not requirements, but each licensee is expected to review them for applicability to its facility and for consideration of applicable actions.

In another instance, during a visit to the Trojan nuclear plant in April 1989, NRC inspectors noted that the hydrogen storage facility was located on the roof of the control building near air intakes. This increased concerns about similar hazards at other nuclear plants. As a result, the staff issued Information Notice 89-44. In addition, it asked each NRC regional office to supply information on the size of hydrogen tank farms and the separation distance from safety-related structures and air intakes at all plants in that region.

As a result of these and other events involving combustible gases, the staff expanded the scope of GSI-106 in 1989 to include both PWRs and BWRs. The expanded scope included risk from

- the storage and distribution of hydrogen for the VCT in PWRs and the main generators in PWRs and BWRs
- other sources of hydrogen such as battery rooms, the waste gas system in PWRs, and the off-gas system in BWRs
- small quantities of hydrogen and other combustible gases such as propane and acetylene that would be used for maintenance, testing, and calibration

The scope did not include risk from the hydrogen storage (gaseous or liquid) and distribution systems for HWC installations at BWRs or the larger quantities of liquified petroleum gas that were considered under Licensing Issue 136.

2 OBJECTIVE

The purpose of the Generic Safety Issue 106 program is to evaluate the risk associated with the use of combustible gases for certain applications at nuclear power plants and to examine the cost effectiveness of alternative measures for reducing this risk.

Probabilistic risk analysis techniques were used to estimate the reduction in core damage frequency (CDF) and the cost effectiveness of the alternative actions. For Unresolved Safety Issue (USI) A–45, "Shutdown Decay Heat Removal Requirements," the staff recommended in NUREG–1289 that the frequency of events related to decay heat removal failure leading to core damage should be reduced to such a level [about 1.0E–5/reactor-year (RY)] that the probability of such an accident in the next 30 years would be about 0.03 based on a population of about 110 plants. A similar objective (1.0E–5/RY) was noted in USI A–44, "Evaluation of Station Blackout Accidents at Nuclear Power Plants," and in GSI–130, "Essential Service Water System Failures at Multi-Unit Sites." The application of such objectives to GSI–106 was limited to using these insights as general guidelines for the decision process described in Section 6. Rigid application of such a quantitative objective to define an absolute requirement is discouraged. This is consistent with the policy guidance in NRC's "Safety Goals for the Operation of Nuclear Power Plants" and in the memorandum from C. J. Heltemes dated August 20, 1991. Similarly, the criterion for cost effectiveness was assumed to be \$1000 per person-rem averted.

3 ALTERNATIVE RESOLUTIONS

As the result of scoping and screening analyses, the possible significant sources of risk associated with combustible gases within the scope of GSI-106 were reduced to the following areas (see Section 4.1):

(1) the hydrogen distribution systems for the volume control tank (VCT) and the electric generator at PWRs

(2) the hydrogen storage facilities at PWRs

3.1 Hydrogen System Characteristics for Volume Control Tank and Generator Applications

The hydrogen distribution systems for VCT and generator applications at PWRs have several characteristics pertinent to the selection of corrective measures to reduce risk. For both applications there is a relatively small average hydrogen consumption rate and an infrequent need for the use of larger quantities over short intervals. In addition, the normal operating conditions and gas volumes result in the storage of large quantities of hydrogen in the generator, several hundred standard cubic feet (scf) in the VCT, and negligible quantities in the piping.

The average hydrogen flow rate to the VCT over the long term is probably less than about 0.1 scf per minute (scfm) for plants without a recombiner in the waste gas system and is about 1 scfm for plants with recombiners. Larger short-term maximum flow rates occur during manual adjustments when hydrogen is added to the VCT, while maximum local flow rates (corresponding to a postulated loss of letdown flow from the reactor coolant system) may be over 20 scfm for some plants. During startup from a cold shutdown, over 700 scf of hydrogen may be needed to purge the VCT and obtain the desired hydrogen conditions in the VCT and reactor coolant.

The hydrogen used to cool the electric generator is circulated through integral water-cooled heat exchangers by fans located near the ends of the rotor. Shaft oil seals prevent the entry of air and the escape of hydrogen. A carbon dioxide system is provided to purge hydrogen from the generator before maintenance and air from the generator before adding hydrogen after maintenance. The average hydrogen consumption rate, which increases with generator size, is probably less than about 0.4 scfm for systems with small leakage. Larger short-term flow rates will occur when hydrogen is added to a generator that is normally isolated from the supply. The volume occupied by the hydrogen in generators ranges from about 3500 to 6000 cubic feet and is maintained at pressures of about 85 psia. Hence, after generator maintenance, over 35,000 scf may be required for purging carbon dioxide and reaching the desired hydrogen purity and pressure conditions. Assuming a 6-hour period for this infrequent purging and filling operation, an average flow rate of about 100 scfm would be needed.

The hydrogen supply line leads through the turbine building to the final pressure regulator at a hydrogen control station located below the generator and one or two levels below the operating deck. This station also has controls for venting and purging and instrumentation for monitoring generator conditions. At the bottom of the typical generator, there are connections for about nine lines leading to the control station (gas sample lines, carbon dioxide and hydrogen supply lines, and drain lines). Leaks or breaks in any of these lines would result in large releases of hydrogen, which would not be limited by the flow restriction provided by pressure regulators. In addition, the seal oil unit that supplies oil to the generator shaft seals is located on one of these levels.

The low average consumption rates for both the VCT and generator mean that monitoring consumption rates with flow totalizers or changes in system pressure with time (e.g., for small supplies or operation with normally isolated VCTs or generators) could be a useful procedure for detecting hydrogen leaks in some cases. This would be supplemented by walkdowns of the systems with hydrogen detectors. Another approach is the use of permanent hydrogen detectors with alarms.

For the VCT, the very low average consumption rates for some plants are such that a limited amount of hydrogen could supply the consumption needs for an appreciable time. The low short-term maximum flow rates also indicate that small restricting orifices or excess flow valves (e.g., excess flow check valves or valves actuated by signals from flow elements) with low setpoints might be used to limit the hydrogen release rate so that the average concentrations in local areas with normal ventilation are kept well below the lower flammability limit of 4 volume percent. A value of 2 volume percent is recommended in SRP Section 9.5.1, Revision 3 (NUREG-0800).

For generators with normal leakage, the daily consumption of hydrogen is probably less than a few percent of the hydrogen stored in the generator. Hence, the slow reduction in generator pressure with normal hydrogen consumption would permit isolation of the hydrogen supply except for periodic (e.g., once-a-shift) adjustments to keep within required hydrogen conditions for the generator load. An alternative approach is to provide a small flow-limiting device with a bypass section for use on the infrequent occasions when higher flow rates are needed (e.g., after generator maintenance).

3.2 Hydrogen Combustion Characteristics

Immediate ignition of the hydrogen released from a leak or break results in a diffusion flame that could damage nearby equipment because of thermal effects. Any delay in ignition could result in the buildup of hydrogen-air mixtures, which could then ignite and lead to either deflagrations or detonations. Deflagrations are premixed flames that advance into the adjacent unburned mixture at subsonic speeds. If the deflagration speed is much less than sonic speed, thermal damage to equipment with little mechanical damage could occur. However, the flame can be accelerated (e.g., by turbulence produced by flow over obstacles in the flame path). As noted in NUREG/CR-5275, if the deflagration speed increases to over 100 m/sec, shock waves are generated. If the deflagration speed is large enough, a deflagration-to-detonation transition (DDT) could occur. Hydrogen detonations, which are premixed flames advancing into the unburned mixture at supersonic speeds, can cause thermal damage and extensive mechanical damage because of the associated overpressures and impulses (NUREG/CR-5275).

As noted in Technical Note 690 (National Bureau of Standards, 1976), the wide flammability limits for hydrogen-air mixtures (about 4 to 74 volume percent for upward flame propagation and 9 to 73 volume percent for downward propagation) and low ignition energies suggest a high probability of ignition of flammable mixtures from random ignition sources. Ignition sources such as small sparks and flames can initiate deflagrations, whereas direct initiation of a detonation in a detonable mixture usually requires much stronger (shock wave) ignition sources such as a high-energy spark or explosive (NUREG/CR-2475). The required energy source for direct initiation of a detonation is relatively low for a stoichiometric mixture (about 30 volume percent hydrogen in air) but increases rapidly as the concentration approaches the detonation limits. Since the presence of high-energy sources needed to initiate detonations near the lean limit is unlikely in the auxiliary building or at distribution levels of the turbine building, deflagration would be the most likely initial mode of combustion for this range of hydrogen concentrations. Depending on such factors as local hydrogen concentrations and compartment geometries, DDT could then be the mechanism for initiating local detonation.

The lean detonation limit for hydrogen-air mixtures at standard conditions is 18 volume percent for laboratory scale tests (National Bureau of Standards, 1976). However, tests and analysis indicate lower limits for larger volumes (e.g., NUREG-1370, NUREG/CR-2475, and NUREG/CR-5275). NUREG/CR-5275 describes tests on the effects of hydrogen concentration, obstacles, and transverse venting on flame acceleration and DDT that were conducted in the FLAME facility, a half-scale model of the upper plenum volume of a PWR ice condenser containment. These tests showed that flame acceleration at 12 volume percent was negligible. DDT was first observed at 15 volume percent, with no transverse venting but with obstacles present. However, with no obstacles and a large degree of transverse venting, DDT did not occur at 28 volume percent. NUREG/CR-5275 provides a methodology for a qualitative classification of the potential for DDT, given an estimate of the local hydrogen concentration and knowledge of local compartment geometry. Local detonations in large, dry PWR containments are discussed in a memorandum from E. S. Beckjord dated March 24, 1992; NUREG-1370; and NUREG/CR-5662.

Predictions of the consequences of postulated releases from hydrogen distribution lines are strongly dependent on plant-specific compartment geometries and equipment locations and involve large uncertainties in predictions of such factors as local hydrogen concentrations, ignition locations, DDT, and subsequent blast damage. For example, inadequate mixing and stratification may result in local detonable mixtures even though average hydrogen concentrations are below the detonation limit. In view of these uncertainties, the alternatives considered for reducing risk primarily involve ways to prevent significant hydrogen releases.

3.3 Design Features at Operating Plants Used To Reduce Risk From Hydrogen Systems for the Volume Control Tank and Generator

Information from final safety analysis reports, supplemented by information from plant visits and surveys, indicated significant plant-to-plant differences in existing hydrogen system design features to reduce the risk from hydrogen line leaks or breaks. Some plants have one large storage facility to supply hydrogen for both the VCT and the generator but do not provide excess-flow protection (NUREG/CR-3551). Hence, in the event of a system failure, a potential exists for discharging large amounts of hydrogen into the auxiliary building or turbine building before the storage facility can be isolated manually. In this case, the maximum release rate probably is controlled by the flow restriction provided by the pressure regulators operating in parallel at the storage facility. The normal ventilation air flow rates for the building as a whole are large. However, the hydrogen release rates as a result of these leaks or breaks could be too large for the dilution capability of normal ventilation in the local building areas involved and could result in estimated local average hydrogen concentrations that are well into the detonable range, particularly if allowance is made for nonuniform mixing. For such releases, damage to compartment walls and blast wave and flame front propagation via ventilation ducts, fire barriers, and passageways could result in loss of safety-related equipment.

Undetected leaks might also result in the buildup of unacceptable amounts of trapped hydrogen in overhead regions with an inverted-pocket geometry and inadequate local ventilation because of low ventilation rates or inadequate inlet and exhaust locations. Hydrogen has a density only about 7 percent of air density and has a large diffusion coefficient. Hence, small leaks at lower elevations of a compartment might be expected to mix quickly with the air and be removed with normal room ventilation. However, hydrogen from moderate releases could stratify and collect in overhead areas. In addition, much of the hydrogen distribution piping is located in overhead areas.

As a result of a review of more than 400 industrial accidents (nuclear and non-nuclear) involving hydrogen, Factory Mutual Research Corporation recommended in its report that hydrogen safety standards emphasize the importance of hydrogen monitoring for leak detection. The basic approach of the National Aeronautics and Space Administration (NASA) to reducing risk from hydrogen fires or explosions includes (1) prevention of leaks, (2) monitoring to detect leaks quickly and take corrective actions, (3) prevention of accumulations of leaked hydrogen by plentiful ventilation, and (4) elimination of ignition sources, but assuming that ignition sources are present (NASA, 1968 and 1992, and the hydrogen safety standard* to be published by NASA).

At typical gaseous hydrogen storage facilities, a pressure control station with two pressure regulators operating in parallel is used to decrease the hydrogen supply pressure (typical maximum pressures from 1500 to 2400 psig) to about 100 psig in the distribution lines to the auxiliary and turbine buildings. Overpressure protection for these lines is provided by relief valves discharging outside. Pressure regulators are then used to control pressures at about 20 psig at the VCT and 70 psig at the generator. At some plants with a single hydrogen storage facility for one or two units, excess flow valves are provided downstream of the pressure control station at the storage facility. However, the excess flow valve has a high setpoint (e.g., shutoff flow rates from 80 to 330 scfm) that was probably selected to meet the flow rate requirement for the infrequent purging and charging operation for the electric generator. Hence, breaks or leaks in the distribution lines for the VCT or the generator with flow rates up to these shutoff values would not be stopped by this excess-flow protection. Other plants use separate, small storage facilities that are normally connected to the VCT by means of a pressure regulator or operate with the VCT normally isolated from the hydrogen supply, except for periodic (e.g., daily) manual adjustments of hydrogen conditions. At one plant a single 200-scf hydrogen bottle is connected to the VCT, but is isolated except for daily adjustment of conditions in the VCT. At a number of plants, small flow-limiting devices (maximum flow rates ranging from about 8 to 25 scfm) are used to limit flow to the VCT. These maximum flow rates were usually low enough so that normal ventilation in the compartment with the leak or break would result in an average compartment hydrogen concentration below the lower flammability limit. One plant combines a small storage facility for the VCT with a small restricting orifice. The configurations to limit flow rate include excess flow check valves, restricting orifices, and valves controlled by a flow element in the VCT line. The valves controlled by the flow element in the VCT line fail closed and are also closed on an auxiliary building isolation signal when normal ventilation air flow to the building is lost. At some plants secondary pressure control stations are located outside the turbine and auxiliary buildings. Since normal leakage results in small rates of decrease in generator pressure, a number of plants also operate with periodic manual makeup to the generator. Other features include seismic piping supports, seismic Category I piping, or sleeved piping for portions of the distribution system with the guard space between the pipes vented directly outside the building. At a few plants, the hydrogen lines had been relocated after start of commercial operation to minimize the amount of piping in the buildings.

Color coding is useful during walkdowns for leak tests and for avoiding inadvertent damage to hydrogen piping. Information on color coding of hydrogen piping was obtained during visits by Idaho National Engineering Laboratory (INEL) personnel to 13 plants in 1989 and from a staff survey. Of the 36 plants covered, 20 use color coding for the VCT and generator lines, 2 use color coding only for the generator lines, 1 uses color coding only for a hydrogen water chemistry (HWC) installation, and 13 do not use color coding.

The amount of hydrogen in the hydrogen supply piping is very small and can be neglected (e.g., 100 feet of 1-inch-diameter supply piping contains only a few standard cubic feet of hydrogen). However, a few hundred standard cubic feet could be released from the VCT as it depressurizes, and about 15,000 to 25,000 scf could be released from generators. The final pressure regulators may limit backflow to breaks in the hydrogen supply line from these sources, but could be backed up by check valves. The use of excess flow check valves to stop flow from the hydrogen storage facility, supplemented by check valves in the lines near the VCT and the generator to stop the backflow of hydrogen in these components to leaks or breaks in the hydrogen supply lines in the auxiliary and turbine buildings, was proposed in a recent individual plant

*NSS/FP-1740.11.

examination (IPE) for a PWR with the hydrogen control station on the level below the generator (Yankee Atomic Electric Company, 1989). This approach protects the supply line, reduces the contribution of the storage facility to releases, and limits potential locations for large releases to the generator itself (e.g., shaft oil seals) and to the sample, drain, and other lines below the generator.

In summary, alternative design features for limiting the consequences of larger breaks or leaks in the hydrogen supply lines for the VCT and generator that have been used or considered for use at operating plants and do not require major system changes involve several basic approaches:

- Limit Supply Amount—use a limited supply normally connected to the VCT to restrict the total amount that could be released during a single event
- Limit Flow Rate From Supply—limit the maximum flow rate from the storage facility to a line break so that normal ventilation would keep local average hydrogen concentrations below the lower flammability limit
- Isolate Storage Facility—limit the available time when discharge from the storage facility could occur by using normally isolated storage facilities
- Limit Backflow of Contained Hydrogen—use check valves or restricting orifices if needed to limit backflow of hydrogen to breaks in the supply lines from the generator and possibly the VCT

These features would reduce the frequency of occurrence and/or the consequences of events involving larger breaks or leaks in the supply line that result in hydrogen release rates so large that there is insufficient time for corrective manual actions. The features also tend to reduce the significance of buildup of trapped hydrogen because of the low limits on hydrogen release rates or total amounts of hydrogen available for release during an event and the additional time available for corrective actions. In the auxiliary building, trapped hydrogen would probably be limited to the immediate areas containing the hydrogen system because of the additional dilution by ventilation in adjoining compartments.

Even with low leak rates, significant quantities of hydrogen are involved. For example, a leak rate of 10 scfm probably results in an average concentration in rooms with normal ventilation that is well below the lower flammability limit for hydrogen-air mixtures, but involves the release of nearly 5000 scf per shift. Hence, any judgments on the significance of trapped hydrogen at a particular plant must be based on plant-specific information such as local confirmed ventilation rates and on construction features obtained from a walkdown of the areas containing the hydrogen piping and components.

Methods for leak detection that have been used at plants include monitoring for abnormal consumption of hydrogen using integrating flow meters or monitoring system pressure changes with time (for small or isolated supplies), and use of permanent and/or portable hydrogen detectors. If normally isolated or limited hydrogen supplies are used, the rate of decrease in pressure could be appreciable for relatively small leaks and the total amount that could be leaked without early corrective action would be limited. For normally isolated hydrogen supplies, existing pressure-sensing instrumentation and low-pressure or other alarms could be used for the VCT and the generator. For the limited supplies, the final pressure regulator to the VCT would maintain VCT pressure until the supply was nearly exhausted. However, existing instrumentation and alarms could be used for monitoring the supply pressure. For large supplies, automatic detection such as the use of permanent hydrogen detectors with alarms to the control room may be needed to identify significant leaks in time for corrective action. This type of detection is covered in the EPRI guidelines (EPRI, 1987) and the NASA approach (NASA, 1992, and the hydrogen safety standard to be published by NASA).

3.4 Alternatives for Volume Control Tank and Generator Hydrogen Distribution Systems and Hydrogen Storage Facilities

The features that have been used or proposed for use in operating plants were considered in selecting alternatives for the VCT and generator hydrogen systems. For the hydrogen storage facilities, the relocation of the storage facility to increase the separation distances was evaluated for cases involving safety-related air intakes and structures. The addition of a blast shield was selected as a means of reducing the consequences of a detonation at the facility. Automatic closure of air intakes was selected as a means of preventing the ingestion of a flammable mixture at the intake following rupture of a hydrogen header at the storage facility.

The following alternatives were evaluated:

Alternative 1—Take No Action

Under this alternative there will be no new regulatory requirements. Consistent with existing regulations, this alternative does not preclude a licensee, or an applicant for an operating license, from proposing to the NRC staff design changes intended to reduce the risk associated with the hydrogen storage and distribution systems on a plant-specific basis.

Alternative 2—Install Low Setpoint Excess Flow Valves, Restricting Orifices, or Check Valves in Hydrogen Supply Line to the Generator

This alternative provides protection against leaks or breaks in the hydrogen supply line from the point of entry into the turbine building to the hydrogen control station below the generator, including any branches from this line to other buildings. A low setpoint excess flow valve or restricting orifice is provided in the supply line outside the building to limit flow from the storage facility to the leak or break. A check valve or restricting orifice could be provided in the supply line near the generator, if needed to prevent backflow from the generator to the leak or break. The alternative also limits flow from the storage facility to leaks or breaks in the piping near the generator and at the generator itself. Preoperational testing and periodic retesting of the excess flow valve to ensure that it will function properly and administrative controls or design features and training to prevent inadvertent operation with the flow-limiting device bypassed are part of this alternative. Larger leaks near the generator would be indicated by the reduction in generator pressure because of the limit on makeup flow from the storage facility. Buildup of significant amounts of trapped hydrogen from smaller leaks in turbine buildings may not be a concern for most PWR plants because of the open construction at each level and between levels (e.g., open hatches, floor grating, and stairs). However, administrative controls should be provided for monitoring hydrogen consumption for indication of leaks and for corrective actions.

Alternative 3—Provide Manual Makeup of Hydrogen to Generator and Check Valve or Restricting Orifice at the Generator

This alternative provides protection against leaks or breaks in the hydrogen supply line from the point of entry into the turbine building to the hydrogen control station below the generator, including any branches from this line to other buildings. It entails operation with the hydrogen facility normally isolated from the generator by an isolation valve outside the building and periodic manual adjustments of hydrogen conditions in the generator. A check valve would be provided in the supply line near the generator if needed to prevent backflow from the generator to leaks or breaks in the supply line. The alternative also prevents flow from the storage facility to leaks or breaks at or near the generator when the generator is isolated. Reduction of generator pressure with hydrogen release would provide warning of larger leaks or breaks, while monitoring hydrogen consumption by monitoring changes in generator pressure or frequency of manual makeup would indicate the presence of smaller leaks. Administrative controls would be used to prevent inadvertent operation with the hydrogen supply connected.

Alternative 4—Enclose Safety-Related Equipment Located in the Turbine Building in Blast- and Fire-Proof Structures

This alternative provides protection against the consequences of leaks or breaks in the supply line or at locations near the generator.

Alternative 5—Install Low Setpoint Excess Flow Valve or Restricting Orifice in Hydrogen Distribution System to VCT and Provide Hydrogen Detectors, if Needed

This alternative entails the use of a low setpoint excess flow valve or restricting orifice (e.g., sized for 150 percent of maximum daily flow rate) in the low-pressure hydrogen supply line outside the auxiliary building to limit the rate of hydrogen flow from the storage facility to the leak or break. The limit should be low enough so that normal ventilation in the compartment with the leak or break would keep the average compartment hydrogen concentration well below the lower flammability limit. This alternative includes (1) preoperational testing and periodic retesting of the excess flow valve to ensure operability and (2) administrative controls and features to prevent inadvertent opening of any bypass around the excess flow valve or restricting orifice and to isolate the supply manually if normal building ventilation is lost. In addition, protection against leaks at flow rates up to the setpoint of the excess flow valves, such as the use of hydrogen leak detectors with alarms to the control room or other suitable measures, should be provided for areas where leaking hydrogen could be trapped in unacceptable quantities. Trapped hydrogen may not have a significant effect on risk for most plants because of such factors as location of vital equipment and adequacy of ventilation at the low release rates. Hence, two options were considered for this alternative. Alternative 5 costs do not include the costs for hydrogen detectors. Alternative 5A costs include the additional costs of permanent hydrogen detectors.

Alternative 6—Limit the Quantity of Hydrogen Normally Connected to the VCT

This alternative entails a limit on the total amount of hydrogen in the storage facility that is normally connected to the VCT. The limit is such that the release and subsequent fire or detonation of the hydrogen in the supply and the VCT would not cause unacceptable damage to safety-related systems in the auxiliary building. Administrative controls, design features, and training should be provided to prevent inadvertent operation with a larger amount of stored hydrogen. Administrative controls should also be provided to monitor hydrogen consumption for indication of leaks and to prevent the buildup of unacceptable amounts of hydrogen in areas where hydrogen could be trapped.

Alternative 7—Provide Normally Isolated Supply With Daily Manual Makeup of Hydrogen to the VCT

This option entails isolation of the hydrogen storage facility from the VCT except for brief daily operations to adjust VCT conditions. Administrative controls, design features, and training should be provided to prevent inadvertent operation without isolating the hydrogen supply. Administrative controls should be provided to monitor hydrogen consumption for indication of leaks and to prevent the buildup of unacceptable amounts of hydrogen in areas where hydrogen could be trapped.

Alternative 8—Relocate Hydrogen Storage Facility To Meet Separation Distance From Safety-Related Structures

Alternative 9—Install Blast Deflection Shield at Hydrogen Storage Facility

Alternative 10—Install Hydrogen Analyzer-Actuated Air Intake Louvres at Safety-Related Air Intakes

4 TECHNICAL FINDINGS

4.1 Introduction

This regulatory analysis is based in part on work performed by Idaho National Engineering Laboratory (INEL) under a technical assistance contract and reported in INEL, 1991; INEL, 1992; and NUREG/CR-5759. The work included the following:

- Surveys of BWR and PWR plant information pertinent to GSI-106 that included the following sources:
  - final safety analysis reports (FSARs)
  - probabilistic risk analyses (PRAs)
  - plant information from site visits
  - information from equipment manufacturers
- A review of observed combustible gas events (precursors) at U.S. nuclear power plants.
- A risk evaluation of hydrogen storage facilities at PWRs and BWRs with respect to damage to safety-related buildings caused by explosions at the storage location and line breaks at the storage location resulting in flammable hydrogen-air mixtures at safety-related air intakes.
- A detailed PRA by INEL of the risk associated with the use of hydrogen for the volume control tank (VCT) and main generator during full-power operation for a representative (base case) PWR plant. A four-loop Westinghouse plant was selected because it was representative of a significant portion of the PWR population, had a Level 3 PRA, and had a completed and detailed fire analysis. The INEL base case PRA was then supplemented by a generic analysis based on sensitivity studies of the variation in plant risk resulting from observed changes in locations of safety-related equipment and plant feed-and-bleed (F&B) capabilities. A similar approach was followed in a scoping PRA for BWRs of the risk associated with hydrogen distribution to the main generator. A BWR/4 with a Mark I containment was selected for the BWR base case plant.
- Screening analyses for the risk associated with portable bottles of combustible gas and with other sources of hydrogen, including the (1) waste gas system at PWRs, (2) off-gas system at BWRs, and (3) battery rooms at PWRs and BWRs.
- Cost-benefit analyses to determine possible plant modifications to reduce risk that could be cost effective.

The scoping PRA for BWRs in EGG-NTA-9082 (INEL, 1991) indicated that the risk associated with the use of hydrogen for cooling the electric generator was small and did not warrant a more detailed study. This was based on the small risk resulting from the absence of safety-related equipment in the turbine building at the six BWR plants reviewed in the study. The screening analyses in EGG-NTA-9082 and NUREG/CR-5759 also indicated that the risk associated with the off-gas system in BWRs, the waste gas system in PWRs, and the station battery rooms and portable bottles of combustible gases in both BWRs and PWRs was very small and did not need to be considered further in this study.

The hydrogen storage facilities at PWR and BWR plants were initially screened by comparing the actual separation distances between storage facilities and safety-related structures and air intakes with the separation distances provided in the Electric Power Research Institute (EPRI) guidelines (EPRI, 1987). The EPRI separation distances for safety-related structures are the distances needed to prevent unacceptable structural damage from postulated hydrogen detonations at the storage facility. The EPRI separation distances for safety-related air intakes are the distances needed to prevent the ingestion of a flammable hydrogen-air mixture at the intake following a postulated pipe break at the facility and release of a jet of unburned hydrogen. Although a number of plants did not pass this screening test, this does not directly imply high risk because credit for plant-specific mitigating features could result in a low hazard. These mitigating features included (1) use of reinforced-concrete storage buildings with one open side facing away from safety-related structures and air intakes, (2) intervening non-safety-related structures, and (3) differences in elevation of storage area and air intakes. An informal survey showed that some of the plants that were screened were not configured to allow credit for such mitigating features. Hence, more detailed, plant-specific risk estimates were also deemed necessary.

As a result of the above evaluations, the more detailed risk and cost-benefit analyses under the scope of GSI-106 were reduced to

- hydrogen storage facilities for PWRs
- hydrogen distribution system for the VCT in PWRs
- hydrogen distribution system for the electric generators in PWRs

4.2 Review of U.S. Nuclear Power Plant Hydrogen Precursors

INEL conducted a literature search to identify hydrogen events at U.S. nuclear power plants through April 1990. Table 1 gives the number of hydrogen events for the hydrogen storage facilities and the hydrogen distribution systems for the VCT and the electric generators. A hydrogen event is identified as an unburned hydrogen leak, a fire, or an explosion. None of the events in Table 1 involved damage to safety-related equipment. Up to the date of this literature search (April 1990), INEL estimated that the total number of reactor operating years including shutdown time [reactor-years (RYs)] was 917 RYs for PWRs and 1424 RYs for PWRs and BWRs. Shutdown time was included because some events occurred during this time.

Electrical Generator Events

Fourteen PWR events and two BWR events involved hydrogen associated with generator cooling (including the supply piping within the turbine-generator building). Experience from BWRs was included because the equipment and operations for generator cooling systems are similar for both types of plants. Of these 16 events, 7 involved unburned leaks, 7 involved fires, and 2 involved explosions. Of the nine fires or explosions (all of which occurred in PWRs), six occurred while the plants were at more than 90-percent power and led to a turbine and/or reactor trip.

INEL attributed one of these nine events to leaks at the hydrogen distribution system levels in the turbine building. The rest were associated with leaks near or at the generator. Most of the generator leaks were at the shaft seal and were caused by such diverse mechanisms as faults in the electrical power to the seal oil system, a clogged seal oil filter, loss of hydrogen cooling because of a loose temperature sensor, and failure of an oil pressure sensing line.

Several fires in turbine buildings at foreign plants have been large and damaging. The event at Vandellos I in Spain in October 1989 (memorandum from R. L. Pressard dated September 4, 1991) was caused by failure of a high-pressure turbine and involved oil and hydrogen fires. The oil and hydrogen fire at the Maanshan plant in Taiwan in 1985 (reported in *Nucleonics Week* on August 8 and 22, 1985; December 19, 1985; and February 6, 1986) apparently was caused by loss of blading in the low-pressure turbine. Failure of lubricating oil lines because of vibration apparently caused the oil fire in the turbine building at the plant in Muehleberg, Switzerland, in 1971 (NRC Translation 2240). A more recent event at Chernobyl in October 1991 was a large hydrogen fire that apparently was caused by an electrical fault (reported in *Nucleonics Week* on October 17, 1991). INEL considered the available information on hydrogen systems and events at foreign plants to be insufficient to make a meaningful evaluation of event frequency for domestic application.

Volume Control Tank System Events

A total of 11 events involved unburned hydrogen leaks from the VCT cover-gas system of PWRs [including the supply piping in the primary auxiliary building (PAB)]. None of these events resulted in either a fire or an explosion. Ten leaks were detected when associated gaseous radioactivity was detected. Ten of the leaks were hardware related; one was caused because a sampling procedure was inadequate. Of the hardware-related events, one was caused by a leaking diaphragm in the hydrogen supply regulator, seven were valve related, and two were caused by a leaking VCT vent header.

Storage Facility Events

Three events occurred at hydrogen storage facilities. Two of those occurred at PWRs and one occurred at a BWR. One of the three events involved an explosion. Although the other two events involved fires, it is also possible that there was an initial explosion with a subsequent fire. No major unburned hydrogen releases were reported. None of the three events resulted in damage to any safety-related equipment or structures.

Recent Events at U.S. Nuclear Power Plants

Several hydrogen events have occurred in the turbine buildings at U.S. nuclear plants since the cutoff date of April 1990 that was used for this review to generate the initiating event frequencies. A failure of a main transformer at the Maine Yankee plant in April 1991 resulted in arcing below the generator that caused a hydrogen leak and fire (Maine Yankee Atomic Power Company, 1991). A turbine overspeed incident at the Salem plant in November 1991 resulted in damage to the low-pressure turbine and a hydrogen fire (Public Service Electric and Gas Company, 1991). In October 1991, at Nine Mile Point Unit 2 (Niagara Mohawk Power Corporation, 1991), about 10,000 scf of hydrogen was released from a broken sight glass below the generator. The leak was isolated and there was no fire or explosion. In December 1991, a 15-minute release of hydrogen from the seals of the generator at the Palisades plant occurred because of blockage of seal oil in an oil filter. There was no fire or explosion (Consumers Power Company, 1991).

4.3 Method of Analysis

4.3.1 General

The INEL analysis in NUREG/CR-5759 of the risk associated with the hydrogen facilities and distribution systems for the VCT and electric generator for the base case PWR was based on a "vital area" analysis. The plant response, modeled by typical probabilistic risk assessment event trees and fault trees, was used to identify vital areas where hydrogen fires or explosions could result in damage to safety-related equipment with a significant conditional probability for core damage. The vital area analysis for the base case plant included the following:

- identification of the applicable accident sequences
- determination of affected safety equipment
- development of new accident sequences for which hydrogen fires or explosions are the initiating events and that include the effects of postulated losses of safety equipment as a result of these fires or explosions

The detailed analysis by INEL is limited to events that occur when the reactor is at full power. In NUREG/CR-5759, INEL concluded that power operation through hot standby (Modes 1 through 3) should be bounded by these full-power results. This conclusion was based on consideration of system operability requirements, decay heat loads, reactor coolant system (RCS) coolant inventory, RCS coolant makeup capacity, containment integrity, and operability of vital auxiliary systems. INEL also concluded that the effects of hydrogen-induced events during hot shutdown (Mode 4), cold shutdown (Mode 5), and refueling (Mode 6) would be insignificant. This conclusion was based on consideration of the typical absence of hydrogen from the in-plant distribution system, the low decay heat loads, increased coolant inventories, and lower coolant temperatures.

The equations for the point estimates of the core damage frequency (CDF) for the generic analyses have the general form of an initiating event frequency for a large hydrogen release, *IF*, multiplied by the probability that the release and resulting fire or explosion damages safety-related equipment, *P*(equipment damage), multiplied by the conditional probability that the loss of the equipment for this scenario results in core damage, *P*(core damage). That is,

$$\text{CDF} = IF^{*}P(\text{equipment damage})^{*}P(\text{core damage})$$

Large quantities of hydrogen are not present near the reactor vessel and control rod drive motors,primary coolant system piping, and steam generators. Hence, pipe-break loss-of-coolant accidents (LOCAs), steam generator tube ruptures, and anticipated-transient-without-scram (ATWS) events should not result from hydrogen release events. The INEL calculations were limited to the following two types of transient-induced core melt scenarios:

(1) transients with failure of decay heat removal (DHR) systems (T/DHR)

(2) transient-induced LOCAs (T/LOCAs)

T/DHR transients can range from simple turbine trips to steamline breaks. These transients involve loss of all forms of core cooling and loss of RCS coolant inventory at high pressure from the pressurizer power-operated relief valves (PORVs) or safety valves. T/LOCA transients involve failure of RCS makeup or recirculation following a reactor coolant pump (RCP) seal LOCA caused by inadequate RCP seal cooling or a LOCA caused by stuck-open PORVs or safety valves. This category includes events such as station blackout and loss of component cooling water.

The initiating events considered were seismically induced or random failures of hydrogen piping or components at the storage facility or in the hydrogen distribution systems in the auxiliary and turbine buildings. In the turbine building, events are considered to occur at the generator and lines from the hydrogen control station to the generator or at the hydrogen supply line to the control station.

4.3.2 Seismic Events

Several studies supported by the NRC (see NUREG/CR-5759, p. 51) have shown that small-diameter piping systems such as those used in the hydrogen systems have a very large seismic capacity (i.e., failure unlikely for low-g earthquakes). Although this conclusion applies to the piping runs, connections to equipment or connecting pipe may be vulnerable to seismic failure, particularly if there is inadequate anchoring or flexibility. At the base case plant, key portions of the hydrogen lines in the auxiliary building are seismically qualified. Hence, no damage is expected for the higher frequency, relatively low-level earthquakes. For a severe (beyond-design-basis) earthquake (e.g., 0.8g), INEL concluded that the contribution of seismically induced hydrogen fires or explosions should be relatively small compared with the direct damage caused by the earthquake itself. For example, a severe earthquake could initiate a loss-of-offsite-power event because of failure of ceramic insulators at the offsite power transformer. Loss of primary cooling equipment (needed for the bleed-and-feed function) could also occur because of failure of either the refueling water storage tank (RWST), PORVs, or piping (including failure of hydrogen piping). The RWST, which has a lower seismic capacity than the hydrogen piping, should fail before the hydrogen piping is damaged. Hence, INEL concluded that the core damage contribution during seismic events associated with the seismically qualified hydrogen piping system in the auxiliary building at the base case plant should be small relative to that already considered in the PRA and could be neglected.

INEL assumed that the fragility of the hydrogen gas system for the main generator at the base case plant could be represented by that for the dry small-bore pipe with threaded joints in the fire protection system at that plant. INEL obtained an initiating event frequency of

5.3E–5/RY for seismically induced breaks of this piping using the Lawrence Livermore National Laboratory (LLNL) seismic hazard curves. For the generic study, INEL assumed that this seismic fragility was representative of the hydrogen storage facility and the distribution system piping and components containing hydrogen for the auxiliary and turbine buildings.

4.3.3 Non-Seismic Events

For non-seismic events, INEL estimated the initiating event frequencies for the VCT and main generator hydrogen distribution systems and storage facilities from the reported numbers of pertinent hydrogen events and the associated number of reactor-years of operation (NUREG/CR–5759, Appendix B). The mean initiating event frequency of a large hydrogen release involving the VCT hydrogen system in the auxiliary building is 5.5E–4/RY. In the turbine building, the mean frequency of a large hydrogen release is 6E–3/RY for the generator level and 1.1E–3/RY for the hydrogen distribution level.

4.3.4 Damage Mechanisms

In the evaluation of hydrogen storage facilities, INEL assumed that the loss of safety-related equipment was caused by detonations with resultant blast damage to nearby safety-related buildings or by large releases of unburned hydrogen that resulted in flammable hydrogen-air mixtures at nearby safety-related air intakes. INEL assumed loss of equipment if the separation distances between the storage facility and the buildings or air intakes did not meet the EPRI guidelines and there were no mitigating factors.

The EPRI calculations were made using the TNT equivalency method, which equates the available amount of hydrogen to an amount of TNT giving the equivalent damage. The blast wave parameters are then obtained from relations for TNT detonations. For these postulated detonations in open air, EPRI assumed that the TNT-hydrogen equivalence is 20 percent on an energy basis (520 percent on a mass basis). On this basis, 1000 scf of hydrogen is equivalent to 27.1 pounds of TNT. This value of 20 percent was considered conservative for outside detonations.

For local detonations in partially or fully enclosed volumes such as compartments and passageways in auxiliary buildings, reflected shock waves from other surfaces within these volumes could cause additional damage to the target surface. Other factors to consider include the lower expected strength of interior walls and the weakness of fire barriers and air ducts that would not be designed to withstand differential pressures occurring during a detonation. Significant hydrogen releases could occur at some plants with large supplies and no special features to limit hydrogen flow to the break. Hence, damage might occur to safety-related equipment in compartments with hydrogen lines or in adjoining compartments.

Large amounts of hydrogen are also available in storage facilities to initiate or exacerbate a fire in the turbine building at some plants if special features to reduce risk (e.g., excess flow check valves or normally isolated supplies) are not provided. Another large source of hydrogen is that contained in the generator. A hydrogen fire in the turbine buildings might not normally be considered to have the potential to directly affect nearby safety-related equipment because of the large size and open design typical of these buildings. However, delayed ignition of hydrogen escaping from a large break in the hydrogen lines or generator could result in the accumulation and eventual ignition of large quantities of hydrogen and result in the propagation of blast waves and fire fronts that could cause direct damage to nearby safety-related equipment. These blast waves or fire fronts could also cause oil leaks and fires, which could then spread and damage safety-related equipment in lower levels of the building.

Large oil fires in the turbine building have always been considered because of the presence of large quantities of turbine lubricating oil in the lower levels of the turbine building. An event involving a break in the oil lines could result in an oil fire caused by burning hydrogen or ignition of the oil from prolonged contact with hot metal surfaces or insulation. Burning oil from the operating level could then cascade to lower levels and spread to other fire zones. Early shutoff of the pumped oil could help prevent a large fire. However, the oil supply system is designed to be highly reliable because loss of the bearing supply could also cause extensive damage to the turbines and generator in the absence of a fire. Design features to increase the reliability of the oil supply include turbine shaft-driven pumps and emergency pumps. After a turbine trip, oil may be supplied to the break and fire for up to an hour as the turbine coasts down. This time can be reduced by breaking the condenser vacuum to slow the turbine and stopping motor-driven pumps.

4.3.5 Hydrogen Explosion Methodology

The conditional probability of damage to safety-related equipment, *P*(equipment damage), following a large hydrogen release was treated as the product of (1) the probability, *P*(delay), that early ignition following a large hydrogen release would not occur and (2) the probability, *P*(blast), that, given the continued accumulation and eventual ignition of the released hydrogen, the resultant blast wave or fire front would incapacitate safety-related equipment.

In the NUREG/CR–5759 generic calculations, INEL assumed that *P*(delay) was equal to 0.01 for large hydrogen releases at the main generator level. This value was based on discussions with INEL combustion experts who concluded that the leakage of large quantities of hydrogen into the ionized air surrounding the generator is almost certain to cause immediate ignition. For releases into the auxiliary building and releases from the hydrogen distribution system in the turbine building, INEL assumed a value of 0.1 for P(delay) to reflect the presence of significant amounts of electrical equipment, such as pump and fan motors, that could provide ignition sources for deflagrations in these buildings. INEL assumed a generic value of 0.1 for P(blast) for the auxiliary building and for the generator and distribution system levels in the turbine building. This choice was based on consideration of the spatial interactions (i.e., relative locations of hydrogen sources and safety-related equipment) and the likelihood of blast waves or fires damaging redundant safety-related equipment.

4.3.6 Uncertainty Analysis

INEL performed the uncertainty analyses for the base case plant and generic analyses using the distribution functions for random variables and the Monte Carlo sampling techniques built into the statistical @RISK computer program (Palisades Corporation, 1988). Some uncertainty information was obtained from the licensee's PRA. For models with random event values based on data from the review of hydrogen events at U.S. nuclear power plants, the distribution function and its parameters were calculated using the methods recommended in NUREG/CR-2300. Uncertainties in the values of P(delay) and P(blast) were treated as statistical uncertainties. Lognormal distributions were assigned to these probabilities, and an error factor of 10 was assigned to reflect the large modeling uncertainty.

4.4 Analysis of Base Case PWR Plant

The base case plant has a four-loop nuclear steam supply system provided by Westinghouse Electric Corporation. The reactor is licensed to operate at a thermal power of 3071 megawatts-thermal, corresponding to a turbine-generator output of 971 megawatts-electric.

4.4.1 Turbine Building

The hydrogen storage facility supplying the main generator at the base case plant is located about 135 feet west of the turbine building. The facility has 45 storage cylinders, each containing about 1150 scf of hydrogen at a pressure of about 1500 psig. Eighteen cylinders are on line as the active supply. Another 18 cylinders supply the reserve manifold, and 9 cylinders supply the emergency reserve manifold. The hydrogen line to the main generator is not equipped with an excess flow valve or restricting orifice to automatically limit the rate of hydrogen flow to a large leak or break in the turbine building. A 1.5-inch-diameter hydrogen supply line runs from the storage facility to the west wall of the turbine building where it enters at the 15-foot level. It passes horizontally through fire zones in which the hydrogen seal oil unit, sample and vent lines, and hydrogen control panel are located and then passes vertically through a fire zone at the 37-foot level to the main generator at the 53-foot level. Each elevation has one large open area that is divided into fire zones for convenience. The fire zones on each level are not separated by any physical barriers. However, different elevations are separated by concrete floors.

None of the fire zones in the turbine building contain safety-related equipment. The closest fire zones containing safety-related equipment are in the control building, which is directly adjacent to the southeast corner of the turbine building. A fire zone on the 15-foot level in the control building contains the switchgear room in which vital 480-V buses and power and control cables for most safety-related pumps are located. The wall separating the turbine and control buildings is about 100 feet from the hydrogen lines at this level. A fire zone on the 37-foot elevation, about 60 feet from the hydrogen lines, contains the cable spreading room in which power and control cables for most safety-related pumps and valves are located. A fire zone on the turbine hall floor at the 53-foot elevation contains the control room in which the control panels and instrumentation for most safety-related systems are located. This level has the largest open volume in the entire plant. The roof is about 100 feet above the operating deck, and the wall is constructed of insulated metal sandwich panels and contains large windows for natural lighting.

The only T/DHR event considered for the turbine building was a main steamline (MSL) break caused by a large hydrogen explosion on the operating deck. The estimated core damage frequency (CDF) for this event was negligible.

The T/LOCA events evaluated for the turbine building were both random and seismically induced failures of the hydrogen distribution lines at the 33-foot level that result in loss of the equipment in the cable spreading room (CSR). The CSR was considered to be the most susceptible fire zone because of the small separation distance from the hydrogen lines and the types of fire barriers and construction of the separating wall at the 33-foot level. A large fire in the CSR would result in the loss of power and control cables for most of the plant safety-related equipment (e.g., high-pressure injection pumps, component cooling water pumps, and residual heat removal and recirculation pumps). Assuming a value of unity for the conditional probability of core damage, given loss of the CSR, the point estimates of the mean CDF from non-seismic and seismically induced failures of the hydrogen distribution system would be about 1.1E-5/RY. However, because the susceptibility of the plant to large fires in the CSR had been recognized, an alternate safe shutdown system (ASSS) was installed at the base case plant in the early 1980s. The power and control cables for the ASSS, which performs a number of critical safety functions, are routed independently of the CSR. INEL obtained the probability of nonrecovery from a T/LOCA condition, using the installed ASSS, from the original base case plant fire PRA. The mean value of 0.046 consists of a human error contribution (0.039) and hardware-related failures (0.07). Hence, with credit for use of the ASSS, the CDF for these events was estimated to be about 5E-7/RY.

4.4.2 Primary Auxiliary Building

The hydrogen supply system for the VCT at the base case plant is independent of the supply system for the main generator. It consists of a 12-bottle supply located next to the primary auxiliary building (PAB). The supply contains a maximum of about 2400 scf of hydrogen at about 2000 psig. There is no excess flow valve or restricting orifice to limit hydrogen flow rate following a large leak or break in the auxiliary building. A hydrogen truck skid about 200 feet away provides refilling capability through a 1-inch-diameter field-run pipe. The 12-bottle bank is used for normal service, and the truck, which is normally isolated, is used as a backup.

The hydrogen supply pipe enters the PAB at the 92-foot elevation, travels horizontally for about 25 feet, enters and travels about 20 feet through a pipe chase, and then enters the VCT cubicle and tank at the 98-foot elevation. In the vital area analysis for this plant, most fire zones in the PAB were screened out either because no safety-related components were present or the fire zone was located two or more levels below the zones containing the hydrogen lines.

The only non-seismic T/DHR event considered was a general turbine trip event caused by a small fire or explosion. The estimated CDF for this event was insignificant. The initiating event frequency for seismically induced failures of the hydrogen lines in the PAB was considered negligible because of the seismic qualification of the lines. A non-seismic T/LOCA event in the PAB was considered because the component cooling water (CCW) heat exchangers in Fire Zone FZ-7A were located on the same level as the VCT. However, in view of the limited hydrogen supply to the VCT, partial shielding by intervening concrete walls, and the separation distance from the hydrogen lines, the probability that the CCW heat exchangers would be lost because of a hydrogen fire or explosion at that level was considered to be very small. As noted previously, seismic events were considered to be negligible contributors to risk in the PAB of the base case plant because of the seismic qualification of the supply line to the VCT.

4.4.3 Hydrogen Storage Facilities

INEL performed a vital area analysis for the generator and VCT supplies and the hydrogen truck skid facility for the VCT. The main generator supply met the EPRI criteria for safe separation distance from safety-related structures and air intakes. The VCT supply and truck skid supply met the EPRI criteria for detonation but did not meet the criteria for air intakes. However, consideration of intervening buildings and differences in elevations along possible paths from the supplies to the safety-related air intakes indicated a negligible likelihood that a safety-related air intake would ingest a combustible hydrogen-air mixture.

4.4.4 Uncertainty Analysis Results

In summary, the evaluation of the risk from hydrogen system failures at the base case plant indicated that the mean core damage frequency for hydrogen events at the storage facilities and in the turbine and auxiliary buildings is less than 1E-6/RY and is negligible when compared with the values from other causes identified in the plant PRA.

4.5 Generic Analysis

The generic analysis addressed the risk from hydrogen storage facilities and distribution systems for PWRs with design characteristics different from those of the base case plant, such as location of hydrogen supply facilities and distribution systems relative to vital equipment [e.g., auxiliary feedwater (AFW) system, diesels, electrical switchgear, cable spreading room, essential service water (SW) system, and component cooling water system] and feed-and-bleed (F&B) capability. As in the base case plant analysis, the generic analysis was based on the fact that the hydrogen system is not near the reactor pressure vessel and control rod drive motors, the primary coolant piping, or the steam generators. Hence, INEL did not consider pipe-break LOCAs, steam generator tube ruptures, and ATWS-type scenarios due to hydrogen events.

4.5.1 Method

The generic approach involved a vital area analysis in which hydrogen release and fire or explosion scenarios were related to specific system failure scenarios. The generic analysis did not include the level of detail used in a typical plant-specific vital area analysis, but was directed at key systems used to mitigate the two categories of transients. In particular, for transients with loss of decay heat removal (T/DHR), attention was focused on the AFW system and systems needed for F&B cooling. For transient-induced LOCAs (T/LOCAs), attention was focused on normal and emergency ac power and the essential SW and component cooling water systems. If this generic approach is used, a plant-specific design feature that produces a special outlier vulnerability will not be identified.

4.5.1.1 T/DHR Transients

INEL separated the T/DHR transients into several categories according to the location of the AFW system and the plant's F&B capability. In some plants, AFW and F&B systems are located in separate buildings away from the hydrogen storage facilities and distribution systems. In these plants, no interactions would be expected between the initiating event and AFW system failure. However, in some plants, AFW systems are located in the auxiliary or turbine buildings. For T/DHR transients in the turbine building, INEL assumed that a hydrogen fire or explosion sufficient to cause loss of the AFW system would also cause loss of the main feedwater (MFW) system. Hence, actions to recover the MFW system or to depressurize the steam generators and use the condensate system would be ineffective.

In some plants, if AFW cooling fails, operators can start a high-pressure safety injection pump and manually open the power-operated relief valves (PORVs) to provide F&B cooling to the primary system. Almost all Westinghouse (W) and Babcock & Wilcox (B&W) plants have this capability. For W and B&W plants, INEL assumed that P(F&B failure) was equal to 0.045. This value is the average of four different F&B failure probabilities from different plant PRAs and depends almost exclusively on human error probabilities and not on design considerations. Because newer Combustion Engineering (CE) reactors do not have PORVs, cooling the core using the F&B function is not possible. INEL also concluded in NUREG/CR-5759 that older CE reactors have marginal F&B cooling capability and cited previous analyses (NUREG/CR-4471 and NUREG/CR-5072) that indicated that only a short time window would be available for initiating successful F&B recovery operations. In view of the higher priority assigned to other recovery operators, INEL assumed in this generic study that F&B cooling was not a viable heat removal mechanism for CE plants.

4.5.1.2 T/LOCA Transients

The majority of PWRs probably do not have systems such as emergency diesels and essential SW systems in buildings where large hydrogen systems are located. However, INEL noted that in at least one PWR, a key portion of the component cooling water (CCW) system (CCW heat exchangers) is located in the turbine building. In most PWRs, the CCW system is located in the auxiliary building. At many PWR plants (including the base case plant), loss of the CCW system (e.g., caused by a large hydrogen explosion failing CCW heat exchangers) would seriously affect the plant's capability to cool the reactor coolant pump (RCP) seals. At many plants, cooling of the RCP seals is performed redundantly by CCW flow to the thermal barrier heat exchangers and by RCP seal injection (which is provided by the charging pumps). But loss of the CCW system leads to loss of the charging pumps; therefore, both means of cooling the RCP seals are lost if the CCW system is lost. Since the oil coolers of the high-pressure safety injection pumps and the charging pumps are cooled by CCW, loss of the CCW system could also lead to loss of the capability to mitigate the small LOCA caused by seal failure (NUREG/CR-5759).

4.5.2 Generic Analysis Results

4.5.2.1 Turbine Building and Auxiliary Building Analyses

The T/DHR and T/LOCA transients are categorized according to the location of the AFW, CCW, and other vital equipment relative to the hydrogen systems and the plant's feed-and-bleed capability. These combinations are covered by the configurations given in Table 2. Table 2 summarizes the mean core damage frequencies for the specific PWR configurations considered by INEL in evaluating the in-plant risk from the hydrogen supply and distribution systems and the specific accident scenarios to be considered in these generic evaluations.

4.5.2.2 Hydrogen Storage Facility Analysis

An informal survey of all plants showed that about 30 plants did not meet the EPRI criteria for separation distances for safety-related air intakes or structures. Of these plants, mitigating factors were insufficient at three plants. The results of additional evaluations by INEL of these three plants are as follows.

At Plant A, the hydrogen storage facility (with 14,400 scf of hydrogen in two tanks) is located about 30 feet from the main steam enclosure, which contains motor-operated AFW valves, main feedwater (MFW) piping, and main steam stop and safety valves. The scenario considered was a random rupture of a hydrogen storage tank resulting in a detonation causing loss of the MFW and AFW systems. Recovery is made using F&B capability. Since the actual separation distance was a few feet greater than the EPRI separation distance criterion, the probability of loss of the MFW and AFW systems, given a detonation, was assumed equal to 0.1. The frequency of all hydrogen fires and explosions, based on data in licensee event reports, was 2.5E-3/RY. From these values and a value of 0.045 for the failure probability of F&B cooling, the estimated mean CDF from the uncertainty analysis is 1E-5/RY. The hydrogen facility is also near the air intake for the pumphouse containing the essential SW pumps. The air-intake scenario considered was a random failure of the hydrogen header upstream of the pressure regulators leading to ingestion of a combustible mixture at the air intakes and a fire or explosion causing loss of the SW pumps and consequent loss of the motor-driven AFW pumps. The turbine-driven AFW pump would still be available. The mean CDF for this scenario is 2.5E-8/RY.

Plant B did not meet the separation criteria for either structures or air intakes. The hydrogen storage facility contains 85 standard hydrogen bottles (about 200 scf each). At least four bottles are on line. The hydrogen supply is not seismically qualified and was assumed to have the same fragility as that used for the hydrogen system piping in the generic calculations for the auxiliary and turbine buildings. The hydrogen supply is close to the two diesel generators. A storage bay containing a large quantity of turbine lubricating oil is located between the hydrogen facility and the diesel generators. The scenario considered was a seismic event causing loss of offsite power because of failure of ceramic insulators at the offsite power transformer and a seismically induced rupture of a hydrogen storage bottle. Since a hydrogen fire or detonation can also cause a large fire at the adjacent lubricating oil storage area, loss of both diesel generators was assumed. Hence, the seismic event could result in a station blackout. The mean values of the initiating event frequency and the CDF for this scenario are 5.3E–5/RY. For the air intake analysis, the concern was also the proximity of the diesel generators. The scenario considered was a random failure of a pipe at the hydrogen storage area during a loss of offsite power that causes loss of both diesel generators because of ingestion of a flammable mixture at the air intakes. The point estimate value of CDF for this event is 6.6E–7/RY.

Plant C did not meet the EPRI separation criteria for air intakes. The concern was the proximity to the hydrogen storage facility of the air intake for the building containing the 4160–V switchgear. Loss of this switchgear would cause loss of most safety-related equipment. Important exceptions are the turbine-driven AFW pump and the diesel generators. The scenario considered was a random failure of a pipe at the facility causing releases of unburned hydrogen, ingestion of a combustible mixture at the air intakes, and an explosion resulting in loss of the switchgear. Recovery from this event is made with the turbine-driven AFW pump. The point estimate value of CDF is 2.5E–6/RY.

4.6 Reductions in Core Damage Frequency for Improvement Alternatives

Sections 4.4 and 4.5 give estimates of the hydrogen-initiated CDF contributions for the base case plant and for other generic PWR plant configurations before any procedural or hardware changes are made to reduce risk. Configuration I scenarios are characterized by a hydrogen event at the generator floor level leading to a general plant transient or steamline break. INEL assumed that the contributions of the Configuration I accident scenario were not reduced by any of the alternatives for the turbine building, since none of the alternatives could prevent large releases of the hydrogen stored in the generator. The reductions in CDF for the alternatives are given in Table 3. The values in the table are the mean values obtained from the uncertainty analysis.

4.7 Dose Consequence Analysis

The dose consequence analysis by INEL for this safety issue was based on the information developed for Safety Issue A–45 (NUREG/CR–4762). For that study, Sandia National Laboratories used Calculation of Reactor Accident Consequences (CRAC) Version 2 computer code results for integrated doses (in person-rem per event) received by the population around the plant out to 50 miles. Lower bound, best-estimate, and upper bound values were calculated for each of seven release categories. For the generic PWR analysis of NUREG/CR–4762, a containment event tree with three containment functions and six containment sequences was used. Each accident sequence contributing to the CDF was mapped to one or more of the containment accident sequences. Each containment sequence was then mapped to containment failure modes with associated probabilities of occurrence per event and release fractions.

4.8 Cost Analysis

The cost-benefit analysis for the various alternatives followed the guidelines of NUREG/CR–3568 and NUREG/CR–4627, Revision 2. Costs were calculated using FORECAST 2.1 (Science & Engineering Associates, Inc., 1990).

All plant cost estimates are given in 1991 dollars and include implementation and recurring costs. INEL assumed that modifications would be made during normal plant operations or scheduled shutdowns and that no replacement energy costs would be incurred. The cost analyses covered the following component costs. These costs are discussed in INEL, 1992; Science & Engineering Associates, Inc., 1992; and NUREG/CR–5759.

- cost of equipment, material, and structures
- installation and removal costs and associated overhead
- engineering and quality assurance costs
- radiation exposure costs
- health physics support costs
- licensee costs for rewriting procedures, staff training, and other technical subtasks
- licensee recurring costs
- NRC implementation costs
- NRC recurring costs

- onsite averted costs representing the averted onsite property damages, including allowances for cleanup, repair, and replacement energy costs

Table 4 gives the point estimates of the total cost for each alternative minus the onsite averted costs for a remaining plant life of 20 years and a best-estimate discount rate of 0.05. Table 5 gives similar results for a remaining plant life of 40 years to illustrate the change in values for a plant with a license renewal for an additional 20 years. A negative value indicates a cost savings is predicted because of the inclusion of onsite averted costs. The calculations are described in detail in INEL, 1992, and NUREG/CR-5759.

5 COST-BENEFIT ANALYSIS

The cost-benefit methodology for analyzing the various alternatives considered for this safety issue is based on the requirements of the backfit rule (10 CFR 50.109) and the guidance in memoranda from E. S. Beckjord dated May 10 and November 18, 1988, and NUREG/CR-3568. One consideration in the decision-making process is the cost-benefit ratio for each alternative, evaluated in terms of cost in 1991 dollars per person-rem averted, which may be compared to a guideline such as $1000/person-rem. The costs used in the cost-benefit ratio are (1) the total cost of an alternative without consideration of the onsite averted costs (OSACs), given by the sum of the first nine component costs listed in Section 4.8, and (2) the net cost of an alternative, which equals total cost minus the OSACs. The other consideration in the decision-making process is the magnitude of the risk reduction achieved by the alternative action. In the following sections, each alternative is described and the results of a cost-benefit assessment are given.

INEL used the @RISK computer program (Palisades Corporation, 1988) to evaluate the uncertainty in the cost-benefit analysis with and without OSACs. Input to the program included the cost of the alternative, the benefit in offsite person-rem averted, and OSACs. Tables 6 and 7 give the results, which were obtained from the cumulative distributions for the cost-benefit ratio for a remaining plant life of 20 or 40 years. These tables give the chance that the cost-benefit ratio is more or less than $1000/person-rem.

5.1 Alternative 1 – Take No Action

Under this alternative there will be no new regulatory requirements. Consistent with existing regulations, this alternative does not preclude a licensee from proposing to the NRC staff other changes intended to reduce the risk associated with the hydrogen storage and distribution systems on a plant-specific basis.

5.2 Alternative 2 – Install Low Setpoint Excess Flow Valves, Restricting Orifices, or Check Valves in the Hydrogen Supply Line to the Generator

This alternative provides protection from large breaks in the hydrogen supply line to the hydrogen control station at the generator by limiting flow from the hydrogen storage facility and backflow from the generator. The alternative also limits flow from the storage facility to leaks or breaks in the lines near the generator and at the generator itself. It applies to Configurations II, III, and IV, which involve leaks or breaks at the hydrogen distribution system levels in the turbine building. Configuration II applies to Babcock & Wilcox (B&W) and Westinghouse (W) plants and the loss of the auxiliary feedwater (AFW) system located in the turbine building. Alternative 2 is not cost effective for this configuration because of the small delta core damage frequency (CDF) at these plants that have feed-and-bleed (F&B) capability. For Configuration III, involving loss of the AFW system located in the turbine building at Combustion Engineering (CE) plants, and Configuration IV, involving loss of vital equipment in the turbine building at all PWRs, INEL obtained a generic best-estimate value of about 1E-5/RY for delta CDF. If onsite averted costs are included, there is a cost savings for Configurations III and IV. Table 6 shows there is nearly a 100-percent chance that the cost-benefit ratio is less than $1000/person-rem for these configurations. INEL assumed that Alternative 2 did not reduce the CDF for Configuration V, which is applicable to hydrogen releases at or near the generator.

5.3 Alternative 3 – Provide Manual Makeup of Hydrogen to Generator and Check Valve or Restricting Orifice at the Generator

Alternative 3 entails operation with the hydrogen facility normally isolated from the generator, except for manual adjustment of hydrogen conditions in the generator, and the installation of a check valve in the hydrogen line near the generator to prevent backflow to the hydrogen line break. A large portion of the cost for this alternative is the recurring costs associated with manual makeup to the generator.

Alternative 3 applies to Configurations II, III, and IV. INEL assumed that this alternative did not reduce the CDF for Configuration V, which is applicable to hydrogen releases at or near the generator. The alternative is not cost beneficial for Configuration II (loss of the AFW system in the turbine building for W and B&W plants) because of the small delta CDF for these plants that have F&B capability. For Configurations III (loss of the AFW system in the turbine building for CE plants) and IV (loss of vital equipment in the turbine building for all PWRs), the generic best-estimate delta CDF is 1.0E-5/RY. If onsite averted costs are included for these configurations, Table 6 shows that there is nearly a 100-percent chance that the cost-benefit ratio is less than $1000/person-rem.

5.4 Alternative 4 – Enclose Safety-Related Equipment Located in Turbine Building in Blast- and Fire-Proof Structures

This alternative, which applies to Configurations II, III, IV, and V, entails structural modifications to protect the vital equipment from damage by large fires or explosions. INEL initially considered it as a possible alternative for plants with higher risks because of safety-related equipment in the turbine building. The alternative is not cost effective with or without onsite averted costs because of the large costs and the generic delta CDFs estimated for these configurations. Table 6 shows more than a 99-percent chance that the cost-benefit ratio is greater than $1000/person-rem.

5.5 Alternative 5 – Install Low Setpoint Excess Flow Valve or Restricting Orifice in Hydrogen Distribution System to Volume Control Tank and Provide Hydrogen Detectors, if Needed

This alternative involves the use of a low setpoint excess flow valve or restricting orifice in the hydrogen supply line outside the auxiliary building (AB). The purpose is to limit the rate of hydrogen flow from the storage facility to larger breaks or leaks to a low value so that normal ventilation in the compartment with the leak or break can keep the average hydrogen concentration well below the lower flammability limit. Protection against the accumulation of unacceptable amounts of trapped hydrogen from leaks at flow rates up to this maximum flow rate would also be provided if necessary. Trapped hydrogen may not be a concern at most plants if the low setpoint excess flow valve or restricting orifice is used. Hence, as discussed in Section 3.4, the costs for this alternative were estimated for two cases. Alternative 5 costs do not include the installation of permanent hydrogen detectors. Alternative 5A costs include the additional costs of permanent hydrogen leak detectors (see EPRI, 1987 and Science & Engineering Associates, Inc., 1992) that provide an input to a local panel sending an alarm to the control room. The costs include the costs of (1) the hydrogen detectors, (2) periodic testing and maintenance of the excess flow check valves and hydrogen detectors, (3) administrative controls and/or design features to prevent the bypassing of the excess flow check valves or restricting orifices, and (4) administrative controls to provide for manual isolation of the hydrogen supply if normal ventilation to the AB is lost.

These alternatives apply to Configurations VI, VII, and VIII, which involve loss of the AFW system or vital equipment in the AB (see Table 2). The alternatives with onsite averted costs included are not cost effective for Configuration VI (loss of the AFW system in the AB for W and B&W plants) because of the small delta CDF at plants with F&B capability. For Configurations VII (loss of the AFW system in the AB for CE plants) and VIII (loss of vital equipment in the AB for all PWRs), the INEL estimate of a generic value for delta CDF is about 0.5E-5/RY. The alternatives are cost effective for these configurations if onsite averted costs are included. Table 6 shows that the chance that the cost-benefit ratio is less than $1000/person-rem is about 100 percent for Alternative 5 and 88 percent for Alternative 5A.

5.6 Alternative 6 – Limit the Quantity of Hydrogen Normally Connected to Volume Control Tank

This alternative involves a limit on the total amount of hydrogen in the storage facility that is normally connected to the volume control tank at any time. The limit is such that the release and subsequent fire or detonation of the hydrogen in the supply and the VCT would not cause unacceptable damage to safety-related systems in the auxiliary building.

This alternative also applies to Configurations VI, VII, and VIII, which involve loss of the AFW system or vital equipment in the auxiliary building. For Configuration VI (loss of the AFW system in the AB for W and B&W plants), the alternative is not cost effective if onsite averted costs are included because of the small delta CDF at these plants that have F&B capability. For Configurations VII (loss of the AFW system in the AB for CE plants) and VIII (loss of vital equipment in the AB for all plants), the generic value of delta CDF is 0.5E-5/RY. This alternative is cost effective for these configurations if onsite averted costs are included. Table 6 shows that there is about a 100-percent chance that the cost-benefit ratio is less than $1000/person-rem.

5.7 Alternative 7 – Provide Normally Isolated Supply With Daily Manual Makeup of Hydrogen to Volume Control Tank

This alternative involves isolation of the hydrogen storage facility from the VCT except for brief daily operation to adjust VCT conditions. The dominant cost for this alternative is the recurring plant cost for manual makeup.

This alternative applies to Configurations VI, VII, and VIII, which involve loss of the AFW system or vital equipment in the auxiliary building. For Configuration VI (loss of the AFW system in the AB for W and B&W plants), the alternative is not cost beneficial if onsite averted costs are included because of the small delta CDF for these plants that have F&B capability. For Configurations VII and VIII, the generic best-estimate value of delta CDF is 0.5E–5/RY. This alternative is still not cost effective because of the higher costs. Table 6 shows that there is a 51-percent chance that the cost-benefit ratio is less than $1000/person-rem.

5.8 Alternative 8 – Relocate Hydrogen Storage Facility To Meet Separation Distance From Safety-Related Structures

This alternative involves the relocation of the hydrogen storage facility to reduce the probability that a detonation at the storage facility will damage safety-related equipment. The mean delta CDFs for this alternative are about 1.0E–5/RY for Plant A and 5.3E–5/RY for Plant B. If onsite averted costs are included, the alternative is not cost effective for Plant A, but is cost effective for Plant B. Table 6 shows that the chance that the cost-benefit ratio is less than $1000/person-rem is 6 percent for Plant A and 97 percent for Plant B.

5.9 Alternative 9 – Install Blast Deflection Shield at Hydrogen Storage Facility

This alternative involves the addition of a blast shield to protect safety-related equipment from a detonation at the hydrogen storage facility. The alternative was considered only for Plant A, since a blast shield could not be used at Plant B because of insufficient space. The alternative does not apply to Plant C, which did not meet the separation distance criteria for air intakes. The best-estimate delta CDF for Plant A is 1.0E–5/RY. Table 6 shows that the chance that the cost-benefit ratio is less than $1000/person-rem is about 100 percent if onsite averted costs are included.

5.10 Alternative 10 – Install Hydrogen Analyzer-Actuated Air Intake Louvres at Safety-Related Air Intakes

This alternative, which involves the addition of shutters actuated by hydrogen detectors to prevent the ingestion of flammable hydrogen-air mixtures at safety-related air intakes, applies to Plants A, B, and C. Since the delta CDFs are small because of the small initial CDFs, this alternative is not cost effective. Table 6 shows that the chance that the cost-benefit ratio is less than $1000/person-rem is less than 8 percent if onsite averted costs are included.

5.11 Other Alternatives

Other alternatives are possible that could also reduce an existing plant vulnerability at either the auxiliary building, the turbine building, or the hydrogen storage facility. The alternatives discussed in Sections 5.1 through 5.10 provide a perspective on a range of options and could serve as guidance on the cost effectiveness and benefits to be expected from other possibilities.

5.12 Life Extension Considerations

The NRC staff is developing the regulatory requirement for the renewal of operating licenses. A license may be renewed for an additional 20 years if the licensee meets the specific requirements of the license renewal rule. The effect of license renewal on the evaluation of this safety issue was included by repeating the calculations for a remaining plant life of 40 years (current remaining life of 20 years plus a license renewal of 20 years). The results are shown in Table 7. The increases in onsite averted costs and benefits with increase in remaining plant life cause a decrease in the cost-benefit ratio (more cost effective) that can be offset, in part, for some alternatives by the increased contribution of recurring costs.

5.13 New Reactors

The implementation of the resolution of GSI-106 includes a recommendation that the Standard Review Plan (NUREG-0800) be modified to include new guidance on hydrogen storage facilities and distribution systems for the VCT and generator at future PWRs and BWRs.

6 DECISION RATIONALE

6.1 Introduction

As noted in Section 5, the estimated cost savings and cost-benefit ratios vary significantly for the alternatives associated with the hydrogen storage facilities and the hydrogen distribution system for the volume control tank (VCT) and electric generator at PWRs.

Hydrogen Storage Facilities

The estimates for the hydrogen storage facilities indicate that Alternative 8, which involves the relocation of the storage facility, results in a delta core damage frequency (CDF) of about 5E-5/RY for Plant B and is cost effective if onsite averted costs are included. For Plant A, Alternative 9, which involves the addition of a blast shield, results in a delta CDF of about 1E-5/RY and is cost effective if onsite averted costs are included. Alternative 10, which involves the air intake louvres, is not cost effective because of the small values of CDF associated with the air intakes for these plants.

Turbine Building

The generic estimates indicate that Alternative 2, which involves the installation of flow-limiting devices, and Alternative 3, which involves operation with a normally isolated generator, would be cost effective in reducing risk for Combustion Engineering (CE) plants with the auxiliary feedwater (AFW) system in the turbine building or all PWRs with vital equipment in the turbine building and hydrogen releases at the hydrogen distribution system level (Configurations III and IV of Table 2). These alternatives result in a best-estimate delta CDF of about 1E-5/RY. Alternative 7, which involves protection of the safety-related equipment, is not cost effective.

Auxiliary Building

For the auxiliary building, the evaluation indicates that Alternatives 5 and 5A and Alternative 6 would be cost effective for CE plants with the AFW system in the auxiliary building or all PWRs with vital equipment in the auxiliary building (Configurations VII and VIII of Table 2) if onsite averted costs are included. The generic best-estimate delta CDF for the alternatives is about 0.5E-5/RY. Alternative 5 involves the use of a flow-limiting device in the supply line to the VCT. Alternative 5A involves the use of a flow-limiting device in the supply line to the VCT and permanent hydrogen detectors. Alternative 6 involves the use of a limited hydrogen supply to the VCT. Alternative 7, which involves the use of a normally isolated supply, is not cost effective. This alternative had the same delta CDF for Configurations VII and VIII, but much larger estimated costs because of recurring costs associated with manual adjustment of VCT conditions.

Plant-Specific Conditions in Auxiliary and Turbine Buildings

A significant number of hydrogen events have occurred and continue to occur at U.S nuclear power plants. In recent years, most of the significant events involving hydrogen fires, explosions, or large hydrogen releases have occurred in turbine buildings. However, hydrogen events in the turbine building are not expected to be significant sources of risk for most plants. For T/LOCA transients, vital equipment is not expected to be in the turbine building for most plants. For T/DHR transients, the risk is small at the Westinghouse and Babcock & Wilcox plants because of their feed-and-bleed capabilities (additional recovery operations include recovery of the main feedwater system or depressurization of steam generators and the use of condensate). At most CE plants there would also be a minimal risk from the T/DHR transient because the AFW pumps are located (1) in a separate building or (2) in both the auxiliary and turbine buildings. Hence, a single hydrogen event would not be expected to result in loss of all AFW. However, for the small number of plants that could be susceptible to core damage resulting from T/LOCA or possibly T/DHR transients because of events in the turbine building, the magnitude of the generic estimates of CDF (1E-5/RY) and cost-benefit ratio indicates that some alternatives considered in this analysis could be warranted.

Although there have been a number of leaks, there have been no fires, explosions, or large hydrogen releases in the auxiliary building. However, some plants are considered to be susceptible to core damage because protective features are lacking to prevent large hydrogen releases or, possibly, the buildup of significant amounts of trapped hydrogen in the auxiliary building. The hydrogen events considered potentially significant are those resulting in loss of vital equipment and a reactor coolant pump seal LOCA. An appreciable number of plants have corrective measures such as normally isolated supplies, limited supplies, flow-limiting devices, and leak detection equipment and procedures. Therefore, a relatively small number of plants may need changes to reduce risk. The generic CDF and cost-benefit ratios for these events indicate that some alternatives could be warranted for those plants that do not have protective features.

The generic delta CDFs for the various alternatives are based on sensitivity studies of the base case plant to better quantify values for other existing plants that (1) have large hydrogen facilities that are normally connected to the VCT and generator via pressure regulators and (2) do not have low setpoint excess flow valves or restricting orifices to limit the rate of flow from the facility following a large break in the hydrogen supply line in these buildings. These generic calculations are characterized by a single set of values for initiating event frequencies and for the probability of a delay in ignition, *P*(delay), and the probability of blast damage to redundant safety systems, *P*(blast). Depending on the relative locations of the safety equipment and hydrogen lines, and other factors such as use of a limited amount of stored hydrogen or excess flow valves and leak detection, these values and, hence, the delta CDFs for a given plant may be significantly lower or higher than the generic values. For example, the probability of damage to component cooling water (CCW) heat exchangers at the base case plant that are located on the same level as the VCT was considered to be very small because of the limited amount of hydrogen, partial shielding by several concrete walls, and a large separation distance. Other fire zones were eliminated from consideration because they contained no safety-related equipment or were located two or more levels below zones containing hydrogen components. Damage to a seismic Category I six-inch service water line located near a short length of hydrogen line in a pipe chase was eliminated from consideration in the base case plant because of a relatively large separation distance, lack of local ignition sources, and significant ventilation.

However, other plants may have such building arrangements that the hydrogen lines are relatively close to vital equipment considered in the risk analysis. Limited information on the location of safety-related equipment relative to the hydrogen lines and VCT in the auxiliary building was obtained from site surveys conducted early in the program. These surveys showed that rooms containing CCW pumps and heat exchangers were at the same level or at levels adjacent to the level containing hydrogen lines at six of nine plants surveyed. Motor control centers at 5 of 6 plants and switchgear rooms at 4 of 14 plants were also at the same or adjacent levels. A survey of the location of the auxiliary feedwater (AFW) system at 14 plants showed that the AFW pumps were in the turbine building at 3 plants, the auxiliary building at 5 plants, and in other buildings at 6 plants. Of the five plants with AFW pumps in the auxiliary building, three had pumps at the same level or levels adjacent to those containing hydrogen lines. An additional review of one of the plants showed that the hydrogen supply line to the VCT in the auxiliary building was located next to the compartment containing the CCW pumps and heat exchangers. The generic estimate of the CDF for the T/LOCA transient following loss of the CCW system is about 0.5E-5/RY. However, the proximity of the hydrogen supply line to the CCW components at this plant could result in a higher conditional probability of damage to safety-related equipment and a corresponding increase in the CDF (e.g., about 1E-5/RY).

6.2 Relationship to Other Generic Issues

Because the T/LOCA transients in this evaluation encompass those hydrogen-induced system failures that lead primarily to reactor coolant pump (RCP) seal LOCAs, GI-23, "Reactor Coolant Pump Seal Failures," is related to GSI-106. The objective of GI-23 is to reduce the probability of RCP seal failures and, hence, make it a small contributor to the total CDF. GI-23 could entail the addition of a separate and independent cooling system for the RCP seals and could provide part of the resolution of GSI-106 because it would eliminate most of the delta CDF for the T/LOCA scenarios.

6.3 Backfit Rule and Plant-Specific Considerations

As discussed in Section 2, the overall objective of GSI-106 is to ensure that the contribution from the use of combustible gases to the total CDF is less than about 1E-5/RY. The generic calculations indicate that some plants may have a CDF due to hydrogen events of more than 1E-5/RY. However, it is apparent that there are large and diverse plant-to-plant differences in

- relative locations of hydrogen systems and safety-related equipment
- hydrogen storage and distribution system safety features, operating procedures, and considerations of trapped hydrogen
- reactor characteristics that affect risk from hydrogen events

Hence, only plant-specific evaluations can determine the extent to which a modification is justified.

6.4 Conclusion

In view of the observed large differences in plant-specific characteristics affecting the risk associated with the use of hydrogen, and the marginal generic safety benefit that can be achieved in a cost-effective manner, it is concluded that this generic issue be resolved simply by making these results available in a generic letter. This information may help licensees in their plant evaluations recommended by Generic Letter 88-20, Supplement 4, "Individual Plant Examination of External Events for Severe Accident Vulnerabilities," June 28, 1991.

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TABLES

Table 1 Number of hydrogen events at each plant location

Event location (reactor–years)	Reactor	Explosions	Fires	Unburned leaks	Total
Turbine building (1424)	BWR, PWR	2	7	7	16
Volume control tank in primary auxiliary building (917)	PWR	0	0	11	11
Hydrogen storage system (1424)	BWR, PWR	2	1	0	3
Total		4	8	18	30

Source: NUREG/CR-5759.

Table 2 Generic plant configurations

Configuration	Plant applicability	Important accident scenarios applicable to configuration	Core damage frequency/ reactor–year
I	All PWRs with auxiliary feedwater (AFW) and vital equipment outside turbine and auxiliary buildings	T/DHR* T/LOCA**	3.4E–8
II	Babcock & Wilcox and Westinghouse plants with AFW system at turbine building distribution system level	T/DHR (feed and bleed credited)	7.3E–7
III	Combustion Engineering plants with AFW system at turbine building dis tribution system level	T/DHR (feed and bleed not credited)	9.4E–6
IV	All PWRs with vital equipment at turbine building distribution system level	T/LOCA [station ac blackout or loss of component cooling water (CCW) or service water (SW) system]	9.4E–6
V	All PWRs with vital equipment at turbine building generator floor level	T/LOCA (station ac blackout or loss of CCW or SW system)	5.2E–6
VI	Babcock & Wilcox and Westinghouse plants with AFW system in auxiliary building	T/DHR (feed and bleed credited)	2.0E–7
VII	Combustion Engineering plants with AFW system in auxiliary building	T/DHR (feed and bleed not credited)	4.7E–6
VIII	All PWRs with vital equipment in auxiliary building	T/LOCA (loss of CCW or SW system)	4.7E–6

*T/DHR = transient-induced loss of decay heat removal.
**T/LOCA = transient-induced loss-of-coolant accident.
Source: NUREG/CR-5759.

Table 3 Delta core damage frequency per reactor-year for alternatives (calculated mean values)

Alternative	Configuration							Plant		
	II	III	IV	V	VI	VII	VIII	A	B	C
Turbine building										
Alternative 2	7.0E-7	9.4E-6	9.4E-6	NA	NA	NA	NA	NA	NA	NA
Alternative 3	7.0E-7	9.4E-6	9.4E-6	NA	NA	NA	NA	NA	NA	NA
Alternative 4	7.0E-7	9.4E-6	9.4E-6	5.2E-6	NA	NA	NA	NA	NA	NA
Auxiliary building										
Alternative 5	NA	NA	NA	NA	1.9E-7	4.6E-6	4.6E-6	NA	NA	NA
Alternative 5A	NA	NA	NA	NA	1.9E-7	4.6E-6	4.6E-6	NA	NA	NA
Alternative 6	NA	NA	NA	NA	1.9E-7	4.6E-6	4.6E-6	NA	NA	NA
Alternative 7	NA	NA	NA	NA	1.9E-7	4.6E-6	4.6E-6	NA	NA	NA
Hydrogen storage facility										
Alternative 8	NA	NA	NA	NA	NA	NA	NA	1.0E-5	5.3E-5	NA
Alternative 9	NA	NA	NA	NA	NA	NA	NA	1.0E-5	NA	NA
Alternative 10	NA	NA	NA	NA	NA	NA	NA	6.1E-8	6.9E-7	2.6E-6

Note: NA = not applicable.
Source: NUREG/CR-5759.

Table 4 Cost of modifications minus onsite averted costs (point estimates) for remaining plant life of 20 years ($)

Alternative	Configuration							Plant		
	II	III	IV	V	VI	VII	VIII	A	B	C
Turbine building										
Alternative 2	8,400	−130,000	−130,000	NA	NA	NA	NA	NA	NA	NA
Alternative 3	95,000	−48,000	−48,000	NA	NA	NA	NA	NA	NA	NA
Alternative 4	1,000,000	950,000	950,000	1,000,000	NA	NA	NA	NA	NA	NA
Auxiliary building										
Alternative 5	NA	NA	NA	NA	9,200	−63,000	−63,000	NA	NA	NA
Alternative 5A	NA	NA	NA	NA	76,000	3,600	3,600	NA	NA	NA
Alternative 6	NA	NA	NA	NA	5,700	−67,000	−67,000	NA	NA	NA
Alternative 7	NA	NA	NA	NA	100,000	31,000	31,000	NA	NA	NA
Hydrogen storage facility										
Alternative 8	NA	NA	NA	NA	NA	NA	NA	340,000	−370,000	NA
Alternative 9	NA	NA	NA	NA	NA	NA	NA	−150,000	NA	NA
Alternative 10	NA	NA	NA	NA	NA	NA	NA	99,000	87,000	57,000

Note: NA = not applicable.
Sources: INEL, 1992, and NUREG/CR-5759.

Table 5 Cost of modifications minus onsite averted costs (point estimates) for remaining plant life of 40 years ($)

Alternative	Configuration							Plant		
	II	III	IV	V	VI	VII	VIII	A	B	C
Turbine building										
Alternative 2	8,600	−190,000	−190,000	NA	NA	NA	NA	NA	NA	NA
Alternative 3	130,000	−61,000	−61,000	NA	NA	NA	NA	NA	NA	NA
Alternative 4	1,100,000	890,000	890,000	980,000	NA	NA	NA	NA	NA	NA
Auxiliary building										
Alternative 5	NA	NA	NA	NA	11,000	−88,000	−88,000	NA	NA	NA
Alternative 5A	NA	NA	NA	NA	78,000	−22,000	−22,000	NA	NA	NA
Alternative 6	NA	NA	NA	NA	4,500	−95,000	−95,000	NA	NA	NA
Alternative 7	NA	NA	NA	NA	150,000	47,000	47,000	NA	NA	NA
Hydrogen storage facility										
Alternative 8	NA	NA	NA	NA	NA	NA	NA	275,000	−690,000	NA
Alternative 9	NA	NA	NA	NA	NA	NA	NA	−210,000	NA	NA
Alternative 10	NA	NA	NA	NA	NA	NA	NA	99,000	84,000	41,000

Note: NA = not applicable.
Sources: INEL, 1992, and NUREG/CR-5759.

Table 6 Cost–benefit uncertainty results for remaining plant life of 20 years

		With onsite averted costs		Without onsite averted costs	
Configu-ration	Alter-native	Percent probability CBR < $1000/ person–rem	Percent probability CBR > $1000/ person–rem	Percent probability CBR < $1000/ person–rem	Percent probability CBR > $1000/ person–rem
II	2	35	65	4	96
	3	<1	>99	<1	>99
	4	0	100	0	100
III	2	100	0	44	56
	3	97	3	13	87
	4	<1	>99	<1	>99
IV	2	100	0	44	56
	3	97	3	13	87
	4	<1	>99	<1	>99
V	2	NA	NA	NA	NA
	3	NA	NA	NA	NA
	4	<1	>99	<1	>99
VI	5	3	97	2	98
	5A	<1	>99	<1	>99
	6	4	96	2	98
	7	<1	>99	<1	>99
VII	5	100	0	32	68
	5A	88	12	9	91
	6	100	0	31	69
	7	51	49	6	94
VIII	5	100	0	32	68
	5A	88	12	9	91
	6	100	0	31	69
	7	51	49	6	94
Plant A	8	6	94	2	98
	9	100	0	56	44
	10	0	100	0	100
Plant B	8	97	3	7	93
	9	NA	NA	NA	NA
	10	<1	>99	<1	>99
Plant C	8	NA	NA	NA	NA
	9	NA	NA	NA	NA
	10	8	92	1	99

Notes: CBR = cost–benefit ratio.
NA = not applicable.
Sources: INEL, 1992, and NUREG/CR-5759.

Table 7 Cost-benefit uncertainty results for remaining plant life of 40 years

Configu-ration	Alter-native	With onsite averted costs: Percent probability CBR < $1000/person-rem	With onsite averted costs: Percent probability CBR > $1000/person-rem	Without onsite averted costs: Percent probability CBR < $1000/person-rem	Without onsite averted costs: Percent probability CBR > $1000/person-rem
II	2	40	60	5	95
	3	<1	>99	<1	>99
	4	<1	>99	<1	>99
III	2	100	0	53	47
	3	91	9	16	84
	4	2	98	<1	>99
IV	2	100	0	53	47
	3	91	9	16	84
	4	2	98	<1	>99
V	2	NA	NA	NA	NA
	3	NA	NA	NA	NA
	4	<1	>99	<1	>99
VI	5	5	95	3	97
	5A	<1	>99	<1	>99
	6	14	96	4	96
	7	<1	>99	<1	>99
VII	5	100	0	39	61
	5A	97	3	15	85
	6	100	0	44	56
	7	44	56	7	93
VIII	5	100	0	39	61
	5A	97	3	15	85
	6	100	0	44	56
	7	44	56	7	93
Plant A	8	21	79	6	94
	9	100	0	71	29
	10	0	100	0	100
Plant B	8	>99	<1	11	89
	9	NA	NA	NA	NA
	10	1	99	<1	99
Plant C	8	NA	NA	NA	NA
	9	NA	NA	NA	NA
	10	15	85	3	97

Notes: CBR = cost–benefit ratio.
NA = not applicable.
Sources: INEL, 1992, and NUREG/CR-5759.

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11. ABSTRACT (200 words or less)

Highly combustible gases such as hydrogen, propane, and acetylene are used at all nuclear power plants. Hydrogen is of particular importance because it is stored in large quantities and is distributed and used continuously in buildings containing safety-related equipment. Large hydrogen releases at the hydrogen storage facilities or in these buildings could lead to fires or explosions that might result in loss of safety-related equipment. This report gives the regulatory analysis for the resolution of Generic Safety Issue 106, "Piping and the Use of Highly Combustible Gases in Vital Areas." Scoping analyses showed that the risk associated with the storage and distribution of hydrogen for cooling electric generators at boiling-water reactors (BWRs), the off-gas system at BWRs, the waste gas system at pressurized-water reactors (PWRs), and station battery rooms and portable bottles of combustible gas used for maintenance at PWRs and BWRs is small. On the basis of generic evaluations, the NRC staff has concluded that several possible methods to reduce risk could provide cost-effective safety benefits at some plants. However, in view of the observed large differences in plant-specific characteristics affecting the risk associated with the use of hydrogen, and the marginal generic safety benefit that can be achieved in a cost-effective manner, it is recommended that this generic issue be resolved simply by making these results available in a generic letter. This information may help licensees in their plant evaluations recommended by Generic Letter 88-20, Supplement 4, "Individual Plant Examination of External Events for Severe Accident Vulnerabilities," June 28, 1991.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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