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INFORMAL REPORT
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CONTAINMENT BUILDING HYDROGEN CONTROL METHODS RELATED TO DEGRADED CORE ACCIDENTS

A. L. Berlad*, M. Sibulkin**, and C. H. Yang*

Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

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*Permanent Address: State University of New York; Stony Brook, New York.

**Permanent Address: Brown University; Providence, Rhode Island.

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ABSTRACT

Degraded core accident-related release of hydrogen under some circumstances may threaten the integrity of pressurized water reactor containment buildings. This report provides a preliminary survey of a spectrum of possible approaches which could be adopted to maintain containment building integrity under accident conditions which lead to the release of hydrogen. Particular attention is directed to large, dry containment of the Zion and Indian Point designs. For any such possible accident, there exists a sequence of time intervals characterizing the accident scenario. This report considers the generic features of these intervals and discusses the suitability of various approaches to hydrogen accident control as related to the characteristics of the interval during which they are applied. It was found that various options exist for hydrogen control strategies and that their usefulness depends on the particular accident scenarios to be considered.

Of all the hydrogen control approaches considered, a strategy of continuous inerting of the containment building is the only one which clearly eliminates the combustion hazard, does not involve adverse environmental effects, and succeeds in a way that is independent of the accident scenario. This study does not consider the potential competing risks to personnel and has not made a cost-benefit analysis of this strategy. This study also has not considered venting and filtering the containment or innovational operator action which might occur if significant time is available.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

LIST OF FIGURES

FOREWORD

This Informal Report represents independent preliminary studies of a group of consultants on combustion technology to the Safety Evaluation Group (Department of Nuclear Energy) at Brookhaven National Laboratory. The Safety Evaluation Group is currently providing technical assistance to the Reactor Systems Branch (Office of Nuclear Reactor Regulation) at the Nuclear Regulatory Commission on the Severe Accident Mitigation Features Program for the Zion and Indian Point Plants (see NRC Memorandum, Action Plan for Indian Point and Zion, Harold R. Denton, March 17, 1980).

For the purposes of developing and preparing this report, BNL staff members provided the consultants with specific background information on the Zion and Indian Point Plants and with particular hypothetical accident conditions which were derived from components of the Severe Accident Mitigation Features Program. The accident conditions considered were based on very low probability hypothetical pipe break or transient-initiated scenarios which assumed either complete loss of off-site and on-site power for an indefinite period or failure of engineered safety systems and which led to full core meltdown with up to 100 percent in-vessel zirconium/steam reaction to produce hydrogen. An additional ex-vessel hydrogen source was obtained from an iron/steam reaction associated with water released from the concrete basemat of the reactor cavity as a result of its interaction with core debris. Large and rapid releases of hydrogen from the reactor vessel were assumed to result from a scenario in which nearly 100 percent zirconium reacted with steam and the release of hydrogen did not occur until the lower head of the vessel failed as a result of the core slumping to the lower head during meltdown. The scenarios also assume that there is no operator action to mitigate the course of the meltdown accident even though there may be significant time available before failure of the reactor vessel. It is to be emphasized that the severe accident conditions treated here are hypothetical and assume that certain sequences of events occur in spite of being highly improbable.

This report is limited in scope in that 1) the filtered-vented containment concept was not addressed and 2) a full comparative risk-benefit evaluation of the alternative hydrogen control strategies has not been performed.

1.0 INTRODUCTION

As a result of the accident at Three Mile Island, and from the results of related studies of hypothetical degraded core accidents, it is recognized that combustion of hydrogen may under some circumstances threaten the integrity of the reactor containment building. The present work is related to the current evaluation by NRC/NRR of severe accident mitigation features for Zion and Indian Point nuclear power plants. In this report we have made a preliminary survey of a spectrum of approaches which could be adopted to assure containment building integrity under conditions leading to the accidental release of hydrogen. In considering this problem, we have become increasingly aware of the present state of uncertainty regarding the amount and timing of the hydrogen release in a variety of potential accidents. It was found that various options exist for hydrogen control strategies and that their usefulness depends on the particular accident scenarios to be considered. Thus we have been led to structure this report in a manner which is independent of the specific accident scenarios. In assessing the advantages and disadvantages of various hydrogen control approaches, we have strongly favored methods which eliminate the combustion of accident-released hydrogen. This decision is based on several factors. The time history of the rate of hydrogen release is uncertain, although it may take several hours for hydrogen to be released into the containment from the time of initiation of the accident. The mixture composition associated with a given release of hydrogen will differ at various locations in the containment building due to nonuniform mixing. The transient pressure rise due to combustion of the nonuniform gas mixture may exceed the final equilibrium value calculated for a controlled deflagration.(1-5)

2.0 DISCUSSION OF THE STUDY APPROACH

A containment building whose normal operation is interrupted by an accident which includes a hydrogen release may be considered to experience a series of characteristic time periods. Correspondingly, the strategies available to deal with the safety hazards will vary from time period to time period. Figure 2.1 provides a schematic diagram of the sequence of characteristic time periods to be considered.

The descriptors which characterize the state (and integrity) of the containment building can vary according to the details of an accident scenario's time history and according to the strategies, devices and/or systems (control measures) employed to secure containment integrity. Control measures selected to deal with an accident-related release of H_2 will involve one or more of the five time periods. Accordingly, we will examine the possible utility of the various devices and/or systems that may prove useful to the safety system designer during each of these time periods.

2.1 Time Intervals for H_2-Related Accident Scenarios

Interval (I): This is the period during which operation of the plant is "normal" and all descriptors of the containment building are characteristically normal.

Interval (II): This time period (generally several hours) is bounded by the accident initiation event and by the point in time which corresponds to "Initiation of Significant H_2 Release." We may define the "significant H_2 release time" to be that point in time which separates the time regime wherein natural or induced combustion phenomena are considered to be insignificant (to any of these considerations) from the time regime wherein natural or induced combustion phenomena of significance may occur.

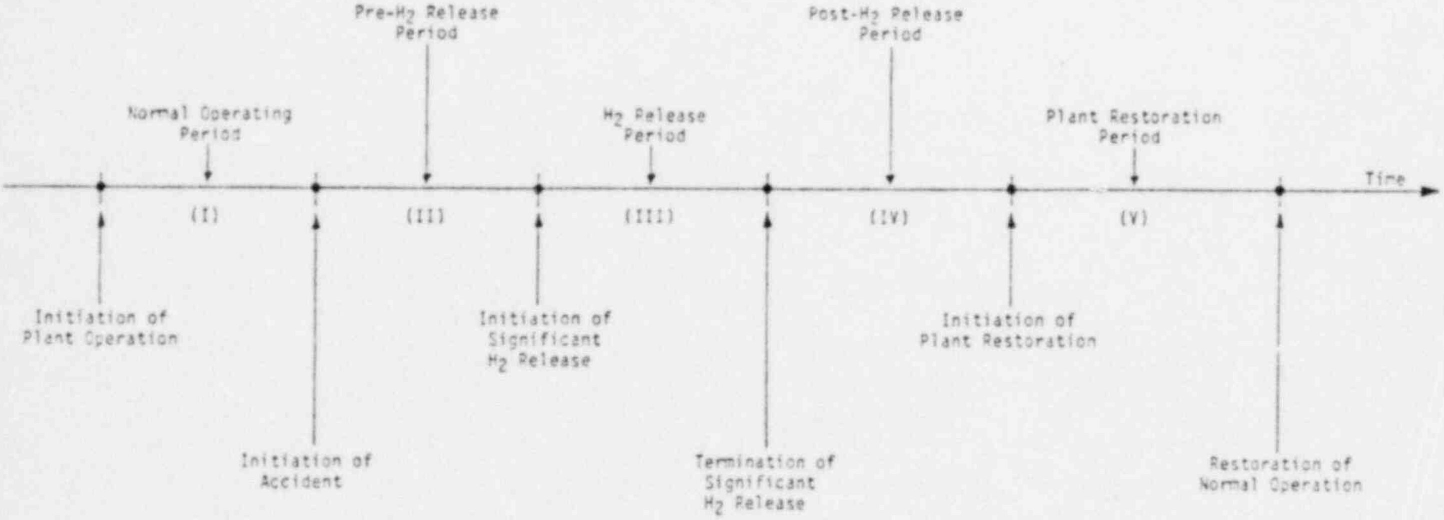

Figure 2.1: Time Intervals for H_2-Related Accident Scenarios.

Interval (III): This is the time period (generally several hours) during which all significant quantities of H_2 are considered to be released.

Interval (IV): This is the post-H_2 release period. It is required that at the termination of this period, the containment building will be free of all threats relating to possible future H_2-related phenomena, natural or induced.

Interval (V): This is the plant restoration period. It is required that during the entirety of this period, plant restoration may proceed unimpaired by threats relating to H_2-related phenomena, natural or induced.

2.2 Systems and Devices Available for Use in Securing Containment Building Integrity Related to Accidental Hydrogen Release

Possibly-useful systems and devices may be considered to be of one or more generic types. These generic categories, and the currently considered elements within each category, are listed below.

2.2.1 Combustion Systems and Devices for Inerting of Containment Building Atmosphere

- Atmospheric Burners
- Igniters
- Electrically Heated Furnaces
- Catalytically Assisted Burners and Recombiners
- Gas Turbine and/or Other High Pressure Combustion Devices

2.2.2 Inert Gas Addition Systems and Devices for Inerting of Containment Building Atmosphere

- (Water) Spray Systems
- N_2 Inerting Systems
- CO_2 Inerting Systems
- He Inerting Systems
- Halon Inerting Systems

2.2.3 Pressure Reduction Systems

- Coolers
- Ice - Condensers
- Water Spray Systems

3.0 STRATEGIES FOR H_2 CONTROL

We now consider the possible utility of the individual systems and devices (Section 2.2) as elements in safety-securing strategies that may be employed during one or more of the Time Periods (I)-(V), (Section 2.1). During any given time period, a given employable system/device need not prove to be a desirable adjunct to some overall strategy aimed at securing containment building safety. Some devices and/or systems may prove to be desirable adjuncts to one particular strategy, but less desirable to another. Ultimately, the desirability of any given system/device derives from its contribution to successful service of a control strategy which meets the essential requirements of safety, as well as those pertaining to capital and operating costs, reliability, environmental effects and public acceptability.

In view of the assumed threat to containment building integrity due to an accidental H_2 release, it is clear that any useful strategy must be initiated no later than sometime within Time Period (III). Some considered strategies may be initiated as early as the beginning of Time Period (I). All considered (H_2-related) strategies should be successfully consummated by no later than the end of Time Period (IV). We now consider the various principal strategies and their system/device adjuncts. These are arranged according to the time period during which their use may be initiated. The use of filtered-vented containment strategies is not considered in this report.

3.1 Strategies That Can Be Initiated During Period (I)

The general purpose of strategies initiated during Period (I) is to create and maintain, during all periods of operation, a containment atmosphere which is completely nonflammable. Systems and devices which may find initial use during Period (I) include:

(a) combustion systems for atmospheric inerting through removal of atmospheric oxygen (see 2.2.1) and possible addition of inert combustion products;

(b) noncombustion systems for atmospheric inerting through addition of inerting agents (see 2.2.2).

All these systems and devices reduce the oxygen concentration of the containment atmosphere. In addition, flammability may be further reduced by replacement of containment oxygen by combustion products which contain noncondensible inerting gas.

An inert atmosphere is defined here to be a gas mixture which will not support combustion under any possible amount of subsequent hydrogen addition. The use of this strategy has several major advantages:

- All hazards related to the burning of hydrogen are eliminated.
- No operator action is required during an accident.
- No equipment must be depended upon to operate properly during an accident.
- No power is required during an accident.

All continuous inerting systems which have been proposed have the operational disadvantage that workers within the containment building must be provided with auxiliary breathing apparatus. Recent work sponsored by the NASA Technology Utilization Office has led to the development of improved individual breathing systems (with an intended application of use by firefighters). A current commercial system (Scott Air-Pak 4.5) weighs 23 pounds and is rated for 30 minutes. For operational needs exceeding 30 minutes, a combination of air supplies external to the individual worker combined with small, individually carried emergency cylinders seems feasible.

3.1.1 Continuous Inerting by Gas Turbine or Other Combustion Utilizing Systems

Continuous inerting of a containment atmosphere by these methods requires combustion devices which can partially consume the oxygen concentration. External source fuel may be employed to achieve this during Time Interval (I). In general, external source-fueled devices, located within the containment building, would tend to "blow-out" (combustion extinction) at containment atmosphere oxygen concentrations higher than those associated with the particular fuel's flammability limits.(5) Accordingly, if containment atmosphere non-fuel concentrations are to guarantee nonflammability for all possible accidental H_2 concentrations that may be subsequently encountered, this kind of Time Interval (I) strategy must utilize combustion systems fed by external supplies of fuel and, at least in part, fed by external supplies of oxidizer. Gas turbines as well as other devices can be so operated.

Inasmuch as Time Period (I) is lengthy, the scale (size and cost) of the equipment required to achieve the desired degree of inerting is relatively small. The gas turbine has several very desirable features.

- Its technology is highly developed and reliable.
- It can achieve second law efficiencies of some 30%-40%, thereby permitting lower rates of containment heating than is possible with more typical, non-work-producing combustion devices.
- Its power per unit volume is high, corresponding to a high pressure combustion chamber operation.

The two most prominent fuel types to be considered for such continuous (combustion-maintained) inerting are H_2 and some typical hydrocarbon. Hydrogen is the easiest to burn. Hydrocarbon combustion will inject CO_2 into the atmosphere (a noncondensible inert) as well as consume atmospheric oxygen (to a required extent). In general, controlled H_2 combustion is easier to make nonpolluting and environmentally acceptable.

Where this strategy is to be invoked (combustion-supported inerting initiated at the beginning of Interval (I)), initiation of the accident (Interval (II)) may or may not cause the inerting system to become inoperative. Nevertheless, inerting during Interval (I) (e.g., reduction of atmospheric oxygen to only 4 percent, by use of a hydrogen fueled combustion device) would make further inerting during Time Intervals (II) and (III) unnecessary. Hydrogen cleanup during Period (IV) may be carried out by use of one or more small combustion devices supported, in part, by external fuel and oxidizer supplies. Small catalytically assisted burners and/or recombiners may also be used successfully during the Period IV cleanup of containment atmosphere hydrogen.

Comment on this method: All required operational actions are restricted to Time Periods (I) and (IV). These are lengthy time periods characterized by no significant intrusion of rapidly changing operational conditions. Accordingly, small, low-cost combustion devices can be predictably and reliably employed. Drawbacks to the method include the thermal and possible compositional pollution of the atmosphere which derive from combustion. The oxygen-deficient containment atmosphere of Interval (I) would require breathing support gear for personnel required to work there. As with other continuous inerting strategies, this method appears to be very reliable.

3.1.2 Continuous Inerting by Systems Utilizing Inert Gas Addition

Continuous inertion can be achieved by the use of the commercial gases CO_2 and N_2. Mixtures of H_2/Air/CO_2 are inert for any admixture of H_2 when the oxygen content in the original atmosphere is less than 8 percent(6) (by volume). The corresponding figure for H_2/Air/N_2 mixtures is 5 percent.* Since this is below the limit for human operation, it appears desirable to keep the oxygen concentration in an inert atmosphere well below the combustion boundary.

Continuous inertion by gas addition requires an on-site source of gas to make up for any losses. The amount of inert gas used depends upon the building leak rate. A design leak rate at maximum containment building working pressure of some 10^{-3} per day by volume has been specified. Using a leak rate of 10^{-4} per day as a conservative estimate means that 260 ft^3/day of containment gas must be inerted. Thus gas leakage requires only minor equipment and expense.

Special procedures would have to be devised for replacement of air by CO_2 or N_2 at the initiation of plant operation.

It should be noted that inertion by the use of helium has been previously suggested. There do not appear to be any advantages to the use of helium for inerting.

Another approach to continuous inerting by gas addition is the use of Halons, e.g., Halon 1301 (CF_3Br). Inertion limits for H_2/Air/CF_3Br mixtures have not been adequately determined.(8) Various relevant data suggest that the inertion limit will not be less than 20 percent(9) (by volume) at atmospheric pressure. At this concentration level, continuous human operation is not possible. Inhalation of 5 to 6 percent concentrations for 4 or 5 minutes is the manufacturer's recommended exposure limit [DuPont Bulletin S-35A]. Thus there does not appear to be any advantage to the use of Halons in Period

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*The minimum oxygen partial pressure for safe human operation corresponds to an oxygen concentration(7) of 16 percent (pressure altitude = 8,000 ft).

(I). There is a disadvantage to the continuous use of Halons in that leakage is environmentally undesirable since Halons adversely affect the stratospheric ozone layer.

3.2 Strategies That Can Be Initiated During Period (II)

Period (II) is a time interval of uncertain length. In general, the duration of Period (II) can be expected to be orders of magnitude shorter than either Period (I) or Period (IV). For a major pipe break accident, this time interval may be only of the order of one hour. Devices and systems which must achieve their functional objectives during this period will have to:

(a) survive the accident,

(b) be of sufficiently large capacity to complete their Period (II) objectives in a short time,

(c) be restricted in their use by containment building pressure and temperature constraints.

3.2.1 Noncontinuous Inerting by Combustion Utilizing Systems

The conditions and constraints on the performance of a gas turbine (or other combustion) system are much more demanding than those encountered by this kind of device, as applied to a Period (I) strategy (see 2.2.1). A pipe break accident may engender pressure increases (above normal) of the containment building. Hot exhaust products (condensible for the case of externally supplied hydrogen fuel, partially noncondensible for the case of a hydrocarbon fuel) may serve to significantly raise the containment building pressure. This could be unacceptable. Performance must be adequate to assure that:

(a) Hydrogen release and/or combustion phenomena to be dealt with during Periods (III) onward will not lead to unacceptable pressure/temperature conditions.

(b) The functioning of combustion equipment is unimpaired by the accident itself or by post accident containment conditions. Where inadequate inerting is achieved during Period (II), continuing the use of this equipment into Period (III) may prove dangerous.

Comment on this method: Large capacity equipment is needed to complete its mission during a brief time period under difficult conditions. Implementation of such a strategy may also involve unacceptably large pressure increases in Period (II) containment building environment.

3.2.2 Inerting by Systems Utilizing Inert Gas Addition

During this period, gas within the containment building cannot be discharged to the atmosphere unless vented through a filter. Thus, addition of an inert gas during Period (II) would tend to raise the pressure in the containment building. This is a major disadvantage which argues against the use of the massive amounts of CO_2 and N_2 needed for inertion.*

Since a much smaller addition of Halon is needed to obtain an inert mixture, the resultant pressure increase might be tolerable if H_2 combustion prevention is sufficient to insure containment integrity. Before detailed consideration of this system can be made, more detailed data must be available on the inertion capabilities of Halons, particularly at all possible containment vessel pressure and temperature conditions. Such a system would need operator action (unless initiated for all accidents). Power may be required to operate flow valves.

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*Addition from standard stored liquid CO_2 or N_2 tanks would cause an initial pressure reduction because of the low temperature of the entering gas. However, since an accident is not restricted to short times, external heat input to a cold gas mixture would raise the mixture pressure.

3.2.3 Pressure Reduction Systems

Pressure reduction systems for unvented buildings achieve their goals through atmosphere cooling. Cooling of both condensible and noncondensible atmospheric gases leads to reduction of all partial pressures. For Zion-Indian Point type containment buildings, there are two primary systems to be considered: coolers and water spray systems. The expected pressure reduction effects to be derived from selected operation of coolers have been investigated at BNL and preliminary results were presented at the NRC Information Exchange Utilities Meeting on Zion and Indian Point (May 20, 1980) and a more detailed report will be issued shortly.

The introduction of a cold water spray into a hot containment atmosphere affects the pressure in two ways. Absorption of heat in the water vaporization process reduces the temperature, and thus the pressure of the gas mixture. The volume change of the water from liquid to vapor increases the pressure of the gas mixture. Calculations based upon an assumption of thermodynamic equilibrium show a net decrease in pressure as desired. The possible existence of positive pressure transients during the nonequilibrium evaporation process needs to be investigated. If a water spray strategy is to be used in Period (III), the limited supply of available water (if recirculation is not effective) may be exhausted by its use in Period (II).

3.3 Strategies That Can Be Initiated During Period (III)

Strategies that are to be initiated during Period (III) are generally responsive to the accident-related hydrogen release scenario. Period (III)-initiated strategies frequently imply combustion of accident released hydrogen as well as partial removal of the containment atmosphere's oxygen concentration. Inerting by systems utilizing gas addition generally requires a system of sufficient capacity and reliability to achieve an atmosphere that is nonflammable and/or nondetonable in a short time. Separately or in conjunction with one or more of the above systems, pressure reduction systems may be utilized. Pressure reduction systems frequently considered include water spray systems, coolers, and ice-condensers.

3.3.1 Combustion Utilizing Systems

The purpose of such systems is generally to prevent unacceptable pressures within the containment building which might otherwise be induced by explosions and/or detonations. For local hydrogen concentrations that are lower than those associated with the flammability limits, catalytically-assisted or furnace-assisted combustion processes are possible. Combustion devices fueled by external sources (e.g., hydrogen or a hydrocarbon) may also be employed. In view of the unvented nature of the building, rapid combustion during Period (III) implies very slow natural cooling of the combustion products. Thus, combustion devices which employ external sources of fuel may impose additional pressure and temperature loading on the containment building. Devices and systems which burn hydrogen fuel only (both internal and external sources of hydrogen) can, if used with adequate coolers, reduce atmospheric pressure (condensible combustion products) as well as serve to inert the atmosphere (removal of both hydrogen and oxygen). For containment building hydrogen concentrations which are within the flammable range, the full range of combustion devices (e.g., see 2.2.1) may be employed to initiate and promote combustion. Where containment building flammability conditions are possible, inerting by combustion may involve one or more of the following difficulties:

(a) Ignition of a spatially nonuniform distribution of hydrogen-air mixtures may occur. Although the spatially-averaged mixture ratio may be nondetonable, local concentrations may be within the detonable range.

(b) Rapid combustion via any phenomenon (explosion, flame propagation, detonation, etc.) leads quickly to adiabatic heating and pressurization of the containment building.

(c) Rapid combustion via phenomena which involve near-sonic or supersonic (detonation) wave forms may provide dynamic pressure and temperature transients which are considerably higher than those associated with the ultimate adiabatic values.

(d) Accidental hydrogen release rates and the associated compositional nonuniformity within the containment building cannot be fully determined. Correspondingly, the combustion behavior of containment building atmospheric combustibles is not fully determined.

(e) Peak values of combustion-generated pressure increments may not be significantly suppressed by cooling systems since cooling rates are generally very slow compared to heating rates associated with rapid combustion phenomena.

(f) Accident-related impairment of the devices to be employed must not be allowed to occur.

3.3.2 Inerting by Systems Utilizing Inert Gas Addition

The discussion provided in Section 3.2.2 provides the elements which apply to possible inert gas addition strategies for Period (III).

3.3.3 Pressure Reduction Systems

Pressure reduction through atmospheric cooling has previously been discussed in Section 3.2.3. The successful use of this strategy demands that the available rate of cooling is rapid compared to the rate of pressure rise caused by the accident. This criterion is expected to be satisfied in Period (II) where the increase in pressure is caused by steam generation from water leakage. However, the rate of pressure rise from a combustion event in Period (III) will exceed normal cooling rates. Thus the success of this strategy depends upon being able to burn limited amounts of hydrogen at intervals exceeding the operational times associated with the cooling devices used.

4.0 CONCLUDING REMARKS

It was found that various options exist for hydrogen control strategies and that their usefulness depends on the particular accident scenarios to be considered. A general conclusion which emerges from our preliminary survey study is that strategies initiated after an accident give less assurance of maintaining the integrity of the containment building because of the accident-related uncertainties characterizing Periods (II) and (III) than a strategy of continuous inerting begun in Period (I). In particular, strategies dependent on the controlled burning of accident-released hydrogen may result in overpressures if burning does not occur in a controlled manner at the desired time(s). A strategy of continuous inerting begun in Period (I) eliminates the hazard from combustion of hydrogen. This strategy appears to meet the essential requirement of improved safety. A quantitative cost study of the capital and operating costs associated with containment building modification is beyond the scope of the present investigation. The problems of manned operation in a non-breathable environment have been in principle solved by other technologies. It should be noted, however, this study does not consider the potential competing risks to personnel resulting from this strategy.

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DISTRIBUTION LIST

Dr. Raymond Alcouffe (1)
Los Alamos Scientific Laboratory
Mail Stop 269
P. O. Box 1663
Los Alamos, New Mexico 87545

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Sandia Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87115

Mr. Robert M. Bernero, Director (1)
Division of Systems & Reliability Research
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Walter R. Butler, Chief (1)
Containment Systems Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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University of California
at Los Angeles
Los Angeles, California 90024

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Division of Systems Integration
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Washington, D. C. 20555

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Washington, D. C. 20555

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Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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Operational Safety Research Branch
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Accident Evaluation Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. William V. Johnston, Chief (1)
Core Performance Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. William Kastenberg (1)
Department of Chemical Nuclear
and Thermal Engineering
University of California
at Los Angeles
Los Angeles, California 90024

Dr. Charles N. Kelber, Assistant Director (1)
for Advanced Reactor Safety Research
Division of Reactor Safety Research
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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Research & Standards Coordination Branch
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. William E. Kreger, Assistant Director (1)
for Radiation Protection
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. James F. Meyer (12)
Reactor Systems Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Warren Minners, Technical Assistant (1)
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. Robert Minogue, Director (1)
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Thomas Murley, Director (1)
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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for Operating Reactors
Division of Licensing
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
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Systems Analysis Branch
Division of Systems & Reliability Research
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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for Reactor Systems
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

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for Generic Projects
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
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Experimental Safety Technology Branch
Division of Reactor Safety Research
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. Themis P. Speis, Chief (1)
Reactor Systems Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Victor Stello, Director (1)
Office of Inspection & Enforcement
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. John F. Stolz, Chief (1)
Systems Interaction Branch
Division of Systems Integration
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. David G. Swanson (1)
Applied Science Associates, Inc.
P. O. Box 214
Hawthorne, California 90250

Mr. Ashok Thadani, Chief (1)
Reliability & Risk Assessment Branch
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dr. Theo G. Theofanous (1)
132 Pathway Lane
Lafayette, Indiana 47906

Dr. Long Sun Tong, Chief Scientist (1)
Assistant Director for Water Reactor
Safety Research
Division of Reactor Safety Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Steven A. Varga, Chief (1)
Operating Reactors Branch No. 1
Division of Licensing
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. Richard H. Vollmer, Director (1)
Division of Engineering
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

	BNL Distribution
DNE Chairman	(1)
DNE Deputy Chairman	(1)
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Safety Evaluation Group	(8)
Nuclear Safety Library	(2)