Resolution of Unresolved Safety Issue A-48, "Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment"

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

C. M. Ferrell, L. Soffer

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Resolution of Unresolved Safety Issue A-48, "Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment"

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ABSTRACT

Unresolved Safety Issue (USI) A-48 arose as a result of the large amount of hydrogen generated and burned within containment during the Three Mile Island accident. This issue covers hydrogen control measures for recoverable degraded-core accidents for all boiling-water reactors (BWRs) and those pressurized-water reactors (PWRs) with ice-condenser containments. The Commission and the nuclear industry have sponsored extensive research in this area, which has led to significant revision of the Commission's hydrogen control regulations, given in Title 10, *Code of Federal Regulations*, Part 50 (10 CFR 50), Section 50.44. BWRs having Mark I and II containments are presently required to operate with inerted containment atmospheres that effectively prevent hydrogen combustion. BWRs with Mark III containments and PWRs with ice-condenser containments are now required to be equipped with hydrogen control systems to protect containment integrity and safety systems inside containment. Industry has chosen to use hydrogen igniter systems to burn hydrogen produced in a controlled fashion to prevent damage. An independent review by a Committee of the National Research Council concluded that, for most accident scenarios, current regulatory requirements make it highly unlikely that hydrogen detonation would be the cause of containment failure. On the basis of the extensive research effort conducted and current regulatory requirements, including their implementation, the staff concludes that no new regulatory guidance on hydrogen control for recoverable degraded-core accidents for these types of plants is necessary and that USI A-48 is resolved.

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EXECUTIVE SUMMARY

Unresolved Safety Issue (USI) A-48 arose as a result of the large amount of hydrogen that was generated and burned within containment during the Three Mile Island Unit 2 (TMI-2) accident in 1979. As a result of the degraded-core accident, approximately 1000 pounds of hydrogen generated by the hot zirconium fuel cladding reacting with steam and water within the pressure vessel produced hydrogen that was later ignited by an unknown source in the containment building producing a 28 psi pressure pulse. Depending upon the hydrogen concentrations, this combustible gas can deflagrate or detonate. Either of these processes can affect containment integrity and/or the operation of safety equipment within containment. USI A-48 covers hydrogen control measures for recoverable degraded-core accidents for all boiling-water reactors (BWRs) and pressurized-water reactors (PWRs) with ice condenser containments.

Following the TMI Unit 2 accident, the Commission and the nuclear industry initiated extensive research programs to control hydrogen produced during degraded-core conditions. This research has led to a significant revision of the Commission's hydrogen control regulations in 10 CFR 50.44. This rule requires that BWRs with Mark I and Mark II small volume containments operate with inerted containment atmospheres. The intermediate volume containments include BWRs with Mark III containments and PWRs with ice-condenser containments. These are required to be equipped with hydrogen control systems to protect containment integrity and safety-related equipment within containment. The nuclear industry has chosen to implement this requirement by the use of hydrogen igniter systems to burn the hydrogen in controlled combustion at low concentrations to prevent the formation of explosive mixtures. Because of the increased containment volume for hydrogen dilution, the large, dry containment types, such as TMI Unit 2, were not included in USI A-48 pending completion of both industry and the NRC hydrogen research programs. Reactor containments of this type are currently being evaluated under Generic Issue (GI) 121 "Hydrogen Control for Large, Dry PWR Containments."

The Commission sponsored an independent review of the hydrogen research program studies conducted by the National Research Council Committee on Hydrogen Combustion. The committee's conclusions and recommendations were published in the report entitled "Technical Aspects of Hydrogen Control and Combustion in Severe Light-Water Reactor Accidents" in 1987. The committee concluded that, for most accident scenarios, current regulatory requirements make it highly unlikely that hydrogen detonation would be the cause of containment failure. They further concluded that the presence of an inert atmosphere is a satisfactory approach to the prevention of detonations and that the use of igniters in intermediate volume containments is a reasonable way to reduce the probability of detonation.

On the basis of the extensive research effort conducted by the NRC and the nuclear industry, current regulatory requirements, including their implementation and the independent review by the National Research Council Committee on Hydrogen Combustion, the staff concludes that no new regulatory guidance on hydrogen control for recoverable degraded-core accidents (like that which occurred at TMI Unit 2) for these types of plants is necessary and that USI A-48 is resolved.

1 INTRODUCTION AND BACKGROUND

Unresolved Safety Issue (USI) Task Action Plan A-48, "Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment," was established in 1980 to provide a focus for the Nuclear Regulatory Commission's (NRC's) rulemaking and technical review efforts associated with hydrogen control. The issue is concerned with hydrogen control under degraded-core conditions in the small volume, boiling-water reactor (BWR) Mark I and Mark II pressure-suppression containments and the intermediate volume, pressurized-water reactor (PWR) ice-condenser and BWR Mark III pressure-suppression containments.

The major elements of this issue include (1) rulemaking efforts for the Mark I and Mark II containments, (2) rulemaking efforts for the Mark III and ice-condenser containments, (3) confirmatory research, and (4) licensing implementation reviews of the lead plants with Mark III and ice-condenser containments.

Large, dry PWR containments have been excluded from USI A-48 because such containments have a much greater ability to accommodate the large quantities of hydrogen associated with a degraded-core accident than the small Mark I, II, and III and ice-condenser containments. Most dry containments have about 2 million or more cubic feet of net free volume. The design pressure for large containments ranges from about 45 to 60 psi. Analyses performed on the Zion and Indian Point plants show that the pressure capabilities are greater than twice the design pressures. Preliminary calculations were performed to determine the pressure in a dry containment resulting from the combustion of hydrogen corresponding to a 75-percent metal-water reaction following onset of a degraded-core accident and while the containment is still near its peak pressure. These calculations for a dry containment indicated a peak total pressure below the failure pressure. Furthermore, various preliminary analyses indicated that essential equipment would function during and after a large deflagration in a dry containment. This conclusion was supported by the Three Mile Island Unit 2 (TMI-2) experience.

On the basis of the above, the staff determined that degraded-core hydrogen control problems in dry containments were not serious enough to warrant their consideration in either the hydrogen control rule related to degraded-core accidents or in USI A-48. However, hydrogen control for large, dry containments has been assigned Generic Issue Number 121 and will be evaluated for rulemaking once research is completed.

USI A-48 includes 24 reactors with Mark I containments, 9 reactors with Mark II containments, 6 reactors with Mark III containments, and 10 reactors with ice-condenser containments. The list of plants included is listed in Appendix A to this report. These represent about 45 percent of the nuclear power plants licensed in the United States. Appendix B provides a list of the documents reviewed during the resolution of this issue.

Considerations of the design-basis loss-of-coolant accident (LOCA) led to the original requirements for hydrogen control measures to provide the capability to control hydrogen accumulation from accidents within a reactor containment. These control measures were established before the TMI-2 accident in 1979. In the event of a design-basis LOCA in a light-water reactor plant, combustible gases, principally hydrogen, may accumulate inside the primary reactor containment as a result of (1) metal-water reaction involving the fuel element cladding, (2) the radiolytic decomposition of the water in the reactor core and the containment sump, (3) the corrosion of certain construction materials resulting from the spray solution, and (4) any synergistic chemical, thermal, and radiolytic effects of post-accident environmental conditions on containment protective coatings and electric cable insulation.

Because of the potential for significant hydrogen generation as the result of a LOCA, Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.44, "Standards for Combustible Gas Control Systems in Light-Water-Cooled Power Reactors," and General Design Criterion 41, "Containment Atmosphere Cleanup," in Appendix A to 10 CFR Part 50 require that systems be provided to control hydrogen concentrations in the containment atmosphere following a postulated design-basis LOCA to ensure that containment integrity is maintained. The amount of hydrogen to be controlled as a result of a LOCA was specified in 10 CFR 50.44 (D)(d)(1) to be that amount produced by a metal-water reaction involving fuel cladding in which there was degradation but not total failure of the emergency core cooling system.

Conventional hydrogen control systems (for example, recombiners) were installed in nuclear power plants to provide the capability to control hydrogen and oxygen accumulation as a result of radiolytic decomposition of water, corrosion of metals inside containment, and hydrogen producing reactions of coatings and insulation. The design capability or margin to control the contribution of hydrogen accumulation resulting from a metal-water reaction involving the fuel cladding is provided in PWR facilities by the relatively large net free volume inside the containment structure. This control is provided in BWR facilities with small volume pressure-suppression containments of the Mark I and II designs by inerted containments. For the PWR plants, the containment free volume is large enough to prevent the hydrogen generated and released from the cladding reaction from reaching a uniform concentration approaching the lower limit of flammability because the amount of metal-water reaction is postulated to be small (that amount consistent with a design-basis accident). Also, the rate of hydrogen release as a result of the cladding reaction specified in 10 CFR 50.44 (D)(d)(1) was assumed to be rapid following a postulated accident (on the order of minutes). This corresponds to a release rate beyond the capability of hydrogen control systems such as recombiners. However, the containment net free volume was found to be sufficient for providing the initial protection, and hydrogen control systems (recombiners) could be actuated later to control hydrogen accumulation from other sources to gradually reduce the hydrogen concentration inside containment.

About 10 hours after the onset of the TMI-2 degraded-core accident on March 28, 1979, a 28 psig containment pressure pulse was recorded in the control room. Post-accident analysis indicated that this pressure pulse was due to the accidental ignition (deflagration) of approximately one-half ton of hydrogen gas that had been generated by hot zirconium fuel cladding materials reacting with steam or water. The heat generated damaged plastics, rubber, and paint. The pressure pulse bent elevator doors, forced open stairwell doors, and crushed barrels stored within the reactor containment. The estimated hydrogen concentration at the time of ignition was about 8 volume percent. The quantity of hydrogen released from the core was well in excess of that that had been specified in 10 CFR 50.44.

Following the TMI-2 accident, analysis showed that the maximum quantities of hydrogen that could be released (assuming reaction of 100 percent of the fuel element cladding with water) were about 2200 pounds and 4400 pounds for PWRs and BWRs, respectively. The TMI-2 accident is estimated to have produced an amount of hydrogen resulting from about 45 to 50 percent of the fuel cladding reacting with water or steam. The zirconium-water reaction is exothermic with a heat of reaction of 6500 KJ/Kg of zirconium. The reaction rate increases rapidly above temperatures of 2500°F. Hydrogen is flammable in the range of 4.0 to 75 volume percent and detonable in the range of 18 to 59 volume percent. (Recent Sandia National Laboratory tests and analytical extrapolations to large scales have indicated that detonability may be attained at values as low as 9.5 volume percent under certain conditions.)* Hydrogen combustion can contribute to containment failure by overpressurization and to equipment failure resulting from thermal and pressure effects.

As the previous discussion has shown, concerns regarding hydrogen generation under accident conditions have occupied a significant place in the NRC's research and regulatory activities over the last 10 years. Resolution of USI A-48 has resolved hydrogen concerns for a large class of accidents beyond the design basis. However, resolution of USI A-48 should not be taken to imply that all research or regulatory actions on hydrogen control are complete. The following discussion provides a brief overview of those ongoing research and regulatory areas with regard to hydrogen generation, combustion, and control, primarily in the area of low-probability severe accidents.

Hydrogen research being carried out by the NRC today is primarily in connection with conditions associated with a severe accident (that is, accident conditions involving a molten core and leading to hydrogen generation greater than the amount of metal-water reaction of the fuel cladding typically associated with a degraded core). The areas of major emphasis include computer code assessment and particularly hydrogen transport after generation and the potential for stratification leading to localized volumes having a high hydrogen concentration. In addition, hydrogen research into the effect of temperature upon detonation limits, especially the potential for a reduction at elevated temperatures in the hydrogen concentration necessary to achieve a detonation, is being pursued.

Closure of severe accident issues is being pursued in accordance with the Commission's Severe Accident Policy Statement (50 FR 32138) issued on August 8, 1985, and via an overall integration plan (SECY 88-147) presented by the NRC staff. Regulatory resolution of hydrogen concerns, among others, arising out of a consideration of severe accidents is being carried out under the auspices of the severe accident implementation effort. A major element of this integration plan is the Containment Performance Improvement (CPI) Program. This effort is intended to examine and assess each containment type for potential generic vulnerabilities with regard to severe accidents and to determine what, if any, generic improvements are warranted.

As part of this program, resolution of the question of the need for redundant power supplies for igniter systems in the event of a station blackout will be addressed. In addition, resolution of the need for hydrogen control requirements for large, dry containments, presently being investigated separately as Generic Issue 121 (GI-121), also will be incorporated into the CPI Program. Finally, hydrogen concerns for all reactor types under severe accident conditions will be addressed as part of the CPI Program.

Questions of hydrogen control requirements also arise in connection with licensing of future reactors. This activity is being pursued as part of the NRC staff review of the Electric Power Research Institute's (EPRI's) document on advanced light-water reactor (ALWR) requirements. At the present time, the staff review is not complete and

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*A description of these tests is provided in Sandia Report SAND/88-0680C, "A Critical Review of High-Temperature Hydrogen Combustion in Reactor Safety Applications," by Douglas W. Stamps and Marshall Berman, October 1988.

has not reached a position on hydrogen control requirements for such reactors.

2 RESOLUTION

2.1 Rulemaking

As a result of the TMI-2 accident, it became apparent that additional hydrogen control and mitigation measures would have to be considered for nuclear power plants with small and intermediate containments. This topic was first addressed in the TMI-2 Lessons Learned Task Force: Status Report and Short-Term Recommendations (NUREG-0578, July 1979) and subsequently included in the TMI Action Plan, NUREG-0660 (Item II.B.7), dated May 1980. As a result of these considerations, it was determined that rulemaking proceedings should be undertaken to define the manner and extent to which hydrogen evolution must be taken into account in plant design and operation.

(1) Small Containments

The small containments include the Mark I and Mark II containments for BWRs. Their design pressures range from about 45 psig to 62 psig for net free volumes ranging from about 200,000 to 300,000 cubic feet. Because containment failure would be a likely result of the combustion of the hydrogen produced by a metal-water reaction involving more than 6 to 9 percent of the fuel cladding, the Commission determined that the containment atmosphere for these units should be inerted. A proposed interim rule implementing this decision was published in *The Federal Register* on October 2, 1980 (45 FR 65466). Inerting the containment atmosphere (by addition of a combustibly inert gas, such as nitrogen) effectively precludes combustion of any hydrogen generated.

The requirements for BWR Mark I and Mark II containment types were published in the form of a final rule (46 FR 58484) on December 2, 1981. These requirements include an inerted containment atmosphere for Mark I and II containments plus provision for either an internal recombiner or the ability to install an external recombiner. Generic Letter 84-09 waived the recombiner requirements of the rule for Mark I containments with purge/repressurization systems, providing certain technical criteria are satisfied. These criteria, in essence, are intended to provide assurance that the containment remains in an inerted state following an accident. This final rule is attached as Appendix C to this report.

The Mark I and II containments for BWR reactors have operated safely for a number of years with an inert containment atmosphere. USI A-48 with respect to Mark I and II containments is complete.

(2) Intermediate Size Containments

Reactors with intermediate size containments include the ice-condenser containments for PWRs and the Mark III containments for BWRs. Their design pressures range from 12 to 15 psig and their volumes from 1.2 to 1.7 million cubic feet. Some extensive structural response analyses have shown that the ice-condenser containments can withstand up to 45 psig without failure. If combustion initiation resulting from ignition sources is assumed to occur at the least favorable time, containment failure would be a likely result of adiabatic combustion of the hydrogen produced by a metal-water reaction involving more than 25 percent of the fuel cladding. The Commission, therefore, found it prudent to require hydrogen control measures for these intermediate size containments.

A proposed rule for BWR Mark III and PWR ice-condenser containments was published for public comment on December 23, 1981 (50 FR 62281). This rule, attached as Appendix D, includes a statement of considerations that explains the bases and requires that all reactors with Mark III or ice-condenser containment types install hydrogen control systems capable of accommodating an amount of hydrogen equivalent to that generated from a 75-percent metal-water reaction of the active fuel cladding without loss of containment structural integrity. This quantity of hydrogen was generally considered to bound the quantity generated by degraded-core events such as the TMI-2 accident. The final rule for BWR Mark III and PWR ice condenser containment types was published on January 25, 1985, and is attached as Appendix E to this report.

2.2 Licensing Implementation

2.2.1 Lead Plant Reviews

The first plants to be licensed with installed hydrogen control systems (igniters) were Sequoyah with an ice-condenser containment and Grand Gulf with a Mark III containment. Sequoyah is owned by the Tennessee Valley Authority (TVA) and Grand Gulf is now owned by System Energy Resources, Inc. (SERI) and South Mississippi Electric Power Association (SMEPA), with 90 percent and 10 percent ownership, respectively. These became the lead plants for implementing the rule requiring hydrogen control systems.

The rule specified the amount of metal-water reaction to be accommodated from a degraded-core accident, but did not specify how this was to be achieved. TVA proposed that this be done by a system of 68 igniters located throughout the Sequoyah containment. The igniters are intended to burn hydrogen in a controlled fashion if it reaches the lower flammability limit, thereby preventing the accumulation of explosive concentrations. These igniters are powered by Class 1E power panels that have normal and alternate power supplies from offsite sources. In the event of a loss of offsite power, the igniters would receive power from the emergency diesel generators. When activated, these igniters have a surface temperature of approximately 1700°F. These igniters are strategically located throughout the containment volume.

The Grand Gulf hydrogen control system consists of 90 diesel engine glow plugs distributed throughout the containment drywell, wetwell, and upper compartment. The igniters are powered from Class 1E power panels that have normal and alternate ac power supply from offsite sources. In the event of loss of offsite power, the igniters would be powered from the emergency diesel generators. These plugs also operate at a temperature of 1700°F when activated. This igniter system can be manually actuated from the control room upon an indication that the water level has fallen to the level at the top of the active fuel or below.

Licensing implementation of the proposed igniter systems on the two lead plants (Sequoyah and Grand Gulf) was included as part of USI A-48 to provide the staff with demonstrated assurance of the effectiveness and ability of such systems to control hydrogen for actual plants under accident conditions. Extensive research programs carried out since 1980 by both the nuclear power industry and the NRC provide the bases for these hydrogen control systems. This research (1) examined hydrogen generation, distribution, and mixing within containment, (2) assessed hydrogen mitigation systems and the capability of the containment and safety-related equipment to withstand hydrogen burns and detonation, and (3) correlated the results of hydrogen combustion analysis with experimental data using computer programs. This research is discussed more fully in the following reviews of Sequoyah and Grand Gulf.

(1) Sequoyah Ice Condenser Review

TVA proposed and installed within the Sequoyah Unit 1 and 2 containments a system of igniters and ancillary equipment. This system is referred to as the interim distributed ignition system (IDIS) and is designed to provide a controlled burning of hydrogen in the event that large quantities of hydrogen are generated as a result of a degraded-core accident. The effectiveness of this hydrogen control system has been and is continuing to be investigated in a series of research programs that started in 1980. This research includes hydrogen generation and its distribution within containment. This system was installed by TVA and reviewed and approved by the NRC staff as a condition of the licensee being allowed to exceed 5 percent power. The staff's interim approval of the IDIS was to be followed by a review of the final system before startup following the first refueling outage. As a part of this interim review, industry and NRC studies were conducted to investigate the effectiveness of igniter systems to handle large hydrogen releases. Preliminary testing and analyses performed by TVA and augmented by NRC confirmatory analyses and testing were used as the bases for evaluating the glow plug igniter system.

A detailed description of the staff's review of the Sequoyah IDIS is provided in NUREG-0011, in Supplements 2 through 6, "Safety Evaluation Report (SER) Related to the Operation of Sequoyah Nuclear Plant, Units 1 and 2, Docket Nos. 50-327 and 50-328." In these supplements, the staff concluded that there was reasonable assurance that the IDIS was adequate to control hydrogen from a TMI-2 type degraded-core accident, pending the outcome of the review of ongoing research.

Following review of the Sequoyah interim system, the staff identified several technical issues requiring additional work before final approval of the Sequoyah permanent hydrogen mitigation system (PHMS). These issues were

- consideration of a spectrum of accidents beyond the base-case scenario assumed in the interim evaluation
- design criteria for the permanent hydrogen control system
- revised containment atmosphere pressure and temperature analyses
- equipment survivability
- combustion phenomena including

    containment mixing
    local detonations
    deflagration transition to detonation
    inadvertent inerting
    continuous burning

The Ice Condenser Owners Group, the Electric Power Research Institute, and the NRC conducted extensive hydrogen research programs to address these issues.

As stated in Supplement 6 to the Sequoyah SER, the staff concluded on December 15, 1982, that the final ignition system proposed by the licensee for Sequoyah Units 1 and 2 is acceptable subject to the installation of additional igniters in the upper compartment and additional testing of the Tayco igniter in a simulated spray environment.

As part of its final evaluation of the Sequoyah PHMS, the staff also identified a number of technical issues that it intended to investigate further as confirmatory items. These items are

- local detonations
- analytical code assessment
- equipment survivability for a spectrum of accidents
- combustion effects at large scale
- combustion phenomena including flame acceleration in the upper ice bed

Since the staff issued its SER on the Sequoyah PHMS, both the industry and the NRC have completed significant research related to hydrogen combustion and control. Generally, these research programs have confirmed the adequacy of hydrogen control with igniter systems and confirmed expected hydrogen combustion phenomena. However, as a result of continued NRC investigations of equipment survivability, the staff has required utility owners of ice-condenser containments to perform additional analyses to demonstrate equipment survivability for a broad spectrum of degraded-core accidents. It is expected that these efforts and staff review will be completed in 1990.

(2) Grand Gulf Mark III Review

As in the case of the licensee for the first ice-condenser containment, the licensee for the first BWR Mark III containment licensed for operation (System Energy Resources, Inc. for Grand Gulf Unit 1) proposed a hydrogen ignition system that is designed to provide a controlled burning of hydrogen in the event that large quantities of hydrogen are generated as a result of a degraded-core accident. The system was installed by the licensee as a condition of its being allowed to exceed 5 percent power. The NRC staff completed and reported its interim review of the Grand Gulf hydrogen ignition system in Supplements 3, 4, and 5 to NUREG-0831, "Safety Evaluation Report Related to the Operation of Grand Gulf Nuclear Station, Units 1 and 2, Docket Nos. 50-416 and 50-417" (July 1982). In these supplements, the staff concluded that the Grand Gulf igniter system was acceptable to reduce the consequences of a degraded-core accident. Additional discussion of the igniter system was provided in Supplement 5 to the SER dated August 1984. Hydrogen-related licensing conditions have been issued for Grand Gulf Unit 1 similar to those discussed above for the Sequoyah ice-condenser containment.

The BWR Mark III Containment Hydrogen Control Owners Group (HCOG) has submitted to the staff the results of a research and development program to confirm the adequacy of the Mark III hydrogen control system. The licensees for Grand Gulf, Perry, Clinton, and River Bend are participants in HCOG. The staff is currently reviewing the HCOG report and a generic SER is scheduled to be issued in 1989. After issuance of the SER, each of the participants in HCOG will submit a final analysis for its plant, based on the approved HCOG report.

2.2.2 Other Plants

All nuclear plants with the Mark III or ice-condenser containment types have installed a hydrogen control system using igniters (e.g., diesel glow plugs) located throughout the reactor containment volume to safely consume the hydrogen in multiple burns as it is formed and before it reaches explosive concentrations in the containment. The licensees for each of these plants have as a condition to their licenses the stipulation that any findings resulting from lead plant reviews will apply to them as well.

2.3 Confirmatory Research

Beginning early in 1980, a number of technical programs were initiated to investigate the control of large amounts of hydrogen in small volume containment designs. The earliest of these was sponsored by individual owners of ice-condenser plants in support of their licensing efforts. Shortly thereafter, the owners of the ice-condenser plants (TVA, Duke Power Company, and American Electric Power Company) formed the Ice Condenser Owners Group (ICOG) to conduct a joint research and development (R&D) program. Later, owners of BWR-6/Mark III containments formed a similar owners group, the Hydrogen Control Owners Group (HCOG), to jointly sponsor hydrogen R&D efforts for the Mark III containment design. In addition to these programs, the Industry Degraded-Core Rulemaking (IDCOR) Group, the Electric Power Research Institute (EPRI), and the Department of Energy initiated hydrogen control research programs.

The industry research was applied to the design and installation of igniter hydrogen control systems for the BWR Mark III and PWR ice-condenser containments. These designs were described and evaluated by the NRC staff in the safety evaluation reports for the lead plants, Grand Gulf (Mark III) and Sequoyah (ice condenser). The Sequoyah SER, NUREG-0011, in Supplements 2 through 6, described the ignition system used in ice-condenser containment types. The Grand Gulf SER, NUREG-0831, in Supplements 3, 4, and 5, described a similar system used in BWR Mark III containments. The TVA analysis and results of experimental work were reported to the Commission for evaluation in licensing action.

The NRC has sponsored an extensive hydrogen research program at Sandia National Laboratories and other facilities. The Sandia research activities included hydrogen behavior, containment and equipment survival experiments, hydrogen combustion and preventive schemes, and computer code development. Appendix F lists the hydrogen references provided by Sandia. Additional studies were conducted for the NRC by Los Alamos National Laboratory and Pacific Northwest Laboratory. The "Light Water Reactor Hydrogen Manual" (NUREG/CR-2726) provides a description of hydrogen production and ignition during the TMI-2 accident. The report covers metal-water reactions, hydrogen transport and mixing, hydrogen ignition pressures and temperatures, and description of various hydrogen mitigation schemes. In addition to the independent research efforts by both the NRC and the nuclear power industry, workshops involving both groups were held. NUREG/CR-2017 provides the "Proceedings of the Workshop on the Impact of Hydrogen on Water Reactor Safety," Volumes I through IV. Volume IV of this report describes the glow plug igniter tests, performed by the Lawrence Livermore National Laboratory, to evaluate the functional ability of glow plugs in environments containing known concentrations of hydrogen, air, and steam. The glow plug successfully initiated combustion during all tests. The report also describes a different glow plug testing program, conducted by the American Electric Power Company, TVA, Duke Power, and Westinghouse, that successfully ignited the hydrogen in all cases.

2.4 Evaluation by the National Research Council

The NRC obtained the assistance of the National Research Council, which is under the auspices of the National Academy of Sciences (NAS), to assess the research on hydrogen control and combustion performed by NRC contractors and the nuclear power industry. The published version of the final report, "Technical Aspects of Hydrogen Control and Combustion in Severe Light Water Reactors," was sent to the NRC on March 17, 1987, and is included as Appendix G to this report. The report concludes that the considerable research on hydrogen control and combustion in severe light-water reactor accidents has properly covered most of the aspects concerning hydrogen combustion.

The report also concluded that, for most accident scenarios, current regulatory requirements make it highly unlikely that hydrogen detonation would be the cause of containment failure. (The remaining accidents of concern fall into the realm of severe accidents, which are being pursued with other staff activities in severe accident implementation.) The presence of an inert atmosphere in small volume containments is a satisfactory approach to the prevention of hydrogen detonations. Further, the use of igniters in intermediate size containments is a reasonable way to reduce the probability of hydrogen detonation. However, one problem raised is that the loss of all onsite and offsite station power, although relatively unlikely, would make the igniter systems inoperative. The report recommended improving the reliability of igniter systems for station blackout scenarios. This issue is being addressed under the staff review of the lead plants. The report further recommended evaluation of zone and field computer models against experimental data and additional research in flame acceleration. Both of these recommendations are being followed. New data is being generated by the Germans under an international program, the Severe Fuel Damage (SFD) Program. The remaining recommendations involve reactors with large, dry containments and these will be covered separately under Generic Issue Number 121.

The National Research Council report contains a minority report by one of the committee members recommending that inerting be used instead of igniters for hydrogen control of intermediate size containments. The minority report indicates that glow coil igniters are passive ignition sources, which cannot operate at a low hydrogen concentration, and that there is a probability that the concentration in the surrounding area would be much higher. The remainder of the committee members support the use of igniters to burn the hydrogen before a large volume reaches a detonable concentration.

3 SUMMARY AND CONCLUSION

Work on the major elements associated with USI A-48 either has been completed or is in its final stages. These elements include (1) issuance of NRC rules to require the inerting of BWR Mark I and Mark II containments, (2) issuance of NRC rules to require hydrogen control measures for degraded-core accidents (up to 75-percent metal-water reaction of the active fuel cladding) for BWR Mark III and PWR ice-condenser containments, (3) a large program of both industry-sponsored and NRC research, and (4) staff reviews of the implementation of these rules at lead plants for Mark III and ice-condenser containments. Work on these activities has not indicated any deficiencies in regulatory guidance.

A number of staff actions are in their final stages, including (1) analyses to demonstrate equipment survivability in ice-condenser containments for a broad spectrum of degraded-core accidents and (2) completion of the generic SER on the HCOG report with regard to the BWR Mark III containments.

The NRC staff's review of the major elements identified as part of USI A-48 indicates that an adequate regulatory basis exists for hydrogen control measures for degraded-core accidents and that no new regulatory guidance for such accidents is necessary. Therefore, the staff concludes that USI A-48 is resolved.

APPENDIX A

PLANTS COVERED BY UNRESOLVED SAFETY ISSUE A-48

Containment Type	**Plant (Unit No.)**	**Location**
Mark I:	Duane Arnold	Palo, IA
	Browns Ferry (1, 2, 3)	Decatur, AL
	Brunswick (1, 2)	Southport, NC
	Cooper	Brownville, NE
	Dresden (2, 3)	Morris, IL
	Fermi (2)	Laguna Beach, MI
	FitzPatrick	Scriba, NY
	Hatch (1, 2)	Baxley, GA
	Hope Creek (1)	Salem, NJ
	Millstone (1)	Waterford, CT
	Monticello	Monticello, MN
	Nine Mile Point (1)	Scriba, NY
	Oyster Creek	Toms River, NJ
	Peach Bottom (2, 3)	Peach Bottom, PA
	Pilgrim (1)	Plymouth, MA
	Quad Cities (1, 2)	Cordova, IL
	Vermont Yankee	Vernon, VT
Mark II:	Limerick (1, 2)	Pottstown, PA
	Nine Mile Point (2)	Scriba, NY
	Susquehanna (1, 2)	Berwick, PA
	WPPSS (2)	Richland, WA
	LaSalle County Nuclear Station (1, 2)	Seneca, IL
	Shoreham	Brookhaven, NY
Mark III:	Clinton (1)	Clinton, IL
	Grand Gulf (1, 2)	Port Gibson, MS
	Perry (1, 2)	Perry, OH
	River Bend (1)	St. Francisville, LA
Ice Condenser:	Catawba (1, 2)	Lake Wylie, SC
	Cook (1, 2)	Bridgman, MI
	McGuire (1, 2)	Cowans Ford Dam, NC
	Sequoyah (1, 2)	Daisy, TN
	Watts Bar (1, 2)	Spring City, TN

APPENDIX B

DOCUMENTS REVIEWED DURING RESOLUTION OF UNRESOLVED SAFETY ISSUE A-48

Commission Papers Related to USI A-48:

SECY-80-107, February 22, 1980, "Proposed Interim Hydrogen Control Requirements for Small Containments."

SECY-81-245, April 16, 1981, "Interim Amendments to 10 CFR Part 50 Related to Hydrogen Control and Certain Degraded Core Considerations."

SECY-83-357A, December 3, 1984, "Amendments to 10 CFR Part 50 Related to Hydrogen Control."

SECY-83-357B, December 3, 1984, "Status of Hydrogen Control Issue and Recommendations in SECY-83-357A."

Lead Plant References:

NUREG-0011, Supplements 4, 5, and 6, *Safety Evaluation Report Related to the Operation of Sequoyah Nuclear Plant, Units 1 and 2*, Docket Nos. 50-327 and 50-328.

NUREG-0831, Supplements 3, 4, and 5, *Safety Evaluation Report Related to the Operation of Grand Gulf Nuclear Station, Units 1 and 2*, Docket Nos. 50-416 and 50-417.

Commissioner's Public Meeting Transcripts:

Discussion of Interim Rule on Hydrogen Control, September 16, 1981.

Briefing on Hydrogen Control Program, November 19, 1982.

Department of Energy Reports:

GEND-INF-023, Volume 1, "Investigation of Hydrogen Burn Damage in the Three Mile Island Unit 2 Reactor Building."

GEND-INF-023, Volume 2, "Estimated Temperatures of Organic Materials in the TMI-2 Reactor Building During Hydrogen Burn."

GEND-INF-023, Volume 4, "Analysis of the Three Mile Island Unit 2 Hydrogen Burn."

APPENDIX C

FEDERAL REGISTER/VOL. 46, NO. 231, WEDNESDAY, DECEMBER 2, 1981, 10 CFR PART 50, "INTERIM REQUIREMENTS RELATED TO HYDROGEN CONTROL"

NUCLEAR REGULATORY COMMISSION

10 CFR Part 50

Interim Requirements Related to Hydrogen Control

AGENCY: Nuclear Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Nuclear Regulatory Commission is amending its regulations to require inerted containment atmospheres, and additionally, both hydrogen recombiner capability to reduce the likelihood of venting radioactive gases following an accident and the provision of high point vents in the primary coolant system. The inerting requirement applies only to boiling water nuclear power reactors with either Mark I or Mark II type containments; the requirement for hydrogen recombiner capability applies to light-water nuclear power reactors that rely upon purge/repressurization systems as the primary means of hydrogen control; the requirement for the provision of high point vents applies to all light-water nuclear power reactors.

EFFECTIVE DATE: January 4, 1982.

FOR FURTHER INFORMATION CONTACT: Morton R. Fleishman, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, telephone 301-443-5981.

SUPPLEMENTARY INFORMATION: On October 2, 1980, the Nuclear Regulatory Commission published in the **Federal Register** (45 FR 65466) a notice of proposed rulemaking on "Interim Requirements Related to Hydrogen Control and Certain Degraded Core Considerations" (Interim Rule) inviting written comments or suggestions on the proposed rule by November 3, 1980. The notice concerned proposed amendments to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," to improve hydrogen management in light-water reactor facilities and to provide specific design and other requirements to mitigate the consequences of accidents resulting in a degraded reactor core.

Thirty-five persons submitted comments regarding the proposed amendments. Although the comment period was scheduled to expire on November 3, 1980, comments received subsequent to that date have been considered, with the latest comment letter being dated February 9, 1981. The comments are part of the public record and may be examined and copied in the Commission's Public Document Room at 1717 H Street NW., Washington, D.C. A summary of the comments along with a comment analysis and a value/impact assessment are also available for inspection and copying in the Public Document Room.

These comments have been carefully reviewed and evaluated during preparation of this final rule. The final rule contains revisions to the proposed rule that reflect these comments. The commenters were about equally divided between those in favor of and those opposed to publishing the interim amendments. Whether or not the commenter favored publishing a final rule, additional detailed comments were generally provided on specific aspects of the proposed amendments.

The NRC's Office of Nuclear Reactor Regulation sent a letter on September 5, 1980 to all nuclear power plant licensees, applicants and construction permit holders providing a "Preliminary Clarification of the TMI Action Plan Requirements." This was followed by a series of four regional meetings, noticed by publication in the **Federal Register** on September 12, 1980 (45 FR 60508) and held during the week of September 22, 1980, in order to provide a more detailed explanation of the requirements and to obtain industry comments. Based on the discussions at the meetings and other comments received, the NRC revised the requirements and notified the applicants, licensees and construction permit holders to this effect by a letter dated October 31, 1980. The letter and revised requirements are included in NUREG-0736, "Clarification of TMI Action Plan Requirements."[1]

On May 13, 1981, the Commission published in the **Federal Register** (46 FR 26491) a notice of proposed rulemaking which proposed licensing requirements for pending operating license applications (OL Rule). The proposed OL Rule was based upon the requirements described in NUREG-0737 and includes, among others, many of the requirements originally included in the proposed Interim Rule published in October 1980.

Items originally proposed in the Interim Rule were:

1. Inerting of Mark I and II boiling water reactors (BWRs).
2. Design analyses for Mark III BWRs and pressurized water reactors (PWRs).
3. Dedicated hydrogen control penetrations.
4. Hydrogen recombiner capability.
5. High point vents
6. Post-accident protection of safety equipment and areas
7. In-plant iodine instrumentation
8. Post-accident sampling
9. Leakage integrity outside containment
10. Accident monitoring instrumentation
11. Detection of inadequate core cooling
12. Training to mitigate degraded core accidents

Of the above list, all except items 1, 2 and 4 were included in the proposed OL Rule and have been appropriately revised to reflect the comments received during the comment period on the proposed Interim Rule. Hence, those items included in the OL Rule have been deleted from this Interim Rule except for item 5 (High point vents). Item 5, while previously included in the OL Rule was felt to be primarily hydrogen related and thus more appropriately included in this Interim Rule. Those public comments received pertaining to the remaining OL Rule items will not be discussed here. All of the public comments may be examined and copied in the Commission's Public Document Room along with the response to the comments (SECY 81-245, "Interim Amendments to 10 CFR Part 50 Related to Hydrogen Control and Certain Degraded Core Considerations").

The final Interim Rule contains revisions to the proposed Interim Rule that reflect all of the applicable comments including those (a) given in response to the notice of proposed rulemaking, and (b) generated during the regional meetings and in response to the clarification letters of September 5, 1980, and October 31, 1980.

Before discussing the comments and the specific revisions resulting from the comments, it should be noted that, while § 50.44 has applied only to light-water nuclear power with zircaloy fuel cladding, the new amendments in the Interim Rule are not as limited and apply to light-water nuclear power reactors with either stainless steel or zircaloy fuel cladding. The Commission will be considering further modification of § 50.44 during the long-term rulemaking effort relative to consideration of degraded or melted cores in safety regulation. Part of this long-term rulemaking will involve a thorough reevaluation of hydrogen generation and control. In the interim, the Commission wishes to leave in place the existing provisions of § 50.44 because of the requirements for dealing with design basis accidents. These include, for example, requiring:

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[1] Copies of this report may be obtained from GPO Sales Program, Division of Technical Information and Document Control, U.S.C. Nuclear Regulatory Commission, Washington, D.C. 20555.

1. The capability for measuring hydrogen concentrations in containment.
2. The capability for ensuring a mixed atmosphere in containment.
3. The capability for controlling combustible gas concentrations in containment following a postulated LOCA.
4. The capability to deal with hydrogen from radiolytic decomposition of the reactor coolant and the corrosion of metals. (These have release characteristics that differ from those associated with metal-water reaction.)
5. That the combustible gas control systems conform with the general requirements of Criteria 41, 42 and 43 of Appendix A of 10 CFR Part 50.

Several commenters have expressed concern that the various rulemakings currently being pursued by NRC should be integrated, i.e., safety goal, degraded core considerations, minimum engineered safety features, siting and emergency planning. The NRC shares this concern. On October 15, 1980, the Executive Director for Operations established a Degraded Cooling Steering Group to coordinate degraded cooling and related rules. This group has completed its work and prepared a plan to ensure future integration of these activities.

Numerous commenters have questioned many of the implementation dates specified in the rule, indicating that they cannot be met for a variety of reasons, such as procurement lead time, need for the design studies, availability of acceptable equipment, etc. The staff agrees with these comments and has made appropriate changes to the implementation dates.

Inerting of Mark I and II BWRs [§ 50.44(c)(3)(i)]

Some commenters, particularly those associated with Mark I boiling water reactors (BWRs), questioned the advisability of requiring inerting of containments and suggested that other hydrogen control options be permitted. This issue has been extensively reviewed and discussed among the Commission, NRC staff and industry participants. Numerous reports and letters have been written and many meetings held in order to thoroughly air the issue. Considering the information previously developed, the Commission continues to believe that it would be prudent, pending completion of the long term rulemaking on degraded core cooling, to require that all Mark I and II BWR containments be provided with an inerted atmosphere during normal operations. However, one utility (Vermont Yankee) has recently expressed a renewed interest in providing a hydrogen control system, other than preinerting, for its facility. Two possible options, post-accident inerting and a deliberate ignition system, could be considered for the Mark I containment of this facility. The Commission has not received any specific proposal or analyses for either of these hydrogen control systems. Thus, it is concluded that, absent any proposed and justified alternative, preinerting is required for Mark I BWRs. If Vermont Yankee (or others) propose an alternative system backed up by suitable tests and analyses, the Commission will review it. If found acceptable, the alternative systems would be permitted, either by subsequent amendment or exemption to this section.

The proposed rule's deadline for installation of inerting systems has been extended to account for delay in publication of a final rule. The rule has also been changed to clarify that the paragraph applies only to Mark I and II BWRs.

Hydrogen Recombiner Capability [§ 50.44(c)(3)(ii)]

Several commenters have recommended that the proposed § 50.44(c)(3)(ii) be modified to allow the use of alternate means of hydrogen control, such as internal recombiners, rather than to restrict the rule to external recombiners. The proposed rule was not intended to preclude this alternative. In fact, if internal recombiners were present before or will be installed in the future, this section of the rule would not apply since purge/repressurization systems would not be the primary means for combustible gas control. This section of the rule only applies to facilities that rely upon purge/repressurization systems as the primary means of controlling combustible gases following a LOCA. Based on existing § 50.44, all facilities must have either internal or external recombiners or purge/repressurization systems for controlling combustible gases following a LOCA. For those BWRs which are inerted and which rely upon purge/repressurization for combustible gas control, the intent of the rule is to require that they be provided with either internal recombiners or the capability to install external recombiners.

It should also be noted that this section of the rule does not require actual installation of external recombiners; rather, it requires only the capability for installation. To avoid confusion, the rule has been clarified to indicate that internal recombiners are an acceptable alternative to the installation of external recombiner capability.

High Point Vents in Reactor Coolant System [§ 50.44(c)(3)(iii)]

A number of commenters have remarked that there is no justification for applying the single failure criterion to the design of the high point vents. Furthermore, it has been suggested that the negative aspects of the high point vents have not been adequately considered and that, in fact, the vents may increase the risk to the public.

In response to these comments, the single failure criterion requirement has been deleted; however, one aspect of the criterion has been retained, namely, that a single failure within the power and control parts of the reactor coolant vent system should not prevent isolation of the entire vent system when required. Also a sentence has been added to require that the use of the high point vents not "aggravate the challenge to the containment or the course of the accident." Finally, the Interim Rule has been revised to relax the implementation date, in response to comments received at regional meetings with industry in September 1980.

Regulatory Flexibility Act

In accordance with the Regulatory Flexibility Act of 1980, 5 U.S.C. 605(b), the Commission hereby certifies that this rule will not, if promulgated, have a significant economic impact on a substantial number of small entities. This rule affects only the licensing and operation of nuclear power plants. The companies that own these plants do not fall within the scope of the definition of "small entities" set forth in the Regulatory Flexibility Act or the Small Business Size Standards set out in regulations issued by the Small Business Administration at 13 CFR Part 121. Since these companies are dominant in their service areas, this rule does not fall within the purview of the Act.

Accordingly, notice is hereby given that, pursuant to the Atomic Energy Act of 1954, as amended, the Energy Reorganization Act of 1974, as amended, and section 553 of Title 5 of the United States Code, the following amendments to 10 CFR Part 50 are published as a document subject to codification.

PART 50—DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES

1. The authority citation for Part 50 reads as follows:

Authority: Secs. 103, 104, 161, 182, 183, 189, 68 Stat. 936, 937, 948, 953, 954, 955, 956, as amended (42 U.S.C. 2133, 2134, 2201, 2232, 2233, 2239); secs. 201, 202, 206, 88 Stat. 1243, 1244, 1246 (42 U.S.C., 5841, 5842, 5846), unless otherwise noted. Section 50.78 also issued under sec. 122, 68 Stat. 939 (42 U.S.C. 2152). Sections 50.80–50.81 also issued under sec. 184, 68 Stat. 954, as amended: (42 U.S.C. 2234). Sections 50.100–50.102 issued under sec. 186, 68 Stat. 955; (42 U.S.C. 2236). For the purposes of sec. 223, 68 Stat. 958, as amended: (42 U.S.C. 2273), § 50.54(i) issued under sec. 161i, 68 Stat. 949, (42 U.S.C. 2201(i)). §§ 50.70, 50.71 and 50.78 issued under sec. 161o, 68 Stat. 950, as amended; (42 U.S.C. 2201(o)) and the laws referred to in Appendices.

2. Section 50.44 of Part 50 is amended by revising paragraph (c) to read as follows:

§ 50.44 Standards for combustible gas control system in light water cooled power reactors.

* * * * *

(c)(1) For each boiling or pressurized light-water nuclear power reactor fueled with oxide pellets within cylindrical zircaloy cladding, it shall be shown that during the time period following a postulated LOCA but prior to effective operation of the combustible gas control system, either: (i) An uncontrolled hydrogen-oxygen recombination would not take place in the containment; or (ii) the plant could withstand the consequences of uncontrolled hydrogen-oxygen recombination without loss of safety function.

(2) If the conditions set out in paragraph (c)(1) of this section cannot be shown, the containment shall be provided with an inerted or an oxygen deficient atmosphere in order to provide protection against hydrogen burning and explosions during the time period specified in paragraph (c)(1) of this section.

(3) Notwithstanding paragraphs (c)(1) and (c)(2) of this section:

(i) Effective May 4, 1982 or 6 months after initial criticality, whichever is later, an inerted atmosphere shall be provided for each boiling light-water nuclear power reactor with a Mark I or Mark II type containment; and

(ii) By the end of the first scheduled outage beginning after July 5, 1982 and of sufficient duration to permit required modifications, each light-water nuclear power reactor that relies upon a purge/repressurization system as the primary means for controlling combustible gases following a LOCA shall be provided with either an internal recombiner or the capability to install an external recombiner following the start of an accident. The internal or external recombiners must meet the combustible gas control requirements in paragraph (d) of this section. The containment penetrations used for external recombiners must either be:

(A) dedicated to that service only, conform to the requirements of Criteria 54 and 56 of Appendix A of this part, be designed against postulated single failures for containment isolation purposes, and be sized to satisfy the flow requirements of the external recombiners, or

(B) of a combined design for use by either external recombiners or purge/repressurization systems and other systems, conform to the requirements of criteria 54 and 56 of Appendix A of this part, be designed against postulated single failures both for containment isolation purposes and for operation of the external recombiners or purge/repressurization systems, and be sized to satisfy the flow requirements of the external recombiners or purge repressurization systems.

(iii) To provide improved operational capability to maintain adequate core cooling following an accident, by the end of the first scheduled outage beginning after July 1, 1982 and of sufficient duration to permit required modifications, each light-water nuclear power reactor shall be provided with high point vents for the reactor coolant system, for the reactor vessel head, and for other systems required to maintain adequate core cooling if the accumulation of noncondensible gases would cause the loss of function of these systems. (High point vents are not required, however, for the tubes in U-tube steam generators.) The high point vents must be remotely operated from the control room. Since these vents form a part of the reactor coolant pressure boundary, the design of the vents and associated controls, instruments and power sources must conform to the requirements of Appendix A and Appendix B of this part. In particular, the vent system shall be designed to ensure a low probability that (A) the vents will not perform their safety functions and (B) there would be inadvertent or irreversible actuation of a vent. Furthermore, the use of these vents during and following an accident must not aggravate the challenge to the containment or the course of the accident.

* * * * *

Dated at Washington, D.C. this 25th day of November 1981.

For the Nuclear Regulatory Commission.

Samuel J. Chilk,
Secretary of the Commission.

[FR Doc. 81-34847 Filed 12-1-81; 8:45 am]

BILLING CODE 7590-01-M

APPENDIX D

FEDERAL REGISTER/VOL. 46, NO. 246, WEDNESDAY, DECEMBER 23, 1981, 10 CFR PART 50, "INTERIM REQUIREMENTS RELATED TO HYDROGEN CONTROL"

7 CFR Part 1135

[Docket No. AO-380-A1]

Milk in the Southwestern Idaho-Eastern Oregon Marketing Area; Decision on Proposed Amendments to Marketing Agreement and Order

Correction

In FR Doc. 81-36[illegible]66, appearing at page 61480 in the issue of Thursday, December 17, 1981, the citation in parentheses in lines 12 and 13 of the second paragraph of column two on page 61480 should have read, "(46 FR 32873)".

BILLING CODE 1505-01-M

NUCLEAR REGULATORY COMMISSION

10 CFR Part 50

Interim Requirements Related to Hydrogen Control

AGENCY: Nuclear Regulatory Commission.

ACTION: Proposed rule.

SUMMARY: The Nuclear Regulatory Commission is considering amending its regulations to improve hydrogen control capability during and following an accident in light-water reactor facilities.

The amendments would require improved hydrogen control systems for boiling water reactors with Mark III type containments and for pressurized water reactors with ice condenser type containments. All light-water nuclear power reactors not relying upon an inerted atmosphere for hydrogen control would be required to show that certain important safety systems must be able to function during and following hydrogen burning.

DATES: Comment period expires February 22, 1982. Comments received after that date will be considered if it is practical to do so, but assurance of consideration cannot be given except as to comments received on or before that date.

FOR FURTHER INFORMATION CONTACT: Morton R. Fleishman, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, telephone 301-443-5981.

ADDRESS: Written comments or suggestions for considertion in connection with the proposed amendments should be submitted to the Secretary of the Commission, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Attention: Docketing and Service Branch. Copies of comments received may be examined in the Commission's Public Document Room at 1717 H Street NW., Washington, D.C.

SUPPLEMENTARY INFORMATION: The accident at Three Mile Island, Unit 2 (TMI-2) resulted in a severely damaged or degraded reactor core, a concomitant release of radioactive material to the primary coolant system, and a fuel cladding-water reaction which resulted in the generation of a large amount of hydrogen. The Nuclear Regulatory Commission has taken numerous actions to correct the design and operational limitations revealed by the accident. Included in these actions are several rulemaking proceedings intended to improve the hydrogen control capability of light-water nuclear power reactors. On October 2, 1980, the Nuclear Regulatory Commission published in the **Federal Register** (45 FR 65466) a notice of proposed rulemaking on "Interim Requirements Related to Hydrogen Control And Certain Degraded Core Considerations" (Interim Rule). The notice concerned proposed amendments to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," to improve hydrogen management in light-water reactor facilities and to provide specific design and other requirements to mitigate the consequences of accidents resulting in a degraded reactor core.

On March 23, 1981, the Commission published in the **Federal Register** (46 FR 18045) a notice of proposed rulemaking on "Licensing Requirements for Pending Construction Permit and Manufacturing License Applications." The notice proposed a set of licensing requirements applicable to construction permit applications that stemmed from lessons learned from the TMI-2 accident. On May 13, 1981, the Commission published in the **Federal Register** (46 FR 26491) a notice of proposed rulemaking on "Licensing Requirements for Pending Operating License Applications" (OL Rule).

As a result of the various activities and considerations relative to the October 2, 1980 notice, the Commission decided to split the Interim Rule into two parts. One part was to be included in the OL Rule. The other part, limited only to hydrogen control, was to be issued separately. The details of this split are described in the companion **Federal Register** notice published on December 2, 1981 (46 FR 58484) concerning hydrogen control related to inerting, hydrogen recombiner capability and high point vents.

The Commission has also been considering the ability of all light-water reactors, particularly pressurized light-water reactor facilities with ice condenser type containments and boiling light-water reactor facilities with Mark III type containment, to withstand an accident with the concomitant generation of large amounts of hydrogen, such as the type which occurred at Three Mile Island, Unit 2 (TMI-2). As a result, three new amendments to the regulations are being proposed for public comment.

Hydrogen Control for Mark III BWRs and Ice Condenser PWRs [§ 50.44(c)(3)(iv)]

It is proposed that boiling water reactor (BWR) facilities with Mark III type containments and pressurized water reactor (PWR) facilities with ice condenser type containments, for which construction permits were issued prior to March 28, 1979, be required to install hydrogen control systems capable of accommodating an amount of hydrogen equivalent to that generated from the reaction of 75% of the fuel cladding (surrounding the active fuel region) with water, without loss of containment integrity. This new requirement is being contemplated as a result of safety issues raised during licensing reviews of new ice condenser and Mark III plants. In these reviews, it has become clear that additional protection is required to provide assurance that large amounts of hydrogen can be safety accommodated by these plants. The particular type of hydrogen control system to be selected is left to the discretion of the applicant or licensee; however, it must be found acceptable by the NRC based upon suitable programs of experiment and analysis. The selection should be supported by comparative analyses of alternative systems to show their relative advantages and disadvantages. These comparisons are to be submitted as part of the analyses required under § 50.44(c)(3)(vi). At present, a distributed igniter system has been found acceptable for the Sequoyah plant with an ice condenser containment, but only as an interim solution while the hydrogen control matter is studied further. A post-accident inerting system has also been discussed for the ice condenser and Mark III containments. Whatever systems are finally proposed and approved for the long term, large amounts of hydrogen must be safely accommodated, and operation of the system, either intentionally or inadvertently, must not further aggravate the course of an accident or endanger the plant during normal operations. The amount of hydrogen to be assumed in the design of the hydrogen control system is that amount generated by assuming that 75% of the fuel cladding surrounding the active fuel region reacts with water. The 75% is judged to be representative of the maximum amount of hydrogen likely to be generated in an accident in which the threat to the containment is limited to the threat posed by the combustion of hydrogen. Events with metal-water reactions in excess of 75% are judged to be associated with core-melt accidents which could pose a threat to containment greater than the combustion of hydrogen. This 75% value also appears to be reasonable because it is sufficiently greater than the fuel cladding-water reaction analyzed to have occurred at TMI-2 to provide a conservative estimate for the cladding reaction that may occur during a TMI type degraded core accident. It is expected that the 75% value will permit plants that are either completed or are well along in the construction stage to have a hydrogen control system added without the need for major modifications to their containment structures. Research now in place will, over the next several years, yield data on the likelihood of termination of sequences with large amounts of cladding interaction.

The Commission would particularly welcome comments on whether the percent of fuel cladding that reacts with water should be less than, equal to, or greater than the 75 percent value being proposed for use in the rules covered by this notice. Supporting analyses, as available, would also be welcome.

Owners of Mark III BWR's now under construction have been surveyed by the NRC staff to determine the effect on their plant designs of the requirement that they do not exceed ASME Service Level A Limits or the Service Load Category during inadvertent full inerting of a post-accident inerting system. This survey was conducted because a post-accident inerting system (rather than a distributed ignition system) was thought to be the preferred approach for the Mark III containments. Based on their responses, the Commission has concluded that there would be no significant impact in specifying these requirements for inadvertent full inerting. Modest deviations from these ASME criteria will be permitted if good cause is shown. A comparable survey was not conducted for ice condenser plants because the distributed ignition system apparently is the approach preferred by the owners of these plants.

There are ongoing programs of reasearch in a number of areas of hydrogen generation, release, burning, and control. These include the analysis of accident sequences, the chronology of hydrogen and steam injection (from the primary system into containment), the analysis of operations to recover coolability, and an assessment of equipment survivability. These studies are expected to reveal the advantages and disadvantages of various hydrogen control systems, including those that involve deliberate burning of the hydrogen within containment. Based on the state of technology as of August 1981, the Commission believes that control methods that do not involve burning provide protection for a wider spectrum of accidents than do those that involve burning.

As a result of the review of the deliberate ignition systems installed at Sequoyah and McGuire, the staff has identified issues which need to be investigated further. A spectrum of degraded core accident scenarios, including those which may lead to inadvertent suppression of combustion in the lower compartment due to a steam rich atmosphere, and several hydrogen combustion phenomena are continuing to be reviewed. In addition, there is incomplete verification of analytical models and equipment survivability. These issues are being addressed in ongoing research by NRC and the nuclear industry. The Commission concludes, based on available information, that the issues are sufficiently resolved to warrant interim approval of deliberate ignition systems for ice condenser plants. However, the Commission has required in individual licensing proceedings and in the section of this rule on analyses (§ 50.44(c)(3)(vi)) that studies of alternative hydrogen management systems be performed prior to the long-term approval of any particular method.

Standards for Safety Systems and Components That Must Function During or After Hydrogen Burn [Sec. 50.44(c)(3)(v)]

The Commission is considering a two-step approach to address qualification of essential equipment during and after a hydrogen burn. As a first step, essential equipment must be demonstrated to "survive" the hydrogen burn and continue to be able to perform its safety function. In this context, the equipment would not have to meet the more rigorous standards of the NRC's equipment qualification program but a different standard as defined below. As a second step, the Commission would require "qualification" of essential equipment.

The Commission feels a two-step approach is justified in light of our lack of knowledge of the probabilities of hydrogen-producing accident scenarios, the environmental conditions during a hydrogen burn, and the effect this environment has on different equipment. The Commission will develop "survivability" criteria which are intended as an interim step to assure the quality of essential equipment until enough information is accumulated from ongoing research to suitably define what equipment performance standards are appropriate. After sufficient information is developed, the Commission may propose long-term standards that are more stringent than the short-term or "survivability" standard being proposed.

The differences in concept between equipment demonstrated to meet the "survivability" standard and equipment that meets the "qualification" standard are described below. The Commission specifically seeks comment on the use of the two step approach for defining equipment standards, the "survivability" and "qualification" standards themselves, and proposals for implementation schedules developed on a well informed basis. Equipment required to be qualified (Eq) and equipment for which survivability must be demonstrated (Es) can be compared as follows:

(a) *Environmental Conditions*—The environmental conditions under which Eq must operate would be calculated using a model that has been demonstrated to be conservative by comparison with numerous experiments and by a long history of usage. For Es, the calculational model contains some conservatisms, but the level of assurance is generally not comparable to that for the Eq model due to a lack of available experimental data for verification.

b. *Testing Conditions*—For Eq, the test conditions would be more severe than the environmental conditions due to extra margins added to account for uncertainties in the test environment, inaccuracies of the measuring devices, variability of the test specimens, etc. For Es, the test conditions need not provide margin beyond the conservatively calculated environmental conditions.

c. *Operability*—Eq and Es would both be required to perform their functions during and after being exposed to their respective test conditions.

d. *Performance*—During and following a test, Eq would be required to perform to specifications determined by accident analyses performed prior to the test; however, for Es, a relaxation of these specifications would be permitted, as defined on a case-by-case (e.g., more instrument drift would be tolerated during a hydrogen burn than during normal operations).

Another possible difference is the criteria used to select test specimens, e.g., individual type testing for Eq versus generic testing for Es. It should also be noted that if the test condition for Eq for a LOCA can be shown to envelope the predicted test condition for a hydrogen burn then the LOCA qualification test would be sufficient to demonstrate survivability.

This requirement would apply to all BWRs and PWRs, for which construction permits were issued prior to March 28, 1979, that do not have an inerted containment atmosphere for hydrogen control. That is, plants for which there exists the possibility that substantial amounts of hydrogen can be burned in the containment will be covered by the proposed new requirement. Safety systems provided on these plants that are needed (a) to shut down the reactor and bring it to and maintain it in a safe cold shutdown condition, and (b) to prevent loss of containment integrity, must meet the "survivability" criteria in the near term and may be required to meet "qualification" criteria in the long term. Thus, for example, if a distributed igniter system is selected for controlling large amounts of hydrogen, the applicants or licensees must assure in the near term that the specified safety systems can survive and continue to perform their needed safety functions during and following hydrogen burning. In the long term the equipment may be required to meet a more stringent equipment qualification standard, considering the environmental effects of hydrogen burning. If no new hydrogen control system is required, as is likely to be the case for PWRs with large dry containments, these applicants and licensees would still have to perform analyses to: (1) Show containment structural integrity, as defined in § 50.44(c)(3)(iv) can be maintained; and (2) assure that the specified safety systems can continue to perform their needed safety functions during and following hydrogen burning and local detonations. The new criteria for certain identified essential systems are needed because the environmental pressures and temperatures associated with hydrogen burning and local detonations can be more severe than the conditions for which the equipment has been previously qualified.

Analyses [§ 50.44(c)(3)(vi)]

The proposed Interim Rule required that for all PWR and BWR plants, except the Mark I and II BWRs, design analyses must be performed for new hydrogen control measures. Many commenters indicated that the description of the design analyses was not precise enough to elicit the desired response. Furthermore, several commenters have suggested that it is inappropriate to have a regulation requiring hydrogen control design studies in view of the fact that unambiguous event descriptions and acceptance criteria are not supplied. The Commission agrees with these comments in part. As a result, the Commission intends to provide supplementary guidance concerning acceptable procedures that should be used, both for design of the hydrogen control systems per § 50.44(c)(3)(iv), for the demonstration of equipment survivability per § 50.44(c)(3)(v), and for the analysis of containment structural integrity.

The Commission is considering three different approaches concerning the supplementary guidance to be provided for performing the analyses. In all of these approaches, licensees are not restricted to the specified scenarios. If because of unique plant design features, other scenarios are known to present a greater risk than those identified by the Commission, the analyses should be based on the scenarios known to present the greatest risk. For example, if for a particular plant an intermediate break LOCA results in a greater risk than the scenarios in Table I, the licensee should base his calculations on the intermediate break LOCA scenario.

In the first approach, the Commission would identify accident sequences or scenarios which are found by probabilistic risk assessment techniques to be significant contributors to the likelihood of core degradation and thus pose a significant hydrogen threat. The licensee would then perform analyses, using these sequences, to determine the time variation of the hydrogen and steam release rates to the containment building. The analyses, which would include the failure assumptions of the different scenarios as well as the accident recovery phase and allowances for uncertainties, would provide the pressure and temperature histories to which the containment would be exposed. A list of possible accident sequences being considered under this approach is given in Table I. The scenarios include the production of substantial amounts of hydrogen as part of core-melt sequences; they were selected, based on experience and engineering judgment, because they are the more probable severe accident sequences which could be terminated short of primary vessel melt-through with available recovery techniques.

In the second approach, a base sequence would be chosen by the Commission based on its significance and characteristics from the standpoint of hydrogen threat. Key aspects of this scenario would then be parametrically varied, by the licensee, in determining the acceptability of the hydrogen control system or the containment response. This would provide a wider range than that of the selected base sequence alone. The acceptability of the analyses used in this approach would depend on the selection and range of the parameters being varied. The range must be chosen to include the effects of physically realistic degraded core accident scenarios with recovery. If licensees have determined that because of their own plant design another scenario presents a greater risk than the small break LOCA, the scenario presenting the greater risk should be chosen for parametric study. The variables and values studied should be determined on a case-by-case basis depending on the particular scenario. Table II represents a preliminary list of parameter variations that appear to provide reasonable extensions of a PWR small-break scenario (Item 1 of Table I). A corresponding BWR list has not yet been prepared.

In the third approach, the Commission would use a set of accident sequences as in Table I, and perform analyses which would define a reasonable envelope of time histories of hydrogen and steam release rates into the containment building. This envelope definition could be based on variations in the progression of different sequences and/or variations due to uncertainties within a particular sequence. The envelope of hydrogen and steam source terms to the containment would then be provided to all licensees for use in subsequent analyses. This approach would avoid the need for case-by-case sequence analyses using codes like MARCH and involving extensive iterative review of the MARCH analyses with the Commission. The intent would be for the Commission to provide hydrogen and steam source terms generic to each reactor type (BWR or PWR) and let the licensees' and NRC's ensuing attention be on the containment analysis. (The staff intends to publish for comment these generic source term analyses during the comment period for this proposed rule.)

TABLE I.—ACCIDENT SEQUENCES LEADING TO A SIGNIFICANT HYDROGEN THREAT

PWR	1. Small LOCA with temporary loss of emergency core cooling (ECC) injection.
	2. Transient with temporary loss of all feedwater and the high pressure ECC system.
	3. Interruption of all AC electric power with failure of the auxiliary feedwater system.
BWR	4. Transient with reactor isolation and temporary failure of all coolant make-up systems.
	5. Small LOCA with temporary failure of ECC injection.
	6. Transient with failure of reactor shutdown systems and interruption of ECC systems.

TABLE II.—PARAMETRIC VARIATIONS OF A PWR SMALL-BREAK SCENARIO

Rate of H_2 release[2] (lb/min)	Timing of H_2 release	Rate of steam/enthalpy release (lb/min (millions of Btu/min))	Concurrent failures and recoveries
2	Starting at time		
10	of Uncovering of Top	600(1)	Fans.
30	of core	3,600(6)	Containment
100	Prior to major steam release.	[1] 10,000(18)	Sprays.
1,000	Concurrent with major steam release.		All AC power.
	Following major steam release.		Recirculation.

[1] This high rate of steam release may occur for about 10 min. during ECC recovery.

[2] These rates should be assumed to be constant during the period of release and represent release from the primary system to the containment building.

The Commission particularly welcomes comments concerning which of the above approaches is preferred as well as suggestions regarding improvements or other alternatives.

The proposed rule has also been modified to clarify the types of analyses required. They can be grouped into four classes, depending upon containment design, as follows:

1. BWRs with Mark I and II type containments are required to be inerted by the companion rule on inerted containments appearing elsewhere in this issue. (See Table of Contents under NRC Rules and Regulations.) There are no further analyses required of these plants.

2. Effective [one year after the effective date of the rule], or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later, analyses would be required for BWRs with Mark III type containments and PWRs with ice condenser type containments to demonstrate that the installed hydrogen control system is adequate and will perform its intended function in a manner that provides adequate safety margins. Analyses should also be performed to assess the effectiveness of alternative systems.

3. Effective [one year after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later, additional analyses, described under item 4, would be required for BWRs with Mark III type containments and PWRs with ice condenser type containments, to show that safe shutdown will be assured and containment structural integrity maintained during degraded core accidents.

4. Owners of all other containments would be required to perform and submit by [two years after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later: (i) Analyses to assure that during degraded core accidents containment structural integrity will be maintained; and (ii) equipment survivability analyses to assure continued containment integrity and safe shutdown capability. These degraded core accidents will be assumed to produce hydrogen releases to the containment resulting from the containment reaction of up to and including 75% of the fuel cladding surrounding the active fuel region with water for a range of time periods consistent with the accident scenarios analyzed.

The analyses required by this section serve two purposes. First, they support continued reliance on the interim requirements of this rule. Second, the results will be considered in a longer term rulemaking on degraded cores.

Paperwork Reduction Act

The proposed rule will be submitted to the Office of Management and Budget for clearance of the application requirements that may be appropriate under the Paperwork Reduction Act (Pub. L. 96–511). The SF–83 "Request for Clearance," Supporting Statement, and related documentation submitted to OMB will be placed in the NRC Public Document Room at 1717 H Street NW., Washington, D.C. 20555. The material will be available for inspection and copying for a fee.

Regulatory Flexibility Act

In accordance with the Regulatory Flexibility Act of 1980, 5 U.S.C. 605(b), the Commission hereby certifies that this rule will not, if promulgated, have a significant economic impact on a substantial number of small entities. This proposed rule affects only the licensing and operation of nuclear power plants. The companies that own these plants do not fall within the scope of the definition of "small entities" set forth in the Regulatory Flexibility Act or the Small Business Size Standards set out in regulations issued by the Small Business Administration at 13 CFR Part 121. Since these companies are dominant in their service areas, this proposed rule does not fall within the purview of the Act.

Accordingly, notice is hereby given that, pursuant to the Atomic Energy Act of 1954, as amended, the Energy Reorganization Act of 1974, as amended, and section 553 of title 5 of the United States Code, adoption of the following amendments to 10 CFR Part 50 is contemplated.

PART 50—DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES

1. The authority citation for Part 50 reads as follows:

Authority: Secs. 103, 104, 161, 182, 183, 189, 68 Stat. 936, 937, 948, 953, 954, 955, 956, as amended (42 U.S.C. 2133, 2134, 2201, 2232, 2233, 2239); secs. 201, 202, 206, 88 Stat. 1243, 1244, 1246 (42 U.S.C. 5841, 5842, 5846), unless otherwise noted. Section 50.78 also issued under sec. 122, 68 Stat. 939 (42 U.S.C. 2152). Sections 50.80–50.81 also issued under sec. 184, 68 Stat. 954, as amended; (42 U.S.C. 2234). Sections 50.100–50.102 issued under sec. 186, 68 Stat. 955; (42 U.S.C. 2236). For the purposes of sec. 223, 68 Stat. 958, as amended; (42 U.S.C. 2273), § 50.54(i) issued under sec. 161i, 68 Stat. 949; (42 U.S.C. 2201(i)), §§ 50.70, 50.71 and 50.78 issued under sec. 161o, 68 Stat. 950, as amended; (42 U.S.C. 2201(o)) and the Laws referred to in Appendices.

2. In § 50.44, paragraph (c) is amended by adding new subparagraphs (3) (iv), (v) and (vi) to read as follows:

§ 50.44 Standards for combustible gas control system in light water cooled power reactors.

* * * * *

(c) * * *

(3) * * *

(iv) Effective [one year after effective date of the rule], or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later, each boiling light-water nuclear power reactor with a Mark III type containment and each pressurized light-water nuclear power reactor with an ice condenser type containment, for which a construction permit was issued prior to March 28, 1979, shall be provided with an acceptable hydrogen control system justified by suitable programs of experiment and analysis. The hydrogen control system must be capable of handling an amount of hydrogen equivalent to that generated from the reaction of 75% of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume) with water, without loss of containment structural integrity (i.e., steel containments must meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsubarticle NE-3220, Service Level C Limits, except that evaluation of instability is not required, considering pressure and dead load alone. Concrete containments must meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 2, Subsubarticle CC-3720, Factored Load Category, considering pressure and dead load alone. These subsubarticles have been approved for incorporation by reference by the Director of the **Federal Register**. A notice of any changes made to the material incorporated by reference will be published in the **Federal Register**. Copies of the ASME Boiler and Pressure Vessel Code may be purchased from the American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, N.Y. 10017. It is also available for inspection at the Nuclear Regulatory Commission's Public Document Room, 1717 H Street NW., Washington, D.C.) If the hydrogen control system relies on post-accident inerting, the containment structure must be capable of withstanding the increased pressure (A) during the accident, where it must not exceed Service Level C Limits or the Factored Load Category (as previously specified in this paragraph) and (B) following inadvertent full inerting that may occur during normal plant operations, where it must not exceed either Service Level A Limits (for a steel containment) or the Service Load Category (for a concrete containment). Equipment required to establish and maintain safe cold shutdown and containment integrity must be designed and qualified for the environment caused by post-accident inerting. Furthermore, inadvertent full inerting during normal plant operations must not adversely effect systems and components needed for safe operation of the plant. Modest deviations from these criteria will be considered by the Commission if good cause is shown.

(v) Each light-water nuclear power reactor, for which a construction permit was issued prior to March 28, 1979, that does not rely upon an inerted atmosphere to control hydrogen inside the containment, shall be provided with systems necessary to establish and maintain safe cold shutdown and maintain containment integrity that are capable of performing their functions during and after being exposed to the environmental conditions created by the burning (or local detonation) of hydrogen. The amount of hydrogen to be considered is equivalent to that generated from the reaction of 75% of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume) with water. This requirement shall be effective as follows: for each boiling light-water nuclear power reactor with a Mark III type containment and each pressurized light-water nuclear power reactor with an ice condenser type containment, on [one year after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later; for every other light-water nuclear power reactor that must meet this requirement, on [two years after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later.

(vi) Analyses shall be performed and submitted to the Director of Nuclear Reactor Regulation for each light-water nuclear power reactor, for which a construction permit was issued prior to March 28, 1979, to evaluate the consequences of large amounts of hydrogen generated after the start of an accident (hydrogen resulting from the reaction of up to and including 75 percent of the fuel cladding surrounding the active fuel region with water) including consideration of hydrogen control measures as appropriate. Each analysis must include the period of recovery from the degraded condition. The accident scenarios to be used in the analyses must be acceptable to the NRC staff. The scope and implementation requirements for the analyses for the various types of light-water nuclear power reactors are as follows:

(A) For each boiling light-water nuclear power reactor with a Mark III type containment and each pressurized light-water nuclear power reactor with an ice condenser type containment, analyses shall be performed that justify the selection of the hydrogen control system required by § 50.44(c)(3)(iv). These analyses shall be completed and submitted by [one year after the effective date of the rule], or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later.

(B) For each light-water nuclear power reactor that does not rely upon an inerted atmosphere to control hydrogen inside the containment, analyses shall be performed to show that containment structural integrity as defined in § 50.44(c)(3)(iv) will be maintained, and systems and components necessary to establish and maintain safe cold shutdown and maintain containment integrity will be capable of performing their functions during and after being exposed to the environmental conditions created by the burning of hydrogen, including the effect of local detonations. These analyses shall be completed and submitted as follows: for each boiling light-water nuclear power reactor with a Mark III type containment and each pressurized light-water nuclear power reactor with an ice condenser type containment, by [one year after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later; for every other light-water nuclear power reactor for which these analyses are required, by [two years after the effective date of the rule] or the date of issuance of a license authorizing operation above 5 percent of full power, whichever is later.

Dated at Washington, D.C., this 18th day of December 1981.

For the Nuclear Regulatory Commission.

Samuel J. Chilk,

Secretary of the Commission.

[FR Doc. 81-36558 Filed 12-22-81; 8:45 am]

BILLING CODE 7590-01-M

CIVIL AERONAUTICS BOARD

14 CFR Part 250

[EDR-436; Economic Regulations Docket No. 39932]

Denied Boarding Compensation Rules; Comprehensive Review

December 9, 1981.

AGENCY: Civil Aeronautics Board.

ACTION: Notice of Proposed Rulemaking.

SUMMARY: The CAB is initiating a comprehensive review of its oversales and denied boarding compensation rules as part of its examination of consumer protection regulations prior to sunset. The Board is seeking comment on, first, eliminating all governmental oversight in this area and, second, retaining the present rules with modifications. This rulemaking is at the Board's initiative.

DATES: Comments by: February 22, 1982; Reply comments by: March 9, 1982.

Comments and other relevant information received after this date will be considered by the Board only to the extent practicable.

Requests to be put on the Service List: January 7, 1982.

APPENDIX E

FEDERAL REGISTER/VOL. 50, NO. 17, FRIDAY, JANUARY 25, 1985, 10 CFR PART 50, "HYDROGEN CONTROL REQUIREMENTS"

7 CFR Part 910

[Lemon Reg. 500]

Lemons Grown in California and Arizona; Limitation of Handling

AGENCY: Agricultural Marketing Service, USDA.

ACTION: Final rule.

SUMMARY: This regulation establishes the quantity of fresh California-Arizona lemons that may be shipped to market at 225,000 cartons during the period January 27–February 2, 1985. Such action is needed to provide for orderly marketing of fresh lemons for the period due to the marketing situation confronting the lemon industry.

DATES: Effective for the period January 27–February 2, 1985.

FOR FURTHER INFORMATION CONTACT: William J. Doyle, Chief, Fruit Branch, F&V, AMS, USDA, Washington, D.C. 20250, telephone 202–447–5975.

SUPPLEMENTARY INFORMATION: This final rule has been reviewed under Secretary's Memorandum 1512–1 and Executive Order 12291, and has been designated a "non-major" rule. William T. Manley, Deputy Administrator, Agricultural Marketing Service, has certified that this action will not have a significant economic impact on a substantial number of small entities.

This final rule is issued under Marketing Order No. 910, as amended (7 CFR Part 910) regulating the handling of lemons grown in California and Arizona. The order is effective under the Agricultural Marketing Agreement Act of 1937, as amended (7 U.S.C. 601–674). The action is based upon recommendations and information submitted by the Lemon Administrative Committee and upon other available information. It is found that this action will tend to effectuate the declared policy of the act.

This action is consistent with the marketing policy currently in effect. The committee met publicly on January 22, 1985, at Los Angeles, California, to consider the current and prospective conditions of supply and demand and recommended a quantity of lemons deemed advisable to be handled during the specified week. The committee reports that lemon demand is good on mid sizes and easier on the smaller and larger sizes of fruit.

It is further found that it is impracticable and contrary to the public interest to give preliminary notice, engage in public rulemaking, and postpone the effective date until 30 days after publication in the **Federal Register** (5 U.S.C. 553), because of insufficient time between the date when information became available upon which this regulation is based and the effective date necessary to effectuate the declared purposes of the act. Interested persons were given an opportunity to submit information and views on the regulation at an open meeting. It is necessary to effectuate the declared purposes of the act to make these regulatory provisions effective as specified, and handlers have been apprised of such provisions and the effective time.

List of Subjects in 7 CFR Part 910

Marketing agreements and orders, California, Arizona, Lemons.

PART 910—[AMENDED]

Section 910.500 is added as follows:

§ 910.500 Lemon Regulation 500.

The quantity of lemons grown in California and Arizona which may be handled during the period January 27, 1985, through February 2, 1985, is established at 225,000 cartons.

(Secs. 1–19, 48 Stat. 31, as amended (7 U.S.C. 601–674))

Dated: January 23, 1985.

William J. Doyle,

Acting Deputy Director, Fruit and Vegetable Division, Agricultural Marketing Service.

[FR Doc. 85–2089 Filed 1–24–85; 8:45 am]

BILLING CODE 3410–02–M

NUCLEAR REGULATORY COMMISSION

10 CFR Part 50

Hydrogen Control Requirements

AGENCY: Nuclear Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Commission is amending its regulations to improve hydrogen control capability for boiling water reactors with MARK III containments and for pressurized water reactors with ice condenser containments. The amendments require improved hydrogen control systems that can handle large amounts of hydrogen during and following an accident. For those of the above reactors not relying upon an inerted atmosphere for hydrogen control, the rule requires that certain systems and components be able to function during and following hydrogen burning. The rule also requires affected licensees to submit analyses to the Commission in support of the previous two requirements. The rule is needed to improve the capability of the indicated types of nuclear power reactors to withstand the effects of a large amount of hydrogen generation and release to containment from an accident, as occurred at Three Mile Island. The new requirements will result in greater assurance that nuclear power reactor containments and safety systems and components will continue to function properly so that reactors can be safely shut down following a Three Mile Island-type of accident.

EFFECTIVE DATE: February 25, 1985.

FOR FURTHER INFORMATION CONTACT: Morton R. Fleishman, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC 20555, Telephone 301–443–7616.

SUPPLEMENTARY INFORMATION:

Background

The Commission has taken numerous actions to correct the design and operational limitations that were revealed by the accident at Three Mile Island, Unit 2 (TMI–2), which resulted in a severely damaged or degraded reactor core, in a concomitant release of radioactive material to the primary coolant system, and in a fuel cladding-water reaction causing the generation of a large amount of hydrogen. Included in these actions are several rulemaking proceedings intended to improve the hydrogen control capability of light-water nuclear power reactors.

On December 23, 1981, the Commission published in the **Federal Register** (46 FR 62281) a notice of proposed rulemaking on "Interim Requirements Related to Hydrogen Control," inviting written comments or suggestions on the proposed rule by February 22, 1982. A notice extending the comment period for an extra 45 days to April 8, 1982, including editorial corrections, was published in the **Federal Register** on February 25, 1982 (47 FR 8203). The notice concerned proposed amendments to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," which would have required that:

a. Each boiling water reactor (BWR) with a Mark III type containment and each pressurized water reactor (PWR) with an ice condenser type containment be provided with a hydrogen control system capable of handling an amount of hydrogen equivalent to that which would be generated if there were at least a 75 percent fuel cladding-water reaction without loss of containment integrity;

b. Each boiling water reactor and each pressurized water reactor that does not rely on an inerted atmosphere for hydrogen control be provided with safety systems needed to establish and maintain safe cold shutdown and maintain containment integrity that can function after the burning of substantial amounts of hydrogen; and

c. Analyses be performed for the reactor categories mentioned above to justify the hydrogen control systems selected and to assure containment structural integrity and survivability of needed safety systems during a hydrogen burn.

It should be noted that the proposed rule was not part of the separate, long-term rulemaking on degraded or melted cores (the "severe accident rulemaking") for which an advance notice of proposed rulemaking was published on October 2, 1980 (45 FR 65474) and which was the subject of the "Proposed Commission Policy Statement on Severe Accidents and Related Views on Nuclear Reactor Regulation," published in the **Federal Register** on April 23, 1983 (48 FR 16014).

General Comments

Twenty-eight persons submitted comments regarding the proposed amendments. The comments and the SECY paper noted above are part of the public record and may be examined and copied, for a fee, in the Commission's Public Document Room at 1717 H Street, NW., Washington, DC. A summary of the comments and a comment analysis are also available for inspection and copying, for a fee, in the Public Document Room.

The comments received have been carefully reviewed and evaluated during preparation of this final rule. The final rule contains revisions to the proposed rule that reflect consideration of these comments. The commenters generally provided many specific comments on all aspects of the proposed amendments. The following discussion represents a distillation of the more significant comments.

Numerous commenters suggested that the implementation of the Hydrogen Control Rule should be deferred until the severe accident rulemaking (see above) when applicable research and probabilistic risk analyses (PRAs) will be completed. The Commission agrees with these comments relative to PWRs with large, dry containments. Dry containment designs have a greater inherent capability to accommodate large quantities of hydrogen because of their high design pressure and large volume; therefore, for these designs the Commission believes that rulemaking with regard to hydrogen control can be safely deferred pending completion of NRC- and industry-sponsored research which includes studying the effects of hydrogen burning at higher concentration to determine effects on equipment survivability. Furthermore, with regard to systems and components that must be able to function during and following hydrogen burning, the fact that TMI-2 was shut down and maintained in a shutdown condition indicates that such systems and components did generally perform their functions following the burn event. In addition, design improvements that have been implemented as a result of NRC directives have served to reduced the likelihood of a degraded core accident.

With regard to BWRs with Mark III containments and PWRs with ice condenser containments, the Commission believes that these containments can safely accommodate the burning in a single event of the hydrogen from about a 25 percent metal-water reaction.[1] However, since the TMI-2 accident showed that a 45–50 percent metal-water reaction was possible, the Commission believes that it is necessary to enhance the hydrogen control capability for reactors with these types of containments and that new regulations are required to ensure that the proper design features are incorporated. Adoption of the final rule will also formalize Commission regulatory decisions currently being applied on a case-by-case basis in individual licensing proceedings and will provide the needed basis for regulatory actions that cover licensing and continued operation of the affected plants.

Several commenters stated that the 75 percent metal-water reaction required to be assumed for design and analysis is unreasonably high based on evaluation of the TMI-2 accident and analyses of recoverable degraded core accidents.[2] The 75 percent metal-water reaction chosen by the Commission is greater than that which occurred during the TMI-2 accident; however, the primary intent of the rule is to require containment designs that can accommodate accident sequences in which hydrogen combustion poses a significant threat to containment integrity. Consquently, the Commission believes it is prudent to specify a value sufficiently greater than that which was estimated to have occurred at TMI-2 so that there will be an appropriate margin of safety. The Commission feels confident that there will be an appropriate margin of safety. The Commission feels confident that the 75 percent value is representative of a limiting case degraded core accident (beyond which a core melt is expected to occur under all circumstances). Finally, the Commission sees no significant benefit in reducing the metal-water reaction to a level such as 50 percent for those plants having Mark III and ice condenser containments since the basic design of the heretofore chosen igniter system would not change.

A number of commenters recommended that the requirement for a hydrogen control system be revised to permit licensees the option of demonstrating analytically that additional hydrogen control systems are not necessary because of intrinsic design capabilities that reduce the likelihood of hydrogen generation. While it is true that design features to reduce hydrogen generation are necessary and desirable, the Commission still believes that, in order to cope with unexpected events, there should be a solution to the hydrogen issue that involves design features that ensure containment integrity, even if a large amount of hydrogen is generated. Thus, while measures to prevent the generation of large amounts of hydrogen are necessary and desirable, the Commission believes that it is also necessary, depending upon containment design, to provide measures to mitigate the effects of large amounts of hydrogen.

Some commenters indicated that, since the primary function of the containment is to prevent excessive radiation dose to the public, the rule should be modified to preclude the loss of containment function rather than to preclude the loss of containment intergrity. The Commission appreciates the fact that some nuclear plants are designed with a multi-building, multi-barrier concept that is intended to prevent the leakage of radiation by diverse methods such as filtering and scrubbing mechanisms, plate-out

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[1] The basis for this belief is contained in SECY 80-107, "Proposed Interim Hydrogen Control Requirements for Small Containments," February 22, 1980, which is available for inspection and copying for a fee at the Commission's Public Document Room at 1717 H Street, N.W., Washington, D.C.

[2] See the following studies, available for inspection at the Commission's Public Document Room at 1717 H Street, NW, Washington, D.C. Also NUREG and NUREG/CR publications may be purchased from the NRC/GPO Sales Program by calling (301) 492–9530.

NUREG/CR2540, "A Method for the Analysis of Hydrogen and Steam Releases to Containment During Degraded Core Cooling Accidents," February 1982.

NUREG/CR-1219, "Analysis of the Three Mile Island Accident and Alternative Sequences," January 1980.

"Report on Hydrogen Control Accident Scenarios, Hydrogen Generation Rates and Equipment Requirements," Rev. 1, July 1982—Submitted by the BWR/6 MARK III Hydrogen Control Owners Group mechanisms, and containment sprays. However, the Commission's safety philosophy remains the same; namely, the containment should be designed to remain intact following a recoverable degraded core accident in order to provide additional assurance that excessive radiation will not be released. In other words, the Commission reaffirms its policy that the prevention of excessive radiation dose to the public can best be assured by maintaining a leak tight containment and that this, in turn, can be provided by assuring that there is structural integrity with margin.

Some commenters stated that the criterion for containment structural integrity is unnecessarily restrictive. They stated that it should not be limited to the provisions of the ASME Boiler and Pressure Vessel Code, but should permit the use of other methods such as realistic analyses using actual material properties. The Commission agrees with this comment and has modified the rule in this regard. Section 50.44(c)(3)(iv) has been changed to indicate that "containment structural integrity must be demonstrated by use of an analytical technique that has been accepted by the NRC staff." The rule includes two alternative methods as examples but does not preclude other methods that may be shown to be acceptable to the Commission. Finite element analysis would be acceptable for use with the methods considered.

It was suggested by some commenters that the rule should address only non-inerted, small-volume, low-pressure containments since, for these containments, it would provide, at best, insignificant improvements in safety. The Commission agrees for the reasons indicated above; therefore, as indicated previously, it has revised the rule to apply only to Mark III BWRs and ice condenser PWRs.

A number of commenters stated that the rule ignores those post-TMI suggested improvements which have been implemented and which reduce the likelihood of a degraded core accident. In the case of PWRs with large dry containments, as discussed above, the Commission believes that the post-TMI improvements, along with the inherent strength of the containments, have indeed provided sufficient safety to permit the delay of any additional rulemaking until completion of ongoing research programs.

It has been recommended that in view of the small probability of occurrence of local detonations as a result of various design features, the rule should permit licensees the option of demonstrating that local detonations. The Commission agrees and has modified paragraphs 50.44(c)(3)v) and (vi) of the rule appropriately.

Many commenters indicated that they believe the requirement that systems and components that can function after a hydrogen burn be provided for "safe cold shutdown" is unnecessary and is inconsistent with the licensing basis for most operating plants which requires only "safe shutdown". Those commenters felt that the safe shutdown criterion should not be an issue with regard to hydrogen control, but that it should be considered in another forum. Because of the fact that a degraded core accident is less likely than a design basis accident, the Commission agrees that the requirement for cold shutdown may be overly conservative. The licensing basis for most plants is, in fact, just safe shutdown. The reference to cold shutdown has been deleted from the rule; but the Commission notes that the issue of safe shutdown versus safe cold shutdown has not yet been resolved. The issue is expected to be addressed within the context of the resolution of Unresolved Safety Issue (USI) A-45, "Shutdown Decay Heat Removal Requirements," which is the subject of current NRC staff effort.

Several commenters have suggested that the implementation schedules should be made more realistic so that design changes logically follow after the required analyses are completed. The Commission agrees. The greatest relief, of course, has come by defering implementation of the rule for PWRs with large dry containments. However, the rule has also been revised to specify that each applicant and licensee subject to the rule shall propose a schedule, to the Commission, for meeting the requirements. A final schedule for implementing the requirements shall be established by the NRC staff either in accord with a previously approved intergrated scheduling system or by accounting for the relative safety priorities and required licensing actions of each case. For those applicants about to receive an operating license the hydrogen control system must be installed and operational prior to operation of the reactor in excess of 5 percent power; however, a completed final supporting analysis may be delayed provided a preliminary analysis has been provided and found acceptable by the NRC staff. Furthermore, if the NRC staff has previously determined for similar plants referenced in this rulemaking that similar hydrogen control systems are acceptable, they may, until the preliminary analysis is completed, also find the hydrogen control system acceptable.

Some commenters noted that in the Supplementary Information accompanying the proposed rule it was stated that the selection of the hydrogen control system should be supported by comparative analysis of alternative systems to show their relative advantages and disadvantages. They stated that this guidance is inconsistent with Commission practice and is unnecessary. They felt that the only requirements should be a demonstration that the selected system is suitable for its intended application.

The Commission agrees that this guidance was inconsistent with Commission practice in the case of operating reactors and reactors for which operating licenses are about to be issued in the near-term. In the final rule, § 50.44(c)(3)(vi) has been modified to delete the implication that comparative analyses are required and to indicate that the analysis is intended to support the design of the hydrogen control system that is selected. Comparative analyses of alternative systems are not required.

Hydrogen Control Systems [§ 50.44(c)(3)(iv)]

As originally proposed, applicants and licensees with boiling water reactor (BWR) facilities with Mark III type containments and pressurized water reactor (PWR) facilities with ice condenser type containments, for which contruction permits were issued prior to March 28, 1979, are required to install hydrogen control systems capable of accommodating an amount of hydrogen equivalent to that generated from the reaction of 75 percent of the fuel cladding (surrounding the active fuel region), with water, without loss of containment integrity. The particular type of hydrogen control system to be selected is left to the discretion of the applicant or licensee; however, the NRC must find it acceptable based upon suitable programs of experiment and analysis. The design of the selected system must be supported by the analyses which are to be submitted as part of the analyses required under § 50.44(c)(3)(vi). The system that is proposed and approved must safety accommodate large amounts of hydrogen, and operation of the system, either intentionally or inadvertently, must not further aggravate the course of an accident or endanger the plant during normal operations. As discussed previously, the amount of hydrogen to be assumed in the design of the hydrogen control system is that amount generated when 75 percent of the fuel cladding surrounding the active fuel region reacts with water.

As discussed above, the limited method proposed to demonstrate containment structural integrity has been expanded. Containment structural integrity may now be demonstrated by use of an analytical technique that has been accepted by the NRC staff. For example, finite element analysis is one acceptable technique for use with the methods considered. One of the acceptable methods is the use of the applicable ASME Boiler and Pressure Vessel Code. However, the Commission will accept other methods, provided that convincing evidence is presented regarding their suitability.

Other changes from the proposed rule are the relaxation of the implementation schedule to one that has been mutually agreed upon by the licensee and the NRC staff, and the elimination of the word "cold" in the phrase "safe cold shutdown."

Systems and Components [§ 50.44(c)(3)(v)]

At the time the proposed rule was issued for comment, the Commission indicated that it was considering a two-step approach to address "qualification" (as defined below) of those systems and components that must be able to function during and after a hydrogen burn. For the reasons explained below, the Commission did not choose this two-step approach. As the proposed first step, there would have been a demonstration that these systems and components could "survive" the hydrogen burn and continue to be able to perform their safety function. This step would not have entailed that these systems and components actually be qualified pursuant to NRC's qualification program. The proposed second step would have entailed the actual "qualification" of these systems and components. The conceptual differences between systems and components demonstrated to be "survivable" and systems and components demonstrated to be "qualified" were also described.

The Commission specifically sought comments on the use of the two-step approach for defining standards, on the "survivability" and "qualification" approaches themselves, and on proposals for implementation schedules. There were numerous comments in response to this request. The overwhelming reaction was that the two-step approach to reaching a survivability determination is unwarranted and will unnecessarily escalate the costs to industry. Many commenters felt that a straightforward survivability approach would be appropriate provided reasonable guidelines are specified. In view of the smaller likelihood of a degraded core accident as compared to a design basis accident, which has been reduced further by post-TMI improvements, the Commission has decided to forego the two-step approach previously described. The Commission now believes, in view of the recent issuance of 10 CFR 50.49, "Environmental Qualification of Electrical Equipment Important to Safety," that there is no significant difference between demonstrating survivability and demonstrating qualification. Paragraph (f) of § 50.49 describes several methods, one of which must be used, for qualifying electrical equipment important to safety. For example, for those licensees which have already demonstrated survivability, as described in the Supplementary information of the notice of proposed rulemaking for this rule on hydrogen control requirements (46 FR 62281, Dec. 23, 1981), the qualification methods described in paragraph (f)(2) and (f)(4) of § 50.49 could be used to show that the systems and components have been qualified. In this regard, the margins considered adequate for a degraded core accident are less than those considered adequate for a design-basis accident due to the lower probability of occurrence of a degraded core accident.

The Commission now views "qualification" as the generation and maintenance of evidence using tests and analyses to assure that systems and components will operate on demand to meet system performance requirements. In the case of a hydrogen burn environment, this means that there must be adequate evidence that systems and components necessary to establish and maintain safe shutdown and to maintain containment integrity are capable of performing their functions during and after exposure to the environmental conditions created by the postulated accident, including the burning of hydrogen. Qualification may be demonstrated in a manner acceptable to the Commission using a combined approach of analysis and testing. Thus, an acceptable thermal analysis would have to be performed for the containment in order to determine the thermal response of the components during a hydrogen burn. This thermal response should then be compared to the thermal response the components had during their qualification testing. The licensee should then demonstrate that the qualification thermal response envelopes the thermal response during a hydrogen burn. Selected tests should also be performed at predicted hydrogen burn conditions (or, other tests previously performed may be referenced if demonstrated to be applicable) to reasonably assure the Commission that the systems and components are qualified to perform their functions during and following a hydrogen burn. The demonstrations of survivability accepted by the staff for Sequoyah and McGuire without more testing, analysis or documentation are equivalent to demonstrations of qualification for a hydrogen burn event, and the staff does not require any other submittal from the licensees except for the previously identified confirmatory items.

Paragraph 50.44(c)(3)(v) applies to those Mark III BWRs and ice condenser PWRs that do not have an inerted containment atmosphere for hydrogen control. At present, this includes all Mark III BWRs and ice condenser PWRs, since no applicant or licensee has as yet elected to use the inerting option for these plants. The systems and components that must be qualified for a hydrogen burn are those needed (a) to shut down the reactor and bring it to and maintain it in a safe shutdown condition, and (b) to prevent loss of containment integrity. These systems and components can be further categorized as follows:

a. Systems and components mitigating the consequences of the accident;

b. Systems and components needed for maintaining integrity of the containment pressure boundary;

c. Systems and components needed for maintaining the core in a safe condition; and

d. Systems and components needed for monitoring the course of the accident.

As discussed previously, these systems and components are described as bringing the reactor to "safe shutdown" rather than "safe cold shutdown." Furthermore, the schedule for implementation has been changed to one that has been mutually agreed upon by the licensee and the NRC staff. Finally, the rule has been revised to indicate that the environmental conditions to be assumed for a hydrogen burn do not have to include the effect of local detonations if it is shown to the Commission's satisfaction that local detonations are unlikely to occur.

Analyses [§ 50.44(c)(3)(vi)]

In the proposed rule, the Commission included a description of three different approaches concerning the supplementary guidance to be provided for performing the required analyses for the design of the hydrogen control system. These were (a) analyses of different accident scenarios, (b) analyses of a single accident scenario with variation of key parameters, and (c) analyses using an "envelope of time histories of hydrogen and steam release rates" to be supplied by the Commission. The Commission requested comments concerning which of the approaches was preferred as well as suggestions regarding improvements or other alternatives.

There was no preponderance of comments leaning toward a particular approach; however, the first two approaches appeared to have greater support. Furthermore, many commenters felt that there should be flexibility in the approach to be used in the selection of the accident scenarios. It was also suggested that the accident scenarios should be considered in order of importance using PRA techniques.

Based on the comments received and in consideration of the improved calculational data base now available, the Commission has decided to adopt the second approach; applicants and licensees need not use the first or third approaches.

In the selected approach, a base sequence will be identified by the licensee or applicant based on the hydrogen threat to containment integrity. Key aspects of this sequence should then be parametrically varied by the licensee or applicant in determining the acceptability of the containment response. This will provide a wider range of parameters than that of the selected base sequence alone. The acceptability of the analyses used in this approach depends on the selection and range of the parameters being varied. A range must be chosen which includes the effects of recovery from the degraded condition. It is expected that each applicant or licensee will review its analytical approach with the NRC staff and arrive at a mutually agreeable method for performing the analyses.

As an example, in the recent Sequoyah case [3], the applicant based its initial analysis on an accident sequence involving a small break LOCA followed by loss of ECCS (S_2D), with a typical average hydrogen release rate of about 20 pounds per minute, which the NRC staff considered to be representative of the accident. However, several concerns remained open. Among these were the possibilities that: (1) Other scenarios might present schedules of steam and hydrogen release not covered by the analysis chosen; (2) steam inerting might occur at some time during the sequence allowing large concentrations of hydrogen to develop; (3) the recovery period might produce an exceptionally large burst of steam or hydrogen; and (4) hydrogen might be released after the loss of the ice heat sink.

In the Sequoyah case, the applicant broadened the studies to include higher rates of steam and hydrogen release and release after the ice melted. The broadened calculations included hydrogen releases rates as high as 6 lb. per second under representative steam conditions, with and without ice. It was shown that a representative selection of scenarios would be bounded by the broadened release rates, including an intermediate break LOCA with loss of ECC (S_1D), a small break LOCA with loss of containment heat removal (S_2C), a transient loss of main feedwater and loss of all AC power (T_BB_1), and a transient loss of main feedwater, loss of auxiliary feedwater and loss of the ECC (T_BLD). The staff concluded that the coverage of these additional scenarios was sufficient to assure that the hydrogen associated with a representative group of degraded core situations could be managed acceptably using the ignition systems.

As another example, in the McGuire case [4], hydrogen release rates up to 4.3 lb. per second under representative steam conditions were considered and the S_2D releases were analyzed with and without ice. The results were considered acceptable by the staff.

The staff has accepted ac-powered igniters without requiring a backup power supply in the two examples cited above. This judgment was based upon the staff's perception that the incremental risk reduction associated with provision of the igniter system backup power supply did not warrant the additional cost at these particular facilities. Provision of a backup power supply is not required by this rule.

It is apparent that applicants and licensees with conceptually different reactors may have to address other scenarios. The appropriate details for Mark III BWRs, for example, are currently being worked out through interaction between the NRC staff and applicants.

Previously approved generic or reference analyses may be employed in lieu of plant specific anlayses where the generic analyses can be shown to be applicable. It is believed that the adoption of the above approach will eliminate the need for repetitive calculation of accident scenarios.

Dissenting Views of Commisssioner Asselstine

I vote to approve publication of the Commission's final hydrogen control rule on December 10, 1984, and I continue to support the version of the rule that was approved unanimously by the Commission on that date. However, I cannot support the Commission's final rule being published today because of a significant sustantive change in the rule that was made by my colleagues at the eleventh hour.

The change adopted by the Commission majority adds the following new sentence to the implementation provisions of § 50.44(c)(3)(vii)(B) of the rule:

> However, the record in this rulemaking shows that such preliminary analyses are not necessary for a staff determination that a plant is safe to operate at full power if the staff has determined for similar plants, referenced in this notice of rulemaking, that similar systems provide a satisfactory basis for a decision to support operation at full power until the preliminary analyses have been completed.

Under this provision, so long as the license applicant's plant is similar to the Sequoyah and McGuire plants (the two ice condenser pressurized water reactor plants referenced in this notice of rulemaking with staff-approved hydrogen control systems) and uses a hydrogen control system similar to the igniter systems used in those two plants, the applicant need not submit, and the NRC staff need not approve, a preliminary analysis of the adequacy of the hydrogen control system prior to the full-power operation of the plant. The practical effect of this new sentence is to deny intervenors in some nuclear powerplant operating license proceedings the opportunity for a hearing on the adequacy of the hydrogen control measures and analyses supporting interim operation of these plants. The immediate purpose of this change is to bolster the Commission's litigation position concerning the handling of hydrogen control issues in one such proceeding—the operating license proceeding for the Catawba plant—the only plant to which this sentence appears to apply.

There are two problems with the Commission's majority's actions that lead me to disapprove the revised rule. First, members of the public were not afforded a fair opportunity to comment

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[3] NUREG-0011, Supplement No. 6, "Safety Evaluation Report Related to the Operation of Sequoyah Nuclear Plant, Units 1 and 2," November 1982. Available for inspection at the Commission's Public Document Room at 1717 H Street, NW., Washington, D.C.

[4] NUREG-0422, Supplement No. 7, "Safety Evaluation Report Related to Operation of McGuire Nuclear Station Units 1 and 2," May 1983. Available for inspection at the Commission's Public Document Room at 1717 H Street, NW., Washington, D.C.

on the option of using the Commission's final hydrogen control rule as means to eliminate the opportunity to litigate the adequacy of hydrogen control systems and analyses in individual nuclear powerplant operating license proceedings. The Commission's proposed rule published for comment on December 23, 1981 would not have affected the opportunity of intervenors to obtain a hearing on the adequacy of hydrogen control systems and analyses to support interim plant operation, and neither the Commission's proposed rule nor the accompanying supplementary information made any mention of this possibility. To the contrary, the supplementary information on the proposed rule, although stating the Commission's general conclusion that there is sufficient information available to warrant interim approval of deliberate ignition systems for ice condenser plants, emphasized the need for individual licensees to demonstrate certain plant-specific elements, including the ability of essential equipment to continue to function during and after a hydrogen burn. Moreover, the supplementary information clearly recognized that the adequncy of hydrogen control systems for certain types of plants (those with ice condenser and Mark III containments) is a significant safety issue affecting full-power operation of these plants. Thus, the proposed rule when read together with the Commission's contemporaneous practice of allowing case-by-case adjudication of hydrogen control issues clearly did not put anyone on notice that the Commission might use the rule to prohibit litigation of this issue in proceedings. The Commission, then, effectively denied members of the public the opportunity to comment on this significant aspect of the final rule.

Second, it is inappropriate for the Commission to use this rulemaking in an effort to bolster its litigation position in the *Catawba* operating license proceeding. The Commission's interest in using this rulemaking proceeding to restrict the case-by-case litigation of hydrogen control issues only developed after the Commission became aware of a potential litigation problem in the *Catawba* operating license proceeding caused by the Licensing Board's refusal to allow intervenors to litigate the adequancy of the Catawba hydrogen control system and analyses supporting interim operation of the plant. The Commission is again tailoring a generic rulemakinig to solve a case-specific litigation problem. Further, this last-minute effort to provide another basis for rejecting the intervenor's hydrogen control contentions in the *Catawba* case is inappropriate and unseemly, and represents still another example of the Commission's hostility to public participants in our licensing proceedings. For the foregoing reasons, I cannot support the revised rule being published by the Commission today.

Apart from these concerns, there are two other deficiencies in the final rule that I would have corrected. However, these two further deficiencies would not have led me to disapprove the rule. First, the rule is limited to boiling water reactors with Mark III containments and pressurized water reactors with ice condenser containments, and fails to include pressurized water reactors with large dry containments. For the reasons set forth below, I believe that the portions of the rule dealing with equipment survivability and containment integrity should apply to pressurized water reactors with large dry containments as well.

This rule establishes a 75 percent metal-water reactor level as the prudent standard to be assumed for the design and analysis of hydrogen control systems that are necessary to ensure no undue risk to the public health and safety. A fundamental element in setting the 75 percent metal-water reaction limit is the assumption that sufficient equipment will survive a hydrogen burn or detonation to arrest the course of the accident and thereby prevent a degraded core accident from proceeding to an accident involving melting of the reactor core—an accident that could involve the generation of much more hydrogen than would be associated with a 75 percent metal-water reaction. In addition, the rule adopts as a principal objective maintaining a leak tight containment following a hydrogen burn or detonation.

At the same time, the rule recognizes that a hydrogen burn or detonation in the containment could damage equipment, cables or penetrations in a manner that would impair or eliminate the capability to arrest the accident or that would result in the loss of containment integrity. For this reason, the rule requires in § 50.44(c)(3)(v) that licensees for plants covered by the rule demonstrate that equipment needed to establish and maintain safe shutdown and to maintain containment integrity will survive a hydrogen burn.

These concerns regarding the survivability of equipment, cables and penetrations following a hydrogen burn apply with equal force to pressurized water reactors with large dry containments. The systems and components necessary to establish and maintain safe shutdown capability and containment integrity for reactor designs in large dry containments are essentially the same as those systems and components in the plants with ice condenser containments. Similarly, the potential for the generation of hydrogen from a 75 percent metal-water reaction is essentially the same in plants with large dry and ice condenser containments. In addition, the systems and components in plants with large dry containments are at least as susceptible to damage from a hydrogen burn produced in a 75 percent metal-water reaction as are the systems and components in plants with ice condenser containments. In fact, given that large dry containments will have no required hydrogen control system to cope with large quantities of hydrogen, higher concentrations of hydrogen can be formed in large dry containments before a random event ignites the hydrogen than would be the case for plants with ice condenser containments and a hydrogen control system. Thus, the environmental conditions in large dry containments could be more challenging than those in the plants with ice condenser containments.

For these reasons, I would have applied the equipment survivability and containment integrity provisions of § 50.44(c)(3)(v) to pressurized water reactors with large dry containments as well. Additional research may well be useful in confirming the accuracy of licensees' analyses on equipment survivability and containment penetration performance, but this ongoing research should not serve as an excuse for delaying the imposition of the equipment survivability and containment integrity requirements of the rule for plants with large dry containments.

Second, I would have revised the rule to specify that the hydrogen control systems required by the rule be automatically initiated based upon plant parameters deemed acceptable by the NRC staff. This change would have eliminated the need to rely on operator action to activate the hydrogen control system.

Chairman Palladino's Statement on Hydrogen Control Rulemaking

I have the following comments regarding the dissenting views of Commissioner Asselstine:

Notice of Proposed Rulemaking

One of the purposes of rulemaking is to address and resolve issues so that they are not the subject of litigation in particular licensing cases unless the final rule provides for that result.

With respect to the hydrogen control rule, the Commission stated in the Notice of Proposed Rulemaking, "The Commission concludes, based on available information, that the issues are sufficiently resolved to warrant interim approval of deliberate ignition systems for ice condenser plants." The rulemaking notice also made reference to the deliberate ignition systems installed at the Sequoyah and McGuire plants.

Regarding the *Catawba* operating license proceeding, the intervenors were placed on actual notice on at least two occasions of the hydrogen control rulemaking. On the first occasion—March 5, 1982—the Licensing Board, in ruling on pending petitions for intervention, declined to admit contentions because the issue they addressed was being considered in the hydrogen control rulemaking. The second occasion came on December 1, 1982 in a second Licensing Board ruling on contentions, where the Board stated that the hydrogen control rulemaking directly addressed the intervenors' hydrogen concerns.

I do not believe that issues which have been addressed in the hydrogen control rulemaking should be the subject of case-specific litigation.

Coverage of the Rule

Two specific technical concerns raised by Commissioner Asselstine were: (1) the rule fails to include pressurized water reactors (PWR's) with large dry containments, and (2) the rule failed to require that hydrogen control systems by automatically initiated. These were specifically addressed during the rulemaking process.

The scope of the rule was limited to include non-inerted boiling water reactors (BWR) III and ice condenser PWR designs and to specifically exclude inerted BWR I and BWR II designs and large containment PWR designs. Regarding inclusion of large dry PWR containment designs, the need for additional regulation is being deferred to the time of the seven accident rulemaking decision since hydrogen control is not considered to be an immediate safety concern.

Regarding the need for automation, the advantages and disadvantages of manual vs automatic actuation of the distributed igniter systems were evaluated as part of the rulemaking, and manual actuation was concluded to be acceptable.

Regulatory Analysis

The Commission has prepared a regulatory analysis for this regulation. The analysis examines the costs and benefits of the rule as considered by the Commission. A copy of the regulatory analysis is available for inspection and copying for a fee at the NRC Public Document Room, 1717 H Street, N.W., Washington, D.C. Single copies of the analysis may be obtained from Morton R. Fleishman, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Telephone (301) 443-7616.

Paperwork Reduction Act

This final rule imposes information collection requirements that are subject to the Paperwork Reduction Act of 1980 (44 U.S.C. 3501, *et seq.*) These requirements were approved by the Office of Management and Budget, Approval Number 3150-0011.

Regulatory Flexibility Act

In accordance with the Regulatory Flexibility Act of 1980, 5 U.S.C. 605(b), the Commission hereby certifies that this rule will not, if promulgated, have a significant economic impact on a substantial number of small entities. This rule affects only the licensing and operation of nuclear power plants. The companies that own these plants do not fall within the scope of the definition of "Small entities" set forth in the Regulatory Flexibility Act or the Small Business Size Standards set out in regulations issued by the Small Business Administration at 13 CFR Part 121. Since these companies are dominant in their service areas, this rule does not fall within the purview of the act.

List of Subjects in 10 CFR Part 50

Antitrust, Classified information, Fire prevention, Incorporation by Reference, Intergovernmental relations, Nuclear power plants and reactors, Penalty, Radiation protection, Reactor siting criteria, and Reporting requirements.

PART 50—DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES

Accordingly, notice is hereby given that, pursuant to the Atomic Energy Act of 1954, as amended, the Energy Reorganization Act of 1974, as amended, and section 553 of Title 5 of the United States Code, the following amendments to 10 CFR Part 50 are published as a document subject to codification.

1. The authority citation for Part 50 continues to read as follows:

Authority: Secs. 103, 104, 161, 182, 183, 186, 189, 68 Stat. 936, 937, 948, 953, 954, 955, 956, as amended, sec. 234, 83 Stat. 1244, as amended (42 U.S.C. 2133, 2134, 2201, 2232, 2233, 2236, 2239, 2282); secs. 201, 202, 206, 88 Stat. 1242, 1244, 1246, as amended (42 U.S.C 5841, 5842, 5846) unless otherwise noted.

Section 50.7 also issued under Pub. L. 95-601, sec. 10, 92 Stat. 2951 (42 U.S.C. 5851). Sections 50.57(d), 50.58, 50.91 and 50.92 also issued under Pub. L. 97-415, 96 Stat. 2071, 2073 (42 U.S.C. 2133, 2239). Section 50.78 also issued under sec. 122, 68 Stat. 939 (42 U.S.C. 2152). Sections 50.80–50.81 also issued under sec. 184, 68 Stat. 954, as amended (42 U.S.C. 2234). Sections 50.100–50.102 also issued under sec. 186, 68 Stat. 955 (42 U.S.C. 2236).

For the purposes of sec. 223, 68 Stat. 958, as amended (42 U.S.C. 2273), §§ 50.10 (a), (b), and (c), 50.44, 50.46, 50.48, 50.54, and 50.80(a) are issued under sec. 161b, 68 Stat. 948, as amended (42 U.S.C. 2201(b)); §§ 50.10 (b) and (c) and 50.54 are issued under sec. 161i, 68 Stat. 949, as amended (42 U.S.C. 2201(i); and §§ 50.55(e), 50.59(b), 50.70, 50.71, 50.72, 50.73, and 50.78 are issued under sec. 161o, 68 Stat. 950, as amended (42 U.S.C. 2201(o)).

2. In § 50.44, paragraph (c)(3) is amended by adding new paragraphs (iv), (v), (vi) and (vii) to read as follows:

§ 50.44 Standards for combustible gas control system in light water cooled power reactors.

* * * * *

(c) * * *

(3) * * *

(iv) (A) Each licensee with a boiling light-water nuclear power reactor with a Mark III type of containment and each licensee with a pressurized light-water nuclear power reactor with an ice condenser type of containment issued a construction permit before March 28, 1979, shall provide its nuclear power reactor with a hydrogen control system justified by a suitable program of experiment and analysis. The hydrogen control system must be capable of handling without loss of containment structural integrity an amount of hydrogen equivalent to that generated from a metal-water reaction involving 75% of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume).

(B) Containment structural integrity must be demonstrated by use of an analytical technique that is accepted by the NRC staff. This demonstration must include sufficient supporting justification to show that the technique describes the containment response to the structural loads involved. This method could include the use of actual material properties with suitable margins to account for uncertainties in modeling, in material properties, in construction tolerances, and so on. Another method could include a showing that the following specific criteria of the ASME Boiler and Pressure Vessel Code are met:

(*1*) That steel containments meet the requirements of the ASME Boiler and Pressure Vessel Code (Edition and Addenda as incorporated by reference in paragraph 50.55a(b)(1) of this part), specifically in Section III, Division 1, Subsubarticle NE-3220, Service Level C Limits, considering pressure and dead load alone (evaluation of instability is not required); and

(*2*) That concrete containments meet the requirements of the ASME Boiler and Pressure vessel Code, Section III, Division 2, Subsubarticle CC-3720, Factored Load Category, considering pressure and dead load alone.

(C) Subsubarticle NE-3220, Divisin 1, and Subsubarticle CC-3720, Division 2, of Section III of the ASME Boiler and Pressure Vessel Code, referenced in paragraphs (c)(3)(iv)(B)(*1*) and (c)(3)(iv)(B)(*2*) of this section, have been approved for incorporation by reference by the Director of the Office of the Federal Register. A notice of any changes made to the material incorporated by reference will be published in the Federal Register. Copies of the ASME Boiler and Pressure Vessel Code may be purchased from the American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, N.Y. 10017. It is also available for inspection at the Nuclear Regulatory Commission's Public Document Room, 1717 H Street N.W., Washington, D.C.

(D) If the hydrogen control system relies on post-accident inerting, the containment structure must be capable of withstanding the increased pressure:

(*1*) During the accident, where it is acceptable to show that it does not exceed Service Level C Limits or the Factored load Category (as described in paragraph (c)(3)(iv)(B) of this section; and

(*2*) Following inadvertent full inerting during normal plant operations, where it is acceptable to show that it does not exceed either the Service Level A Limits of Subsubarticle NE-3220 (for a steel containment) or the Service Load Category of Subsubarticle CC-3720 (for a concrete containment.)

(*3*) Modest deviations from the criteria in paragraph (c)(3)(iv)(D) of this section will be considered by the Commission if good cause is shown.

(E) If the hydrogen control system relies on post-accident inerting, the systems and components required to establish and maintain safe shutdown and containment integrity must be designed and qualified for the environment caused by such inerting. Furthermore, inadvertent full inerting during normal plant operations must not adversely affect systems and components needed for safe operation of the plant.

(v) (A) Each licensee with a boiling light-water nuclear power reactor with a Mark III type of containment and each licensee with a pressurized light-water nuclear power reactor with an ice condenser type of containment issued a construction permit before March 28, 1979, for a reactor that does not rely upon an inerted atmosphere to control hydrogen inside the containment, shall provide its nuclear power reactor with systems and components necessary to establish and maintian safe shutdown and to maintain containment integrity. These systems and components must be capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen. Environmental conditions caused by local detonations of hydrogen must also be included, unless such detonations can be shown unlikely to occur.

(B) The amount of hydrogen to be considered is equivalent to that generated from a metal-water reaction involving 75% of the fuel cladding surrounding the active fuel region (excluding the cladding surrounding the plenum volume).

(vi) (A) Each applicant for or holder of an operating license for a boiling light-water nuclear power reactor with a Mark III type of containment or for a pressurized light-water nuclear power reactor with an ice condenser type of containment issued a construction permit before March 28, 1979, shall submit an analysis to the Director of the Office of Nuclear Reactor Regulation.

(B) The analysis required by paragraph (c)(3)(vi)(A) of this section must:

(*1*) Provide an evaluation of the consequences of large amounts of hydrogen generated after the start of an accident (hydrogen resulting from the metalwater reaction of up to and including 75% of the fuel cladding surrounding the active fuel region, excluding the cladding surrounding the plenum volume) and include consideration of hydrogen control measures as appropriate;

(*2*) Include the period of recovery from the degraded condition;

(*3*) Use accident scenarios that are accepted by the NRC staff. These scenarios must be accompanied by sufficient supporting justification to show that they describe the behavior of the reactor system during and following an accident resulting in a degraded core.

(*4*) Support the design of the hydrogen control system selected under paragraph (c)(3)(iv) of this section; and,

(*5*) Show that for those reactors described in paragraph (c)(3)(iv) of this section that do not rely upon an inerted atmosphere to control hydrogen inside the containment:

(*i*) The containment structural integrity as described in paragraph (c)(3)(iv) of this Section will be maintained; and

(*ii*) Systems and components necessary to establish and maintain safe shutdown and to maintain containment integrity will be capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen, including the effect of local detonations, unless such detonations can be shown unlikely to occur.

(vii) (A) By June 25, 1985, each applicant for or holder of an operating license subject to the requirements of paragraphs (c)(3) (iv), (v) and (vi) of this section shall develop and submit to the Director of the Office of Nuclear Reactor Regulation a proposed schedule for meeting these requirements. The schedule may be developed using integrated scheduling systems previously approved for the facility by the NRC.

(B) For each applicant for an operating license as of the effective date of this section, the schedule shall provide for compliance with the requirements of paragraph (c)(3)(iv)(A) of this section prior to operation of the reactor in excess of 5 percent power. Completed final analyses are not necessary for a staff determination that a plant is safe to operate at full power provided that prior to such operation an applicant has provided a preliminary analysis which the staff has determined provides a satisfactory basis for a decision to support interim operation at full power until the final analysis has been completed. However, the record in this rulemaking shows that such preliminary analyses are not necessary for a staff determination that a plant is safe to operate at full power if the staff has determined for similar plants, referenced in this notice of rulemaking, that similar systems provide a satisfactory basis for a decision to support operation at full power until the preliminary analyses have been completed.

(C) For those holders of operating licenses containing license conditions on Hydrogen Control Measures covered by this section, the schedule shall be consistent with those license conditions, or approved amendments thereto.

(D) For those facilities not having an NRC approved integrated scheduling system, a final schedule for meeting the requirements of paragraphs (c)(3) (iv), (v) and (vi) of this section shall be established by the NRC staff within 90 days of receipt of a proposed schedule from the licensee or applicant, taking into account the current status of efforts at the facility to comply with the requirements; analyses that may be provided by applicants or licensees regarding the impacts of these requirements on other scheduled plant modifications, including any NRC-mandated safety modifications, and their relative importance to safety; and the Commission's objective that these requirements be complied with without undue delay.

Dated at Washington, D.C., this 18th day of January 1985.

For the Nuclear Regulatory Commission.

Samuel J. Chilk,

Secretary of the Commission.

[FR Doc. 85-1965 Filed 1-24-85; 8:45 am]

BILLING CODE 7590-01-M

COMMODITY FUTURES TRADING COMMISSION

17 CFR Part 3

Registration

AGENCY: Commodity Futures Trading Commission.

ACTION: Final Order.

SUMMARY: The Commodity Futures Trading Commission ("Commission"), by order, is deferring from March 31, 1985 to March 31, 1986 the expiration date of the registration of any floor broker whose initial application for registration is granted on or after January 1, 1985, which expiration date otherwise would be March 31, 1985. The Commission is taking this action to enhance the efficient administration of the Commission's registration program.

EFFECTIVE DATE: January 25, 1985.

FOR FURTHER INFORMATION CONTACT: Kevin M. Foley, Chief Counsel, or Robert P. Shiner, Assistant Director for Registration, Division of Trading and Markets, Commodity Futures Trading Commission, 2033 K Street, N.W., Washington, D.C. 20581. Telephone: (202) 254-8955 or (202) 254-9703, respectively.

SUPPLEMENTARY INFORMATION: Effective December 3, 1984, the Commission authorized the National Futures Association ("NFA") to process and, where appropriate, grant initial and renewal applications for registration of

APPENDIX F

LIST OF HYDROGEN REFERENCES

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APPENDIX G

TECHNICAL ASPECTS OF HYDROGEN CONTROL AND COMBUSTION IN SEVERE LIGHT-WATER REACTOR ACCIDENTS

N | NAS
R | NAE
C | IOM

Technical Aspects of Hydrogen Control and Combustion in Severe Light-Water Reactor Accidents

Technical Aspects of Hydrogen Control and Combustion in Severe Light-Water Reactor Accidents

Technical Aspects of Hydrogen Control and Combustion in Severe Light-Water Reactor Accidents

A Report Prepared by the
Committee on Hydrogen Combustion
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

Although it was understood by reactor safety analysts in the late 1950s that hydrogen production during a severe reactor accident could pose additional hazard, and requirements for protecting against the consequences of hydrogen production and combustion were introduced, extensive studies of hydrogen generation and control were not initiated. The accident at the Three Mile Island Unit Two (TMI-2) nuclear power plant in 1979 resulted in the generation of appreciable quantities of hydrogen and a subsequent deflagration (the present study was completed prior to the Chernobyl nuclear power station accident in the USSR which also seems to have involved hydrogen). This incident stimulated a significant interest in gaining a better understanding of hydrogen generation and control in nuclear reactor accidents. Extensive analytical and experimental work was sponsored by the Nuclear Regulatory Commission (NuRC) and the nuclear power industry toward this end. Much of the work sponsored by the NuRC was performed at Sandia National Laboratories, Albuquerque, New Mexico.

In evaluating means of control in different containments, a decision was made by the NuRC to require a hydrogen control system in some containments, to eliminate the free hydrogen generated before dangerous concentrations could be reached. Igniters are installed in many containments for this purpose.* Deliberate ignition has also at times been considered for use in other containments such as large drys (containment structures with large volumes, on the order of 56,000 m^3, or about 2 million ft^3, and no suppression systems). Since severe core damage will almost inevitably lead to production of hydrogen, and in light of the possibility of accidental ignition such as at TMI-2, much of the research has focused on hydrogen distribution and combustion that might occur during a postulated severe accident and on implications for containment and equipment integrity.

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*The committee engaged in serious discussion of this approach. See Appendixes C and D, the minority report and a response to it, for the pros and cons of the issue.

The study leading to the present report was undertaken in response to a request made to the National Research Council's Energy Engineering Board by the Nuclear Regulatory Commission. The Committee on Hydrogen Combustion was formed in 1985, at a time when a large body of results had been collected by the hydrogen-related research programs. The committee was asked to assess the technical issues related to the fate and control of hydrogen generated in severe light-water reactor (LWR) accidents to determine the degree to which current knowledge may support regulatory decision making. In particular the committee was asked to consider several specific areas (see Statement of Task, Appendix A).

The committee was composed of seven experts in areas such as nuclear reactor safety, physics, gas dynamics, combustion, chemical kinetics, and hazard analysis.

The full committee met on August 19-20 and on October 1, 1985, in Washington, D.C. To solicit the opinion of additional experts on combustion and effects of detonation, a number of invited guests appeared before the committee. At the meeting on October 1, 1985, the following were invited to a roundtable discussion with the committee: Dr. Wilfred Baker (Southwest Research Institute, San Antonio, Texas), Dr. Martin Hertzberg (U.S. Bureau of Mines), Dr. John Lee (McGill University, Montreal, Canada), Dr. Roger Strehlow (emeritus, University of Illinois, Urbana-Champaign, Illinois), and Dr. Theofanis Theofanous, University of California, Santa Barbara. A meeting also occurred on November 18-19, 1985, in Albuquerque, New Mexico, with briefings by researchers in the Hydrogen Behavior Program at Sandia National Laboratories, Albuquerque, New Mexico. Visits were also made to Sandia's hydrogen combustion experimental facilities. Several committee members also visited the 1/4-scale model of a Mark III containment at Factory Mutual Corporation's site in West Glocester, Rhode Island. The committee had a final meeting to reach a consensus on the report and associated conclusions and recommendations on March 24, 1986.

The report is organized in six chapters. Chapter 1 provides a brief summary and lists the major conclusions and recommendations. Chapter 2 reviews the mechanisms by which a hydrogen problem might occur in a severe LWR accident and the concerns and actions that have arisen in response. The research programs undertaken are briefly reviewed as background for the succeeding technical discussion. Chapter 3 focuses on the modeling efforts that have been conducted for hydrogen migration and combustion and the reliability of inferring conditions in full-size containments from model results. The impacts of deflagrations and diffusion flames, as well as the influence of suspended water droplets on flames, are addressed in Chapter 4. Detonation phenomena, lean limits for detonation, influence of suspended water droplets and diluents, and implications for different containments of detonations are addressed in Chapter 5. Deliberate ignition and autoignition are the subject of Chapter 6. Appendix C contains the contributions of

Professor Oppenheim and the minority report he provided. Appendix D is a response by the committee to Professor Oppenheim's position. The reason for this is that Professor Oppenheim was, right from the outset of the committee's deliberations and throughout their conduct, quite critical of the particular form in which its tasks were specified, claiming that they were ill-posed and misdirected. This opinion was not shared by others, impairing his participation as a co-author of the report.

The committee thanks Dennis Miller, Executive Director of the Energy Engineering Board, for initiation and direction of this study; Dr. James Zucchetto, Senior Program Officer, for direction, organization, and preparation involved in the committee's work and its final report; and Professor Adel Sarofim for working closely with the committee as liaison from the Energy Engineering Board. Heartfelt thanks are also extended to the administrative support given by Drusilla Alston, Helen Johnson, and Cheryl Woodward.

Norman C. Rasmussen, Chairman
Committee on Hydrogen Combustion

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LIST OF SYMBOLS AND ACRONYMS

AECL	Atomic Energy of Canada Limited
AEP	American Electric Power Company
BWR	Boiling Water Reactor
BNL	Brookhaven National Laboratory
CJ	Chapman-Jouguet
DDT	Deflagration to Detonation Transition
d_s	Minimum Cloud Diameter of Hydrogen for Detonation
d_t	Threshold Tube Diameter That can Sustain a Detonation
EPRI	Electric Power Research Institute
FITS	Fully Instrumented Test Site
FLAME	Flame Acceleration Measurement Experiments
FMRC	Factory Mutual Research Corporation
FSAR	Final Safety Analysis Report
HCOG	Hydrogen Control Owners Group
HECTR	Hydrogen Event: Containment Transient Response (computer code)
HMS	Hydrogen Migration Studies
H_R	Heat of Reaction
H_2	Molecular Hydrogen
IDCOR	Industry Degraded Core Rulemaking Program
L	Mixing Length
LANL	Los Alamos National Laboratory
lbm	Pound Mass
LFL	Lower Flammability Limit
LLL	Lawrence Livermore National Laboratory
LOCA	Loss of Coolant Accident

LWR	Light-water Reactor
l_2	Induction Length
M	Mach Number
MAAP	Modular Accident Analysis Program (hydrogen generation computer code; versions exist for different types of PWR's and BWR's)
MARCH	Meltdown Accident Response Characteristics (hydrogen generation computer code)
MJ	Megajoules
MW	Megawatt
MWe	Megawatt Electric
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NuRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
PWR	Pressurized water reactor
q	Kinetic Energy
RSS	Reactor Safety Study
SNL	Sandia National Laboratories
TMI	Three Mile Island
TMI-2	Three Mile Island Unit 2
TVA	Tennessee Valley Authority
V_D	CJ Detonation Velocity
VGES	Variable Geometry Experiment System
WNRE	Whiteshell Nuclear Research Establishment
Zr	Zirconium
ZrO_2	Zirconium dioxide
γ_t	Turbulent Diffusivity
λ	Cell Size
ϕ	Equivalence Ratio

EXECUTIVE SUMMARY

The National Research Council's Energy Engineering Board, at the request of the Nuclear Regulatory Commission, formed in 1985 the Committee on Hydrogen Combustion. This committee has assessed (prior to the Chernobyl accident) the technical issues related to the fate and control of hydrogen generated during severe light-water reactor (LWR) accidents. The Commission is concerned about safety issues associated with the burning and/or detonation of hydrogen during such accidents because the combustion of hydrogen at high enough concentrations might either threaten the integrity of containment structures enclosing nuclear reactors or cause the failure of important safety equipment inside the containment. Thus, the committee sought to understand the degree to which current knowledge may support regulatory decision-making related to nuclear reactor safety. Over the years, a great deal of safety related hydrogen combustion research has been carried out under the auspices of the Commission and the nuclear power industry. For example, to simulate conditions in containment during a hydrogen generating severe LWR accident, experiments have been performed in smaller vessels and computer models have been developed. Because of the importance of this work, the committee was asked to comment on the ability to scale up, interpret, and extrapolate data from small-scale experiments to actual containments, and to assess whether all important areas of research had been adequately addressed.

At present, a variety of safety strategies are used by power plant operators to deal with the problem of hydrogen generation. There are several different containment designs used to enclose nuclear reactors. Small volume containments (Mark I and II) are made inert with nitrogen to avoid combustion. Medium volume containments (boiling water reactor Mark III and pressurized water reactor ice condenser plants) have electrical igniters distributed throughout the containments to eliminate hydrogen generated before detonable concentrations are reached. (This strategy of burning hydrogen is referred to as deliberate ignition.) Assuming uniform mixing in large volume containments (subatmospheric and large drys), these are generally considered to have enough volume so that hydrogen concentrations would not be sufficient to support a global detonation and there would be no threat to containment. Further, the Commission's position has been that the likelihood of reaching detonable concentrations in large regions of these containments is so small that neither inert atmospheres nor igniters are required.

The committee has concluded that the considerable research on hydrogen control and combustion in severe LWR accidents has properly covered most technical aspects concerning hydrogen combustion. The committee has further concluded that, for most accident scenarios, current regulatory requirements make it highly unlikely that hydrogen detonation would be the cause of containment failure. The presence of an inert atmosphere in small volume containments is a satisfactory approach to prevent detonations. Further, the use of igniters in the medium volume containments is a reasonable way to reduce the probability of detonation. However, one problem of concern is that the loss of all on-site and off-site station power, albeit unlikely, would make the igniter systems inoperative. For the larger containments, none of which presently have igniter systems, the somewhat smaller volume of the subatmospheric containments reduces the margin of safety in comparison to other large dry containments. Finally, nonuniform mixing of hydrogen in these large containments may result in localized detonations whose impacts are not fully understood.

The committee did not see the need for more extensive and large-scale experimental programs, although some further work is required. Among its recommendations are the following:

- While computer models developed for characterizing the release, movement and combustion of hydrogen in reactor containment provide reasonable results, significant uncertainties still exist requiring further improvement in the models. Among the needs are the incorporation of some zone and field modeling efforts and the evaluation of model predictions with experimental results. Furthermore, a committee (including experts on mathematics of numerical analysis) should be formed to provide a critical assessment of modeling techniques used and/or under development.
- While igniters will work under the conditions anticipated in severe accidents, enhanced reliability for station blackout scenarios is desirable and the development of methods for improving the reliability of igniter systems is warranted. One approach is to use catalytic igniters which do not need an external source of electric power. It is recommended that their development continue.
- Evaluating the pros and cons of alternative control strategies was outside the committee's scope, but in response to a committee member who wrote a minority report in opposition to the strategy of deliberate ignition, the committee recommends that the benefits, risks, and liabilities of alternative means of control to igniters be investigated
- Further research should be conducted to reduce some of the uncertainty regarding the burning of hydrogen as a detached diffusion flame or as a subsonic premixed flame in a highly obstructed, compartmentalized containment.
- A reanalysis of the likelihood of failure of subatmospheric containments under detonation loads should be performed for use as the basis for deciding what, if any, further actions are needed.
- For the larger containments, further evaluation should be conducted of possible damage to equipment and structures, including containment, by shock waves from localized detonations.

- The possibility of detonation should be reexamined for large dry containments having fan coolers (which remove water vapor from the containment atmospheres and, in so doing, increase hydrogen concentrations) to determine if a satisfactory safety margin exists.
- The original intention of containment sprays was to reduce containment pressure and remove radioactive aerosols from its atmosphere. Since sprays also affect hydrogen combustion, an analysis should be conducted to establish if sprays should be initiated for conditions other than containment overpressure.

TECHNICAL SUMMARY

The burning and/or detonation of hydrogen are of concern in reactor safety analysis for several reasons. First, a large enough energy release might threaten the integrity of the containment. Second, even if the containment survives, important safety equipment might be damaged, thus increasing the severity of an accident. To aid designers and planners and to account for hydrogen deflagrations (premixed subsonic flame propagation) in containments, theoretical models have been developed and are being applied. However, they have certain limitations. For example, except for the Three Mile Island (TMI) accident, there have been very few large-scale sources of data. As a consequence, calculational methods must be benchmarked against numerous smaller scale experiments. Recognizing these constraints, the committee has reviewed calculational models and experimental work on this subject carried out under federal government and private sector sponsorship.

The committee's work is organized in the chapters that follow. Chapter 2 gives background to the hydrogen problem by discussing sources of hydrogen in nuclear power plant accidents, reactor accident sequences, information gained from the TMI accident, and hydrogen research programs undertaken by the Nuclear Regulatory Commission (NuRC) and elements of the nuclear power industry. Calculational models such as computer codes have been employed to estimate conditions that would exist in a large-scale containment under postulated conditions of hydrogen release and combustion. These methods are reviewed in Chapter 3. Since hydrogen combustion may occur in the form of diffusion flames (which consists of an exothermic reaction zone separating unmixed regions of oxidizer and fuel gases) or deflagrations, Chapter 4 addresses the ability to extrapolate data on deflagrations and diffusion flames from various experimental facilities in order to predict temperatures and pressures that would occur in a reactor containment. Aspects of detonation are addressed in Chapter 5, including an evaluation of the conditions under which a detonation might occur, the resulting pressures and temperatures, the influence of suspended water droplets, and the implications for the various types of reactor containments. Finally, Chapter 6 considers ignition of a hydrogen jet emerging into a containment atmosphere, the use of deliberate ignition strategies, and the influence of containment sprays.

The question of scale-up of experimental data depends on the combustion mode considered. For deflagrations, direct extrapolation of subscale tests to full-size containments is too complicated, but enough tests have been performed to identify scaling trends for simple geometries. More complicated situations involving sprays, ventilated flows, and flame propagation around equipment and between compartments may require further evaluation of burn fraction (fraction of available hydrogen actually burned) and flame speeds. Data can be obtained from diffusion flame experiments to estimate thermal loads on major safety equipment. Diffusion flame lift-off and detachment phenomena require more study to better understand where diffusion flames will burn in a containment. To a large degree, experiments did explore flame acceleration pertinent to large containment volumes. As for detonation, conservative estimates, based on theory and experiment, can be made for the lean detonation limit. However, it is not possible to calculate lean detonation limits as a function of steam content. There is still uncertainty concerning the models of hydrogen transport and combustion for full-scale containments (see individual chapters for more details).

The programs sponsored by the NuRC and the nuclear power industry have properly covered most aspects of concern regarding hydrogen combustion. The committee does not see the need for more extensive and large-scale experimental programs, especially with regard to lean detonation limits. However, as described in the report, some further analytical and experimental work is recommended regarding hydrogen transport models, deflagrations, diffusion flames, detonation loads for subatmospheric and large dry containments, igniter system reliability, catalytic igniters, and optimum strategies for containment spray activation (see individual chapters for details).

CONCLUSIONS AND RECOMMENDATIONS

Hydrogen Control

To ensure that hydrogen combustion or detonation from a severe accident does not compromise containment integrity, a number of control measures have been used. For boiling water reactors (BWR) with Mark I and Mark II containments, the containment atmosphere is made inert with nitrogen to prevent combustion. Igniters are installed in ice condenser containments of pressurized water reactors (PWR) and in Mark III containments of BWRs to burn up the hydrogen generated before concentrations are reached which, if burned or detonated, could threaten containment. Large dry containments used for some PWRs do not have igniters for hydrogen control. If hydrogen is mixed uniformly throughout these containments, the concentration is low enough so that the possibility of a detonation is remote. Likewise, the probability of a detonation in containments operating at 2/3 of an atmosphere, the so-called subatmospheric containments, is judged to be small. None of these approaches completely eliminates the possibility of a detonation since, for example, during shutdown and during the start-up period for BWRs the containment is not made inert. Clearly, since the igniters require electricity, if power is lost the igniters will fail. In large dry containments, nonuniform mixing may pose a problem. Thus, all that these approaches can do is reduce the probability of a hydrogen-caused containment failure. The goal of these mitigative features, therefore, is to attempt to ensure that containment failure by hydrogen burning or detonation will be acceptably low.

The committee concluded that regulatory requirements have been established by the NuRC for ensuring that a hydrogen detonation after a severe nuclear plant accident is not likely to be the cause of containment failure. It further concludes that for most accident sequences current requirements generally reflect an adequate margin of conservatism. Some exceptions are noted in the report. In a few cases, particularly accidents involving loss of all station power, the uncertainties are large enough so that this margin of safety may not be sufficient. Two important contributors to the uncertainty are the amount of hydrogen generated during the accident and the degree of nonuniform mixing of hydrogen. Investigation of hydrogen generation lies outside the charge and expertise of this committee, although it is recognized that the uncertainty in hydrogen generation needs to be reduced. The applied research programs jointly sponsored by the NuRC and the nuclear industry have provided a credible basis for judging the adequacy of the control measures. If the margin of conservatism is to be reduced in the future, additional research should be undertaken. This should be basic research, leading to a more fundamental understanding of the distribution of hydrogen in a containment and the combustion process in its various forms. Research of this kind can be used as the foundation of analytical methods that rest on first principles, and that can be used for more confident calculations of the threats to the containment.

Modeling

One method by which a full-size containment accident scenario can be modeled is through the use of computer programs that simulate hydrogen release, movement, and combustion in a containment vessel. Lumped-volume models, where specified volume elements are assumed to be well-mixed, such as in a code called HECTR (Hydrogen Event: Containment Transient Response), have been used extensively and are a viable way to achieve reasonable simulations when used by experienced users. Their accuracy deteriorates if well-mixed conditions in a containment atmosphere do not pertain and effects of stratification and buoyancy begin to dominate both fluid mixing and motion. Their accuracy could be improved by using a zone modeling approach, in which the zones in the containment are defined on the basis of physical and fluid dynamic principles. Field models in which one solves the governing equations of mass, momentum, energy, and chemical species for incremental regions of the flow could result in a greater level of detail. However, field models have not been as successful as lumped-parameter models for a region the size of a containment and require impractically large amounts of computer time. They can generate more detail than the lumped-volume or lumped-parameter models.

Recommendation

As noted, recently developed models for characterizing the release, movement, and combustion of hydrogen in the containment give reasonable results when used by knowledgeable analysts but still have a significant uncertainty. Several improvements, as outlined below, could yield more accurate results.

The results of lumped-parameter code calculations should be compared to a few large-scale experiments. These experiments could be carried out using inert gases in an actual containment or a structure of similar size. Comparison with data from Factory Mutual Research Corporation's 1/4-scale tests would be useful in this regard. If well-mixed conditions do not pertain, lumped-volume codes could be made more reliable by using zone models, which subdivide a region into zones based on physical features of the flow. The Center for Fire Research of the National Bureau of Standards (NBS) is actively developing zone models for fires within structures. This technology is very similar to lumped-parameter modeling of hydrogen transport and combustion in containments. Coordination of NBS and NuRC efforts in this area would be beneficial to both programs and should be pursued.

Field models should be considered for providing the structure of the flow within compartments, and experiments should be conducted in actual containments or similar multicompartment structures to validate the models. These results could then be used to develop empirical parameters for the lumped-parameter models. Development of field models would be enhanced by cooperation between NuRC and the National Aeronautics and Space Administration's Lewis Research Center which is actively developing field models to simulate turbulence. In addition, coordination of efforts between the NuRC and NBS would be beneficial to both programs.

Deflagrations and Diffusion Flames

Enough different size tests have been performed for deflagration flames and their consequences that scaling trends can be identified for simple geometries. Thus, one can reasonably extrapolate deflagration flame data for simple geometries but must resort to computer code calculations for more complicated configurations involving internal equipment, water sprays, and multiple compartments. Lack of fundamental quantification of turbulence effects associated with these configurations prevents rigorous implementation of both zone and field models

In the case of diffusion flames, temperature and velocity distributions as well as flame lengths can be scaled up for both subsonic jet flames and buoyant diffusion flames, but there are significant uncertainties (as much as 80 percent in flame length) in the case of weak steam-diluted releases and underexpanded jets (both examples of releases from high-pressure vessels) at high flow rates and large release diameters. If these uncertainties are tolerable, this information can be used to estimate thermal loading without further testing. Froude scaling of diffusion flame data from geometrically similar subscale enclosures such as the Mark III 1/4-scale test facility should not be expected to simulate convective and radiative heat fluxes precisely; but measured gas temperatures and velocities, together with analysis of departures from Froude scaling, can be used to estimate thermal loads on major safety equipment. The spatial resolution to be expected from this approach is limited to the length scale of actual containment equipment and structures included in the subscale test facility.

Recommendation

Computer models are used to evaluate conditions that would exist in a containment. Input to these codes includes parameters such as burn fraction and flame speed. Scaling of test data for these parameters would be more reliable if turbulence effects associated with ventilated flows, containment sprays, and flame propagation around equipment and between compartments were included. Parametric calculations for these effects, for example, with different values of burn fraction and flame speeds, should be conducted. If the resulting analysis from the computer codes used for evaluation of containment conditions indicated possible failure of containment, then further tests focusing on these turbulence effects might be warranted.

With regard to diffusion flames, they usually burn as an attached flame at a hydrogen release site, but they may also detach and burn in other parts of the containment. Conservative calculation of thermal loads on key safety equipment in the vicinity of attached flames will determine whether the uncertainties in flame length and temperature/velocity fields warrant additional testing for containments and accident scenarios not included in the current Mark III 1/4-scale tests.

Flame lift-off and detachment of diffusion flames as observed in the Nevada Test Site experiments are of particular concern. Such detached flames might lead to the possibility of thermal damage to equipment in remote regions of the containment as well as to equipment in the vicinity of the hydrogen release site where steady diffusion flames are expected at the earlier stages of the release transient. Consequently, additional work should be considered and undertaken to delineate flame lift-off and relocation/reattachment criteria relevant to these scenarios.

Detonation Aspects

The conditions under which detonation might occur were analyzed and several conclusions were reached. With respect to scale-up, there appears to be a definite correlation between cell size and the size of a container in which a detonation might develop. It is very unlikely that initiation energies high enough to cause direct detonation of hydrogen-air mixtures near the lean detonation limit would be available in a containment environment. Another possible mechanism for detonation would be through flame acceleration and transition to detonation. In the part of a containment with linear dimensions on the order of 50 m, theoretical analysis indicates that a 9 to 11 percent hydrogen-air mixture might be detonable. Increasing temperature increases the sensitivity of a given mixture to detonation but in most postulated nuclear power plant accidents, this effect would be offset by the presence of water vapor as a diluent. Carbon dioxide also decreases the sensitivity of a mixture to detonation. Thus, it is estimated that a 20 percent dilution by either carbon dioxide (20 percent CO_2 and 80 percent air by volume) or water vapor would raise the lean detonation limit in a reactor containment to about 13 percent. For protection against hydrogen detonation in small-volume BWR containments, inerting is satisfactory. In medium-volume containments, igniters are a reasonable way to reduce the probability of detonation. For water-hydrogen-air mixtures that must be assumed present in most large-volume containments during a severe accident, the lower limit of detonation is greater than 13 percent hydrogen. Thus, for the case of uniform mixing in which the hydrogen concentration is 10 percent or less, the possibility of detonation would be remote. Cases of some concern are those plants having fan coolers which can efficiently remove water vapor and a failure of igniters to operate due to loss of power. Finally, it is also clear that uniform mixing is not likely in all cases so that detonations of a limited size, in contrast to a global detonation, are possible. They are of particular concern in large dry containments.

With regard to thermal loading resulting from a limited detonation, any precautionary measures taken to preserve equipment from thermal loading resulting from a deflagration should be adequate for thermal loading from a detonation. However, pressure effects from the shock waves need to be considered.

Recommendation

Subatmospheric containments are a special case for large dry containments because their volume is about 50,400 m^3 (about 1.8 million ft^3) and their operating pressure is about 2/3 of an atmosphere. Since there is less air, less hydrogen is needed to reach a given concentration. Although the presence of water vapor during a postulated accident reduces the probability of a detonation, the margin of safety is less than for the other large dry containments. Therefore, a reanalysis of the likelihood of subatmospheric containment failure under detonation loads should be performed and used as a basis for deciding what, if any, further actions are needed.

For the case of uniformly mixed large dry containments without fan coolers, the possibility of detonation is remote. However, the presence of fan coolers reduces the humidity and, therefore, the margin of safety. In the large dry containments where the maximum hydrogen concentration might be as much as 8 percent, there is still a reasonable margin of safety. However, in the smaller containments where the maximum hydrogen concentration may be 10 percent, the margin of safety will be reduced. Hence, the possibility of detonation should be examined in each large dry containment having fan coolers to determine if a satisfactory safety margin exists. In addition, detonable concentrations of hydrogen may occur in local regions in large dry containments. Because of the distinct possibility of localized detonations, the area of possible damage to equipment and structures by shock waves from localized detonations requires evaluation. This should include the modelling of localized detonations to examine their decay and ascertain structural safety.

Ignition and Igniters

As to the question of whether or not an escaping turbulent hydrogen jet would autoignite, it was concluded that gas dynamic effects alone are inadequate for ignition. However, under the conditions present in a highly turbulent jet in an accident scenario, other means of ignition cannot be ruled out, for example, either static charges or sparks from dust or pieces of material. Hence, there is a reasonable probability that a jet would ignite. With regard to igniters, tests indicate that shielded igniters would operate reliably under conditions anticipated in nuclear accidents.

Recommendation

Igniters will operate reliably under conditions anticipated in nuclear reactor accidents. However, enhanced reliability for station blackout scenarios is desirable. Further work should be conducted on developing methods for improving the reliability of igniter systems for station blackout scenarios. Development of catalytic igniters should continue, as well as methods to improve the reliability of the power supplies for the thermal igniters until the most desirable approach can be chosen.

Water Droplets and Sprays

The original function of containment water sprays was to reduce containment pressure and remove radioactive aerosols from the containment atmosphere. However, they can also influence hydrogen combustion. They can raise the detonability limit. They can also enhance turbulence, resulting in increased flame speeds in lean hydrogen-air mixtures, and cause peak pressures to be closer to the adiabatic, constant-volume values. However, these sprays would also enhance cooling of the burned gases and therefore cause pressures and temperatures to decrease more rapidly to precombustion levels. Thus, depending on the relative safety margins for pressure loads and thermal loads, the sprays can be either beneficial or detrimental during premixed combustion. They are definitely beneficial for postcombustion cooling and for mitigating the effects of diffusion flames anticipated with deliberate ignition.

Recommendation

The original intention of containment sprays was to reduce containment pressure and remove radioactive aerosols from the containment atmosphere. Experimental data suggest that sprays and water droplets may have an impact on the hydrogen combustion process. Thus, it appears there are conditions in addition to the original ones that would be affected by spray activation under circumstances other than high pressure and high radioactivity. Therefore, analysis should be conducted to establish if sprays should be initiated for conditions other than containment overpressure.

Documentation of Hydrogen Accidents

During the course of its study, the committee recognized the dearth of information which it could draw on regarding accidents involving hydrogen, especially with regard to industrial accidents. The NuRC is maintaining a file on hydrogen uses, incidents and production as well as on unconfined vapor cloud detonations. However, it is important to recognize the different behavior of hydrogen from hydrocarbons in industrial explosions. An available data base on hydrogen-related industrial accidents could have been extremely valuable in making informed judgments.

Recommendation

It is important that the NuRC continues to keep track of any past and future accidents involving hydrogen that have occurred or might occur in its production, use, or handling. These accidents should be studied on a continuing basis with the aim of finding any possible similarity between them and what might occur in a reactor accident. This information could be used by the NuRC for making decisions regarding hydrogen-related mitigation procedures in the future.

Alternative Means of Hydrogen Control

The minority report and the response to it (Appendixes C and D) discussed the issue of using igniters to control hydrogen. All members of the committee came to the agreement that it is worthwhile to study other means of control, a task beyond the charge of the present committee.

Recommendation

A careful analysis of the benefits and liabilities of alternative hydrogen control systems in comparison to igniters should be conducted.

Proposed Committee on Modeling Techniques

In the discussions contained in the minority report and the response to it (Appendices C and D), everyone recognized that a critical assessment of modeling techniques would be worthwhile.

Recommendation

A committee of experts should be formed to conduct a critical assessment of modeling techniques used and/or under development as well as to consider their future use and development. In particular, this assessment should focus on numerical fluid mechanics applied to transient flow problems involving turbulence.

2

THE NATURE OF THE HYDROGEN PROBLEM IN NUCLEAR POWER PLANTS

In this chapter the nature of the problems created in nuclear power plants by the various processes that generate hydrogen is reviewed. In the first section, the sources of hydrogen generation during both normal and accident conditions will be discussed. The second section will examine the possible effects of hydrogen combustion on reactor safety. The third section addresses the types of system failures that can potentially create the conditions that lead to significant hydrogen production. The accident at the Three Mile Island Unit 2 (TMI-2) nuclear power station in Pennsylvania is also reviewed with particular attention to the role of hydrogen in that event. A final section contains a synopsis of the research programs undertaken to understand hydrogen behavior and control during severe accidents.

SOURCES OF HYDROGEN

Metal-Water Reactions

It has been known by chemists for a long time that hot metals can chemically react with water, creating metal oxides and hydrogen. By the late 1950s (Bostrom, 1954; Lemmon, 1957) reactor safety analysts became concerned that reactions of this type might occur in severe reactor accidents, in which cooling is lost, exacerbating the consequences of such events (Thompson and Beckerley, 1973).

Present analysis shows that in most postulated severe nuclear accidents the dominant process for producing hydrogen is the reaction of steam with overheated fuel rods. The fuel rods in U.S. light-water reactors (LWRs) are always uranium dioxide in a cladding of Zircaloy, which is an alloy of zirconium, tin, iron, chromium, nickel, and oxygen. The chemical reaction is one in which zirconium (Zr) reacts with water (H_2O) to produce zirconium dioxide (ZrO_2) and hydrogen gas (H_2):

$$\mathrm{Zr} + 2\ \mathrm{H_2O} \dashrightarrow \mathrm{ZrO_2} + 2\mathrm{H_2} + H_R.$$

This reaction is exothermic, with a heat of reaction (H_R) of approximately 6,500 kJ/kg of Zr. The reaction rate increases rapidly above a temperature of about 1,370°C (2,500°F). In a large (1,200-megawatt electric; MWe) pressurized water reactor (PWR), the core contains about 20,400 kg (45,000 pound mass; lbm) of Zr. It is possible to postulate accidents in which a significant fraction of the Zr (25 to 50 percent) reacts with steam in periods as short as tens of minutes. Such an event might produce as much as 225 to 450 kg (500 to 1,000 lbm) of hydrogen. However, in recent work (Gieseke et al., 1984) somewhat lower rates than this have been calculated for typical accident scenarios, most often peak values of less than 1 kg/s and average values of 0.1 kg/s or less. In one particular postulated accident initiated by loss of all station power for an extended period of time, the rate of release may be 10 to 15 kg/s. This is the result of a meltthrough of the reactor vessel while the system is still pressurized.

In addition to Zr, the structural steel in the reactor core in some severe accidents is postulated to reach temperatures high enough so that it could react with the steam. In cases where the core is postulated to melt, the molten mass may fall into a pool of water in the lower head of its vessel and further metal-water reactions may occur. Finally, if the molten fuel falls on the concrete floor, hydrogen will be produced when water released from the concrete bubbles through the molten mass. All of the above processes have the potential for producing hydrogen.

There are currently in use in the United States two large computer codes for calculating the amounts and rates of hydrogen production. They are the MARCH (Meltdown Accident Response Characteristics) code, developed by the Battelle Memorial Institute at Columbus, Ohio (Wooten and Avci, 1980), funded by the U.S. Nuclear Regulatory Commission (NuRC), and the MAAP (Modular Accident Analysis Program) code, developed by Fauske and Associates (Baker et al., 1982), funded by the Industry Degraded Core Rulemaking Program (IDCOR). Both of these codes indicate that in the most serious accidents the dominant contributor to hydrogen generation would be oxidation of the Zr cladding. A large fraction of the Zr would oxidize during the heat-up phase while the core geometry would remain intact. Most of the rest of the hydrogen would be produced during the reaction with concrete.

The two codes predict somewhat different amounts of hydrogen which could be produced and released to containment. The MAAP code for severe accidents predicts an amount of hydrogen equal to 20 to 40 percent of the Zr reacted, whereas MARCH typically predicts 30 to 60 percent. The resolution of this difference is beyond the scope and expertise of this committee, but the results are close enough so the difference in the range between the two is not very important since safety analysts typically use the upper bound value. As noted previously, some of this hydrogen is generated by steam reacting with steel or other very hot structural materials in the containment. The codes include these other sources of hydrogen as part of the total amount generated. However, they make only a small addition to the amount generated by the $Zr-H_2O$ reaction while the fuel remains in the reactor vessel. The amount of hydrogen generated by reaction with steel is small compared to the ranges of uncertainty stated above and is henceforth not included in our discussion of "metal-water reactions."

Other Sources of Hydrogen

There are two processes that will produce lesser amounts of hydrogen over much longer periods of time. They are radiolysis of water and corrosion of materials in the containment. The latter is so small that it is not important to reactor safety considerations.

Radiolysis refers to the dissociation of the hydrogen molecule as a result of its bombardment by ionizing radiation. It has been a concern for reactors since the early 1950s (Pigford, 1952). In addition to producing hydrogen and oxygen, sometimes this process produces partial dissociation of the water molecule forming free radicals. The presence of the free radicals leads to back reactions that recombine with hydrogen to form water (Speis, 1984). Reactions of interest are the oxidation of molecular hydrogen:

$$H_2 + OH \dashrightarrow H + H_2O$$

and reaction with other free radicals:

$$OH + H \dashrightarrow H_2O$$

$$OH + OH \dashrightarrow H_2O + O.$$

These reactions make the calculation of the net production of hydrogen difficult and require knowledge of the reaction rates and the concentration of the reactants. The process of radiolysis creates both molecular oxygen (O_2) and hydrogen (H_2). This can be important in cases where the containment is made inert (filled with nitrogen) to prevent hydrogen burning. If radiolysis proceeds for a long enough time it may become possible to produce enough oxygen to cause the containment atmosphere to become flammable. This is judged to be a very unlikely event because the long time period involved gives so much opportunity for such remedial action as installation of recombiners or possible venting of the containment. Most reactors have recombiners capable of handling this relatively small amount of hydrogen generation. Experience at TMI-2 showed that it was a simple task to connect a recombiner of appropriate size to the containment.

EFFECT OF HYDROGEN ON SAFETY

An important engineered safety feature of all commercial nuclear reactors in the United States is the containment. This is an airtight structure that surrounds the reactor and is designed to prevent the accidental release of radioactivity. In assessing the risk to the public it is important to know if hydrogen can be concentrated in the containment to the point where, if ignited, its combustion might threaten the integrity of the containment. In addition, even if the combustion of hydrogen would not cause the containment to fail, it might cause failures of important safety systems located inside the containment.

Threat to Containment

To evaluate the threat to the containment, the quantity of hydrogen released, the containment volume and strength, the hydrogen distribution, and the possibility of ignition should be known. Figure 2-1 shows the volumes and design strengths of the six major types of containment used in U.S. nuclear plants. Figure 2-2 shows the volume percentage of hydrogen that would exist, assuming uniform mixing, in each of these containments as a function of the percentage of metal-water reaction. The Mark I and II designs used for early boiling water reactors (BWRs) are characterized by small volumes and moderate design pressures. The strength and volume were selected to withstand the steam pressure that would occur in containment if the primary system were to rupture during operation, allowing the hot primary system water to flash to steam. The small volume of a BWR containment is sufficient because it is designed so that steam releases are directed through a large pool of water to prevent overpressure. To cope with the hydrogen problem, these containments are made inert by replacing their atmospheres with nitrogen when the plants are in operation.

The intermediate-volume containments, the BWR MRK III and the PWR ice condenser, have systems for condensing steam and suppressing increases in pressure: the former uses a water pool, the latter a large volume of ice. The larger volume of these containments permits a lower design pressure. Because of the high hydrogen concentrations that might be reached if a large fraction of the Zr reacted with steam, for these reactors considerable effort has been expended to reduce the possibility of a hydrogen detonation. They now have igniters distributed throughout their containments to burn hydrogen before it could reach concentrations that could sustain a detonation.

Most of the PWRs have large so-called free-volume containments. A typical volume is about 56,000 m^3 (2 million ft^3). This volume causes the maximum steam pressure in postulated accidents to be limited to values below the containment design pressure without requiring dramatic steam condensation as provided by a suppression pool or ice condenser. The large volume limits the global concentration of hydrogen, assuming uniform mixing, to a range of 8 to 13 percent, even at 75 percent metal-water reaction. Numerous calculations have led to the conclusion that the burning of hydrogen in these containments would not threaten their integrity. It has been the NuRC policy that the likelihood of reaching detonable concentrations in large regions of these containments is so small that neither inerting nor igniters are required. As a result of nonuniform mixing, there might be regions in which a detonable concentration might exist. Subatmospheric

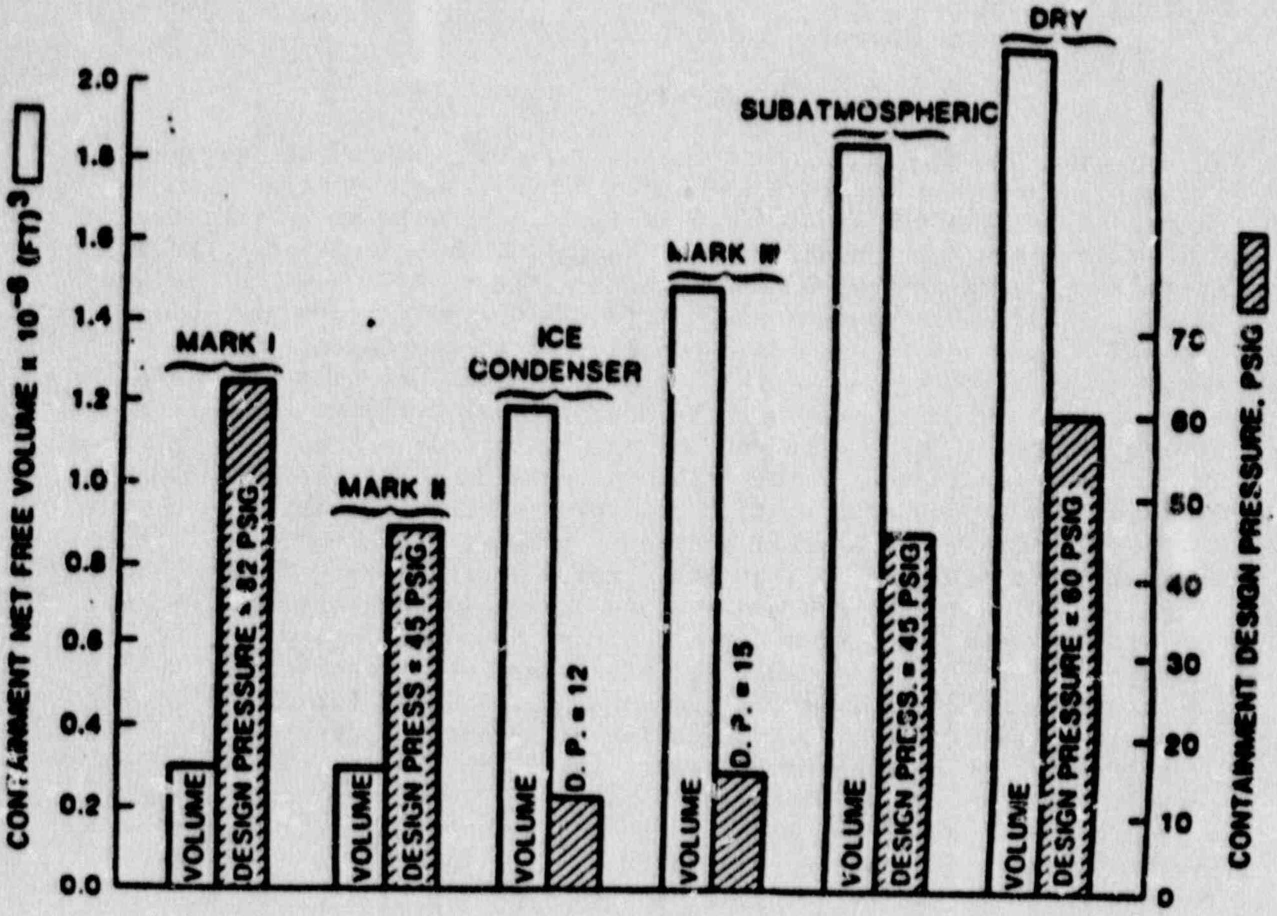

FIGURE 2-1 Comparison of containment volumes and design pressures for different containments (typical 1,200-MWe plants).

Source: Berman and Cummings (1984)

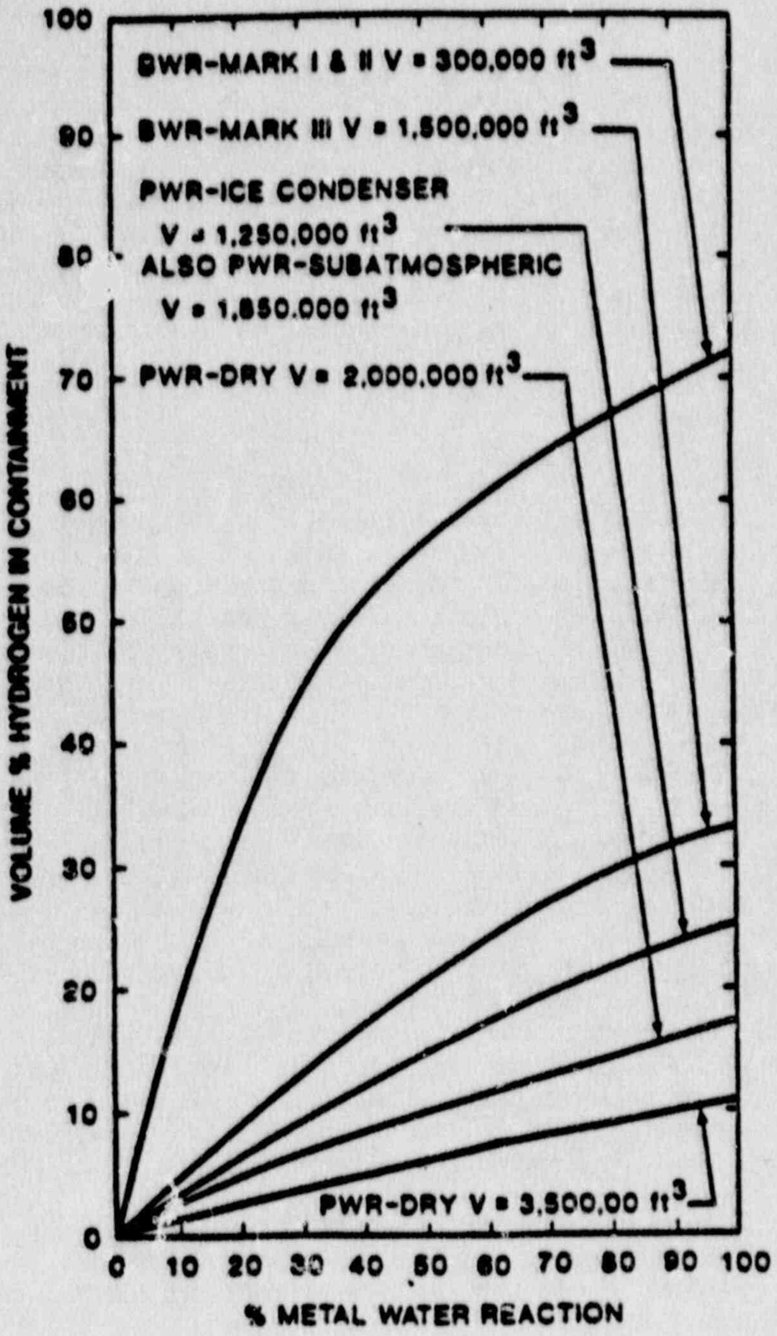

FIGURE 2-2 Hydrogen concentrations in various reactor containments as a function of the extent of metal-water reaction in the core. Uniform mixing is assumed

Source: Berman and Cummings (1984).

containments must be considered a special case because of their smaller volume and lower air content. These issues are discussed in more detail in Chapter 5.

Damage to Equipment

In addition to the threat to containment integrity, there is also the possibility that the combustion of hydrogen might damage equipment in the containment. The damage might be due either to thermal effects from hydrogen burning or to mechanical damage resulting from a pressure wave generated by a rapid flame propagation or detonation. Such damage could increase the accident risk if it seriously degraded the performance of any of the required safety systems. This issue is further discussed in Chapter 5.

REACTOR ACCIDENT SEQUENCES

As noted above, the metal-water reactions needed to rapidly produce large volumes of hydrogen require system failures that would lead to serious overheating of the fuel. Many different combinations of equipment and human failures could cause this condition. In safety analysis, each particular combination of events that could produce an accident is called an accident sequence. The first organized attempt to identify the accident sequences that would lead to serious fuel damage was the Reactor Safety Study (RSS) (NuRC, 1975). This study used the event tree-fault tree method in an endeavor to identify all the accident sequences that significantly contribute to the probability of core damage. Tables 2-1 and 2-2 give those results for the PWR and the BWR, respectively. Each release category is associated with a specific release of radioactivity from the containment. Release category 1 provides the largest release: 90 percent of the noble gas radionuclides and between 30 and 70 percent of the volatile fission products of I, Ru, Te, Cs. The smallest release is in release category 9, a tiny fraction of the release in category 1. In the BWR case (Table 2-2) only five categories are needed to conveniently classify the various accidents. Note the rather large uncertainty bounds on the release probabilities. This is due to uncertainties in estimates of component failure rates.

For the reader unfamiliar with the safety design rationale, a discussion of these issues can be found in Appendix IX of the RSS (NuRC, 1975) or any nuclear power plant Final Safety Analysis Report. Since the RSS was completed a decade ago, nearly two dozen such analyses have been done on individual plants; these newer studies include significant improvements over the RSS but the general structure of the approach to the problem is nearly the same. The dominant accident sequences remain about the same as given in Tables 2-1 and 2-2. There are some disparities due to differences in specific design features. These more recent risk assessments have improved techniques for calculation of the failure pressure of the containment. Typical results predict failure pressures in the range of 2.5 to 4 times design pressure for various designs.

TABLE 2-1 PWR Dominant Accident Sequences Versus Release Categories

	RELEASE CATEGORIES						Core Melt	No Core Melt	
	1	2	3	4	5	6	7	8	9
LARGE LOCA A	AB-α $1x10^{-11}$ AF-α $1x10^{-10}$ ACD-α $5x10^{-11}$ AG-α $9x10^{-11}$	AB-γ $1x10^{-10}$ AB-δ $4x10^{-11}$ AHF-γ $2x10^{-11}$	AD-α $2x10^{-8}$ AH-α $1x10^{-8}$ AF-δ $1x10^{-8}$ AG-δ $9x10^{-9}$	ACD-β $1x10^{-11}$	AD-β $4x10^{-9}$ AH-β $3x10^{-9}$	AB-ε $1x10^{-9}$ AHF-ε $1x10^{-10}$ ADF-ε $2x10^{-10}$	AD-ε $2x10^{-6}$ AH-ε $1x10^{-6}$	A-β $2x10^{-7}$	A $1x10^{-4}$
A Probabilities	$2x10^{-9}$	$1x10^{-8}$	$1x10^{-7}$	$1x10^{-8}$	$4x10^{-8}$	$3x10^{-7}$	$3x10^{-6}$	$1x10^{-5}$	$1x10^{-4}$
SMALL LOCA S_1	S_1B-α $3x10^{-11}$ S_1CD-α $7x10^{-11}$ S_1F-α $3x10^{-10}$ S_1G-α $3x10^{-10}$	S_1B-γ $4x10^{-10}$ S_1B-δ $1x10^{-10}$ S_1HF-γ $6x10^{-11}$	S_1D-α $3x10^{-8}$ S_1H-α $3x10^{-8}$ S_1F-δ $3x10^{-8}$ S_1G-δ $3x10^{-8}$	S_1CD-β $1x10^{-11}$	S_1H-β $5x10^{-9}$ S_1D-β $6x10^{-9}$	S_1DF-ε $3x10^{-10}$ S_1B-ε $2x10^{-9}$ S_1HF-ε $4x10^{-10}$	S_1D-ε $3x10^{-6}$ S_1H-ε $3x10^{-6}$	S_1-β $6x10^{-7}$	S_1 $3x10^{-4}$
S_1 Probabilities	$3x10^{-9}$	$2x10^{-8}$	$2x10^{-7}$	$3x10^{-8}$	$8x10^{-8}$	$6x10^{-7}$	$6x10^{-6}$	$3x10^{-5}$	$3x10^{-4}$
SMALL LOCA S_2	S_2B-α $1x10^{-10}$ S_2F-α $1x10^{-9}$ S_2CD-α $2x10^{-10}$ S_2G-α $9x10^{-10}$ S_2C-α $2x10^{-8}$	S_2B-γ $1x10^{-9}$ S_2HF-γ $2x10^{-10}$ S_2B-δ $4x10^{-10}$	S_2D-α $9x10^{-8}$ S_2H-α $6x10^{-8}$ S_2F-δ $1x10^{-7}$ S_2C-δ $2x10^{-6}$ S_2G-δ $9x10^{-8}$	S_2DG-β $1x10^{-12}$	S_2D-β $2x10^{-8}$ S_2H-β $1x10^{-8}$	S_2B-ε $8x10^{-9}$ S_2CD-ε $2x10^{-8}$ S_2HF-ε $1x10^{-9}$	S_2D-ε $9x10^{-6}$ S_2H-ε $6x10^{-6}$		
S_2 Probabilities	$1x10^{-7}$	$3x10^{-7}$	$3x10^{-6}$	$3x10^{-7}$	$3x10^{-7}$	$2x10^{-6}$	$2x10^{-5}$		
REACTOR VESSEL RUPTURE - R	RC-α $2x10^{-12}$	RC-γ $3x10^{-11}$ RF-δ $1x10^{-11}$ RC-δ $1x10^{-12}$	R-α $1x10^{-9}$				R-ε $1x10^{-7}$		
R Probabilities	$2x10^{-11}$	$1x10^{-10}$	$1x10^{-9}$	$2x10^{-10}$	$1x10^{-9}$	$1x10^{-8}$	$1x10^{-7}$		
INTERFACING SYSTEMS LOCA (CHECK VALVE) - V		V $4x10^{-6}$							
V Probabilities	$4x10^{-7}$	$4x10^{-6}$	$4x10^{-7}$	$4x10^{-8}$					
TRANSIENT EVENT - T	TMLB'-α $3x10^{-8}$	TMLB'-γ $7x10^{-7}$ TMLB'-δ $2x10^{-6}$	TML-α $6x10^{-8}$ TKQ-α $3x10^{-8}$ TKMQ-α $1x10^{-8}$		TML-β $3x10^{-10}$ TKQ-β $3x10^{-10}$	TMLB'-ε $6x10^{-7}$	TML-ε $6x10^{-6}$ TKQ-ε $3x10^{-6}$ TKMQ-ε $1x10^{-6}$		
T Probabilities	$3x10^{-7}$	$3x10^{-6}$	$4x10^{-7}$	$7x10^{-8}$	$2x10^{-7}$	$2x10^{-6}$	$1x10^{-5}$		
(Σ) SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORY									
MEDIAN (50% VALUE)	$9x10^{-7}$	$8x10^{-6}$	$4x10^{-6}$	$5x10^{-7}$	$7x10^{-7}$	$6x10^{-6}$	$4x10^{-5}$	$4x10^{-5}$	$4x10^{-4}$
LOWER BOUND (5% VALUE)	$9x10^{-8}$	$8x10^{-7}$	$6x10^{-7}$	$9x10^{-8}$	$2x10^{-7}$	$2x10^{-6}$	$1x10^{-5}$	$4x10^{-6}$	$4x10^{-5}$
UPPER BOUND (95% VALUE)	$9x10^{-6}$	$8x10^{-5}$	$4x10^{-5}$	$5x10^{-6}$	$4x10^{-6}$	$2x10^{-5}$	$2x10^{-4}$	$4x10^{-4}$	$4x10^{-3}$

Note: The probabilities for each release category for each event tree and the Σ for all accident sequences are the median values of the dominant accident sequences summed by Monte Carlo simulation plus a 10% contribution from the adjacent release category probability

TABLE 2-1 (continued)
Key to PWR Accident Sequence Symbols:

A - Intermediate to large LOCA.

B - Failure of electric power to ESFs.

B' - Failure to recover either onsite or offsite electric power within about 1 to 3 hours following an initiating transient which is a loss of offsite AC power.

C - Failure of the containment spray injection system.

D - Failure of the emergency core cooling injection system.

F - Failure of the containment spray recirculation system.

G - Failure of the containment heat removal system.

H - Failure of the emergency core cooling recirculation system.

K - Failure of the reactor protection system.

L - Failure of the secondary system steam relief valves and the auxiliary feedwater system.

M - Failure of the secondary system steam relief valves and the power conversion system.

Q - Failure of the primary system safety relief valves to reclose after opening.

R - Massive rupture of the reactor vessel.

S_1 - A small LOCA with an equivalent diameter of about 2 to 6 inches.

S_2 - A small LOCA with an equivalent diameter of about 1/2 to 2 inches.

T - Transient event.

V - LPIS check valve failure.

α - Containment rupture due to a reactor vessel steam explosion.

β - Containment failure resulting from inadequate isolation of containment openings and penetrations.

γ - Containment failure due to hydrogen burning.

δ - Containment failure due to overpressure.

ϵ - Containment vessel melt-through.

Note: LOCA: loss of cooland accident; ESF: engineered safety feature; LPIS: low pressure injection system.

TABLE 2-2 BWR Dominant Accident Sequences of Each Event Tree versus Release Category

	Core Melt				No Core Melt
	RELEASE CATEGORIES				
	1	2	3	4	5
LARGE LOCA DOMINANT ACCIDENT SEQUENCES (A)	AE-α 2×10^{-9} AJ-α 1×10^{-10} AHI-α 1×10^{-10} AI-α 1×10^{-10}	AE-γ' 3×10^{-8} AE-β 1×10^{-8} AJ-γ' 2×10^{-9} AI-γ' 2×10^{-9} AHI-γ' 2×10^{-9}	AE-γ 1×10^{-7} AJ-γ 1×10^{-8} AI-γ 1×10^{-8} AHI-γ 1×10^{-8}	AGJ-δ 6×10^{-11} AEG-δ 7×10^{-10} AGHI-δ 6×10^{-11}	A 1×10^{-4}
A Probabilities	8×10^{-9}	6×10^{-8}	2×10^{-7}	2×10^{-8}	1×10^{-4}
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S_1)	S_1E-α 2×10^{-9} S_1J-α 3×10^{-10} S_1I-α 4×10^{-10} S_1HI-α 4×10^{-10}	S_1E-γ' 4×10^{-8} S_1E-β 1×10^{-8} S_1J-γ' 7×10^{-9} S_1I-γ' 7×10^{-9} S_1HI-γ' 6×10^{-9}	SE-γ 1×10^{-7} S_1J-γ 3×10^{-8} S_1I-γ 4×10^{-8} S_1HI-γ 2×10^{-8} S_1C-γ 3×10^{-9}	S_1GJ-δ 2×10^{-10} S_1GE-δ 2×10^{-10} S_1EI-ϵ 1×10^{-10} S_1GHI-δ 2×10^{-10}	
S_1 Probabilities	1×10^{-8}	9×10^{-8}	2×10^{-7}	2×10^{-8}	
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S_2)	S_2J-α 1×10^{-9} S_2I-α 1×10^{-9} S_2HI-α 1×10^{-9} S_2E-α 5×10^{-10}	S_2E-γ' 1×10^{-8} S_2E-β 4×10^{-9} S_2J-γ' 2×10^{-8} S_2I-γ' 2×10^{-8} S_2HI-γ' 2×10^{-8}	S_2E-γ 4×10^{-8} S_2J-γ 8×10^{-8} S_2I-γ 9×10^{-8} S_2HI-γ 9×10^{-8} S_2C-γ 8×10^{-9}	S_2CG-δ 6×10^{-11} S_2GHI-δ 6×10^{-10} S_2EG-δ 3×10^{-10} S_2GJ-δ 6×10^{-10} S_2GI-δ 2×10^{-10}	
S_2 Probabilities	2×10^{-8}	1×10^{-7}	4×10^{-7}	4×10^{-8}	
TRANSIENT DOMINANT ACCIDENT SEQUENCES (T)	TW-α 2×10^{-7} TC-α 1×10^{-7} TQUV-α 5×10^{-9}	TW-γ' 3×10^{-6} TQUV-γ' 8×10^{-8}	TW-γ 1×10^{-5} TC-γ 1×10^{-5} TQUV-γ 4×10^{-7}		
T Probabilities	1×10^{-6}	6×10^{-6}	2×10^{-5}	2×10^{-6}	
PRESSURE VESSEL RUPTURE ACCIDENTS (R)		P.V. RUPT. 1×10^{-8} Oxidizing Atmosphere	P.V. RUPT. 1×10^{-7} Non-oxidizing Atmosphere		
R Probabilities	2×10^{-9}	2×10^{-8}	1×10^{-7}	1×10^{-8}	
SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORIES					
MEDIAN (50% VALUE)	1×10^{-6}	6×10^{-6}	2×10^{-5}	2×10^{-6}	1×10^{-4}
LOWER BOUND (5% VALUE)	1×10^{-7}	1×10^{-6}	5×10^{-6}	5×10^{-7}	1×10^{-5}
UPPER BOUND (95% VALUE)	8×10^{-6}	3×10^{-5}	8×10^{-5}	1×10^{-5}	$1\times10^{-}$[illegible]

NOTE: The probabilities for each release category for each event tree and the Σ for all accident sequences are the median values of the dominant accident sequences summed by Monte Carlo simulation plus a 10% contribution from the adjacent release category probability.

TABLE 2-2 (Continued)
Key to BWR Accident Sequence Symbols

A - Rupture of reactor coolant boundary with an equivalent diameter of greater than six inches.

B - Failure of electric power to ESFs.

C - Failure of the reactor protection system.

D - Failure of vapor suppression.

E - Failure of emergency core cooling injection.

F - Failure of emergency core cooling functionability.

G - Failure of containment isolation to limit leakage to less than 100 volume per cent per day.

H - Failure of core spray recirculation system.

I - Failure of low pressure recirculation system.

J - Failure of high pressure service water system.

M - Failure of safety/relief valves to open.

P - Failure of safety/relief valves to reclose after opening.

Q - Failure of normal feedwater system to provide core make-up water.

S_1 - Small pipe break with an equivalent diameter of about 2"-6".

S_2 - Small pipe break with an equivalent diameter of about 1/2"-2".

T - Transient event.

U - Failure of HPCI or RCIC to provide core make-up water.

V - Failure of low pressure ECCS to provide core make-up water.

W - Failure to remove residual core heat.

α - Containment failure due to steam explosion in vessel.

β - Containment failure due to steam explosion in containment.

γ - Containment failure due to overpressure - release through reactor building.

γ' - Containment failure due to overpressure - release direct to atmosphere.

δ - Containment isolation failure in drywell.

ε - Containment isolation failure in wetwell.

ζ - Containment leakage greater than 2400 volume per cent per day.

η - Reactor building isolation failure.

θ - Standby gas treatment system failure.

Note: ECCS: Emergency Core Cooling System; HPCI: high pressure coolant injection; RCIC: reactor core isolation cooling.

Source: NuRC (1975).

In Table 2-1 the first seven release categories are all associated with accidents that would lead to core melt. Events in categories 8 and 9 would not seriously overheat the fuel, so they are of no concern with regard to hydrogen issues. The first four categories in Table 2-2 would all lead to core melt and the last category would not The bottom of each column gives the probability per year of occurrence of each category. The median and confidence limits of a lognormal distribution are given.

Listed vertically are six types of initiating events that start the accident sequences. The first three are pipe breaks of different sizes, the fourth is a rupture of the reactor vessel, the fifth is a special loss of coolant accident (LOCA) that would put high pressure into the low-pressure injection system, and the last refers to all types of reactor trip (shutdown) which would require the decay heat-removal system to operate. Of particular note is the PWR sequence TMLB' in which the plant is assumed to lose all electric power. This accident sequence is an important contributor to risk for many of the PWRs analyzed.

The symbols for the PWR are defined in the associated key. The English letters are used for various system failures and the Greek letters are used for containment failure states. Note that the symbol γ is used for containment failure due to hydrogen burning. Analyses based on more recent information (Indian Point Probabilistic Safety Study, 1982) yield much smaller values for the probability of both α and β than those of the RSS.

A PWR accident sequence of particular interest is TMLB'. The sequence assumes loss of all offsite and onsite power for greater than 3 h. It further assumes that all ability to cool the steam generator is lost. The reactor goes subcritical but the decay heat boils off primary inventory through the pressure relief valve Thus the reactor losses coolant while remaining at pressure. The fuel melts and causes the vessel, which contains water, steam, molten fuel, and hydrogen at pressure, to fail. Such a pressurized release causes the highest rate of hydrogen release to the containment in the range of 10 kg/s or more. Always released with hydrogen and molten fuel in these postulated events will be substantial amounts of steam which, until it condenses, effectively make the mixture inert.

In the case of the BWR the symbol γ stands for overpressure failure. Since BWRs with the Mark I and II containments are made inert, their failure due to hydrogen burning is considered to have a negligibly small probability. The Mark III BWR containment is not made inert and employs igniters to deal with the hydrogen problem.

Core Melt Process

The predicted steps in a hypothetical core melt process will depend upon the particular accident sequence; however, some of the general features are worth noting. As the coolant water level lowers, the top of the core would no longer be cooled, the rods would begin to heat up, and the Zr-steam reaction would begin. Over the period when the fuel geometry is expected to be maintained, calculations of the hydrogen production rate are quite accurate. Once the fuel slumps and the geometry changes the calculation becomes more difficult. In some sequences, molten core debris would be temporarily held up on the lower support plate, and the failure of the support plate would dump a significant volume of molten debris into a pool of water in the lower head. There is some uncertainty in estimated hydrogen generation in such an event. It depends upon the degree of fragmentation of the debris. The MAAP program predicts that hydrogen production during this phase would be small compared to that during the Zr-steam phase. It is assumed that if the core were to melt and fall into the lower head, it would melt through the vessel and fall on the floor below. This is what would occur without any intervention. In some sequences there would be another pool of water under the vessel. Finally, the molten material would begin to attack the concrete with the potential for more hydrogen production as water would be released from the concrete. Clearly, there is great uncertainty in the calculation of all these processes. However, reasonable estimates suggest that the first and the last steps in the processes will be the most important. The hydrogen generated in the intermediate steps would depend strongly on how the molten debris breaks up when it falls into the water. To obtain large hydrogen releases the resulting particles must be quite small. Analysis to date suggests that the particle size would be rather large (greater than 1 cm) which would lead to rather low levels of hydrogen production. For this reason the intermediate steps are not considered to be important contributors to the overall hydrogen production.

HYDROGEN GENERATION DURING THE TMI-2 ACCIDENT

All of the analyses of the accident in the PWR at TMI-2 indicate that large amounts of hydrogen were generated, predominantly by Zr-water reactions, and that the pressure spike (Figure 2-3) evident on the strip chart recorder at about 10 h after the turbine tripped was due to a hydrogen deflagration in the containment. Using a variety of methods, various authors (Cole, 1979; Electric Power Research Institute [EPRI], 1980; Henrie and Postma, 1983; Leung, 1980; Rogovin and Frampton, 1980; Wooten et al., 1980) have made estimates of the total amount of hydrogen in the containment at the time of the burn. All of these estimates have required assumptions because of the lack of exact measurements of all required parameters and, as would be expected, have led to different values (Figure 2-4) for the amount of hydrogen released to the containment prior to the hydrogen burn. These values fall in the fairly narrow range of 270 to 370 kg, except for the early estimate of about 125 kg by the Battelle Memorial Institute (Wooten et al., 1980) based on an early version of the MARCH code.

The Factory Mutual Research Corporation analysis (Zalosh, 1985) concludes that at the time of the deflagration the hydrogen concentration in the containment was fairly uniform at 7.3 to 7.9 volume percent. Calculations based upon changes in temperature and pressure in the containment before and after the deflagration give estimates that

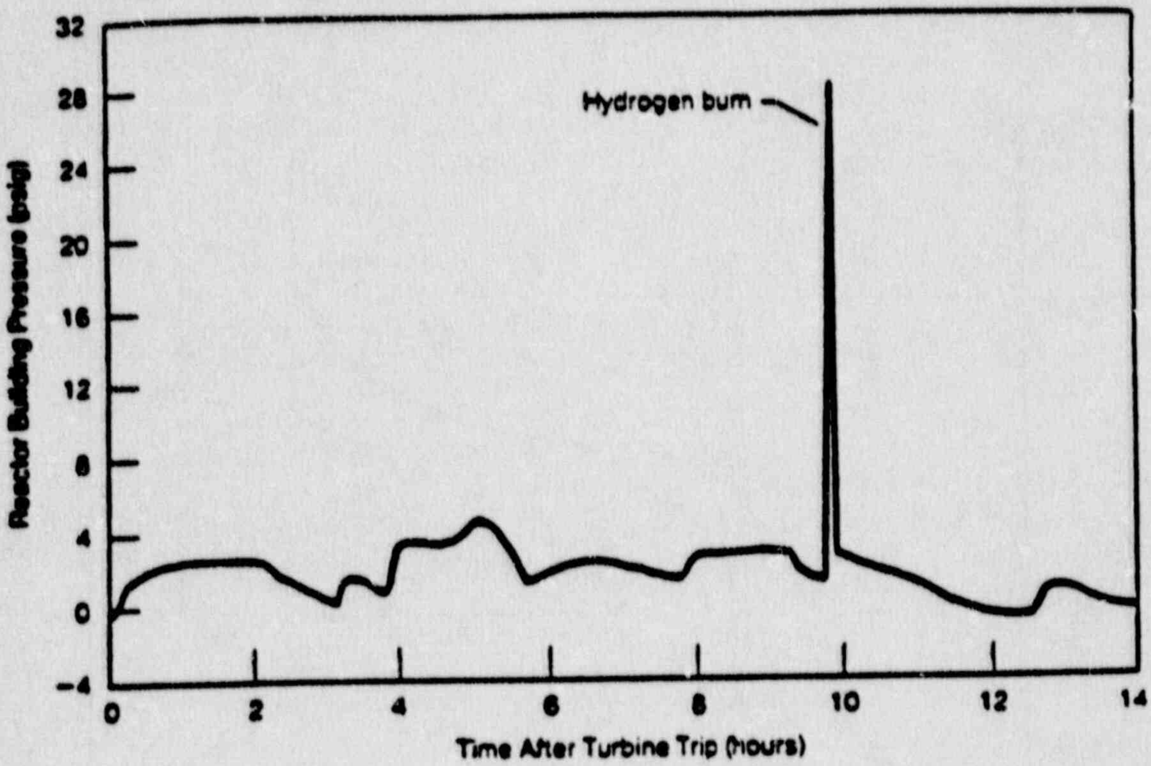

FIGURE 2-3 Reactor building pressure versus time at TMI-2.

Source: EPRI (1980).

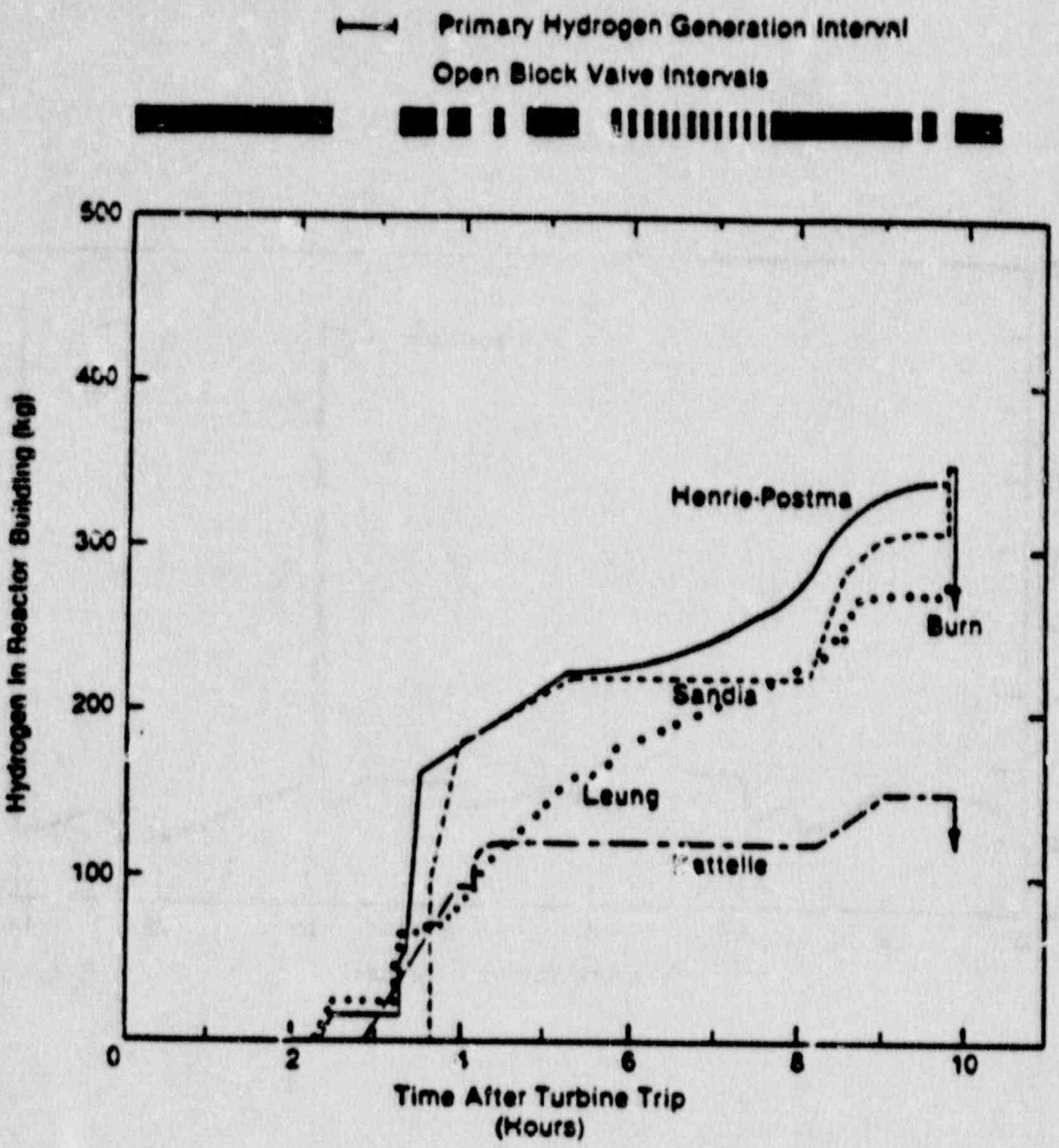

FIGURE 2-4 Comparison of hydrogen accumulation estimates in reactor building at TMI-2. The Sandia results are reported in Rogovin and Frampton (1980).

Source: EPRI (1980)

range from 270 to 400 kg for the amount of hydrogen that burned. These calculations suggest that a large percentage of the amount present actually burned, as would be expected (see Table 2-3). It is of interest to recall that at one point during the TMI-2 accident, concern was raised that the gas bubble in the reactor vessel might be a detonable mixture of hydrogen and oxygen from radiolysis of water. Numerous analyses (Rogovin and Frampton, 1980) have shown that this is not possible. Since the hot zirconium is such a good oxidizing agent, there clearly could have been no free oxygen in the vessel during the accident. Hydrogen and oxygen produced together by radiolysis after the accident in the circumstances of TMI-2 would have readily recombined because of the catalytic properties of the impurities and hydrogen present in the vessel, and therefore there would have been no free oxygen to sustain an in vessel hydrogen detonation. Furthermore, the results of Pakczwski and Benaroya (1984) show that a net rate of radiolysis will not occur in subcooled water when significant amounts of hydrogen are present.

Henrie and Postma (1983) show a hydrogen balance with calculations that give a high estimate of 370 kg for the hydrogen generated (Table 2-3). These authors suggest that after the deflagration about 89 kg of additional hydrogen was released from the primary system to the containment as a result of the venting of the pressurizer that continued for some time after the deflagration. About one-half (45 kg) of this hydrogen was estimated to be from radiolysis of water, the other half from the Zr-water reaction. Thus, less than 10 percent of the total hydrogen was estimated to be produced by radiolysis (Henrie and Postma, 1983).

The total amount of Zr in the core region was about 23,600 kg (51,900 lb). Of this, about 18,770 kg (41,300 lb) was fuel cladding. The rest was in Zircaloy used in core structures. It can be concluded from Table 2-3 that the Zr-water reaction produced about 415 kg of hydrogen gas or 208 kg mol. Since this reaction produces 2 mol of H_2 for each mol of Zr reacted, the amount of Zr reacted is 140 kg mol or about 9,400 kg. Thus, about 40 percent of all the Zr was oxidized, or if all the reaction occurred in the cladding, about 50 percent of the cladding was oxidized.

Examination up to now indicates that most of the top half of the core has been displaced and is in a rubble bed at the lower half of the reactor vessel. It appears to be part of the rather loose rubble bed filling roughly the bottom half of the vessel. Several feet below the surface of this rubble bed is a hard crust that has been found by probing. The exact nature of this crust and what is below it are not known. Visual observation of the lower head shows it to be partially filled with previously molten material. All of this indicates that most of the fuel appears to have been at highly elevated temperatures in the presence of steam at some time during the course of the accident.

TABLE 2-3 Containment Hydrogen Balance

Date and Time	Hydrogen added		Hydrogen removed		Hydrogen inventory	
	Dry (%)	kg	Dry (%)	kg	Dry (%)	kg
March 28, 1979						
13:50	8.2	370			8.2	370
13:52			7.1	319[b]	1.1	51
15 00	0.6	24[a]			1.7	75
April 1, 1979	0.5	21[a]			2.2	96
May 1, 1979	1.1	44[a,c]	2.6	112[d]	0.7	28
July 1980			0.7	28		0
Total		459		459		

[a] From the reactor cooling system.
[b] Hydrogen burn.
[c] From waste gas decay tanks and radiolysis.
[d] Rockwell International Hydrogen Recombiner.

SOURCE: Henrie and Postma (1983).

HYDROGEN REGULATIONS

The regulatory requirements that have been adopted to ensure that combustion of hydrogen during a severe accident does not compromise containment integrity are generally contained in Part 50.44, Title 10, of the Code of Federal Regulations.

In 1981, after consideration of the pressure pulse induced during the TMI-2 accident, the NuRC issued a rule requiring inerting of the atmosphere within the containment structure of all BWRs with Mark I and Mark II containments when these reactors are in operation.

In 1982 a separate set of requirements was issued in a rule concerning hydrogen control for pending construction permits and manufacturing license applications. This called for measures to ensure limitations on hydrogen concentrations after a degraded core accident, and assurance of continued containment integrity.

In 1985 a rule was issued requiring igniters in ice-condenser containments of PWRs and in Mark III containments of BWRs, with the intent of ensuring that under no conditions may the hydrogen concentration approach the value at which detonation can develop. Igniters are now installed in all nuclear plants of these types that are licensed to operate. Igniters are distributed about the dry and wet wells of the BWRs, and in all compartments of the PWR ice-condenser containments.

REVIEW OF HYDROGEN RESEARCH PROGRAMS

Research on combustion and detonation of hydrogen in air is a subset of the broader field of research on combustible and explosive mixtures of gases in general. Research has been under way in all these areas for many years. Some studies have covered the basic chemistry, dynamics, and thermal effects. Others have been directed to more applied questions such as safety, combustion in internal combustion engines and in jet and rocket engines.

The occurrence of the hydrogen deflagration during the accident at the TMI-2 nuclear reactor led to a great deal of activity to further our understanding of the generation, behavior, and control of hydrogen during severe LWR accidents. The NuRC has sponsored research directed toward improved understanding of safety questions associated with potential hydrogen generation during an accident that severely damages a reactor core. Sandia National Laboratories (SNL) has served as the principal contractor for this NuRC-sponsored research. Much of this work has concentrated on various aspects of hydrogen combustion. Additional research has been sponsored by the nuclear power industry.

Nuclear Regulatory Commission Programs

The NuRC has supported hydrogen programs at several of the national laboratories including SNL (Albuquerque, New Mexico, and Livermore, California), Lawrence Livermore National Laboratory, Los Alamos National Laboratory (LANL), and Brookhaven National Laboratory. The bulk of the research effort was conducted at SNL and LANL and amounted to $14.8 million from fiscal year 1981 (FY81) through FY85 (see Table 2-4).

The Combustible Gases in Containment Program provided data on rates and quantities of hydrogen that could be generated from corrosion of coating materials during degraded core accidents. Expenditures have amounted to $563,000. The Hydrogen Migration Studies (HMS) Program at LANL has developed the HMS code which solves a model of three-dimensional, time-dependent flow with multiple species transport. Hydrogen distribution and combustion are included in this code. Through the end of FY85, $515,000 was expended. Projected expenditures for FY86 are $175,000. A Hydrogen Burn Survival Program at SNL has been used to evaluate the performance of equipment subjected to possible hydrogen deflagrations.

The Hydrogen Behavior Program is the most comprehensive of the research undertakings and is aimed at investigating and quantifying important combustion phenomena including deflagrations, accelerated flames, detonations, and diffusion flames. To date, $8.66 million has been expended, with the expectation that several million dollars will be expended from FY85 through FY88. Projected expenditures in FY86 are $1.2 million. The objectives of this program are (1) to quantify the threat to nuclear power plants (containment structure, safety equipment, and the primary system) posed by hydrogen combustion; (2) to disseminate information on hydrogen behavior, detection, control, and disposal; and (3) to provide program management and technical assistance to the NuRC on hydrogen-related matters (Reactor Safety Research Quarterly Report July-September 1984, 1985a). Information has been disseminated mainly through NuRC reports (called NUREG reports) and NuRC-supported meetings. Approximately 50 reports or report chapters, 70 papers in conference proceedings or books, and a dozen journal articles have been published.

Analytical work has been directed toward the development of a computer model (code) called HECTR (Hydrogen Event: Containment Transient Response) which computes the transport and combustion of hydrogen in a containment volume. Experimental work has been used to yield parameters for this model. To complement the experimental work on flames, a two-dimensional computer code (CONCHAS-SPRAY), developed at LANL and used at SNL, for modeling flame development in a rectangular channel is under development. Models for diffusion flame- and momentum-dominated jets are also being developed. Analyses have been conducted of hydrogen control measures for the Sequoyah Nuclear Power Plant (Berman et al., 1981), on an evaluation of the adequacy of the hydrogen igniter system for the Grand Gulf Nuclear Power Station, and on the pressure and temperature effects of local and global detonations. Other work has included reviews of the Hydrogen Control Owners Group (HCOG) and Nevada Test Site (NTS) hydrogen combustion experiments.

TABLE 2-4 Major Expenditures by Fiscal Year for Hydrogen Research at Sandia National Laboratories[a]

Fiscal Year	Total [illegible]enditures (mill[illegible]f dollars)
1981	1.271
1982	2.85
1983	4.205
1984	3.199
1985	2.426
SUBTOTAL	13.951
Nevada Test Site	0.87
TOTAL	14.821
Projected 1986	1.575

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[a] Programs include hydrogen behavior, combustible gases, hydrogen burn survival, hydrogen migration studies, and hydrogen mitigation. Expenditures include work at SNL (Albuquerque and Livermore) and LANL.

To fully understand hydrogen transport and combustion behavior, a number of experimental facilities have been built and operated. Work at the NTS was sponsored by both NuRC and EPRI to investigate hydrogen deflagrations as well as diffusion flames in both air and air-steam mixtures. The survivability of safety-related equipment to the results of combustion were investigated through experiments performed in a 2,048-m^3 spherical vessel. Mixtures of hydrogen, steam, and air were ignited by glow plugs or heated resistance coils.

The so-called Variable Geometry Experimental System (VGES) consists of a set of experimental facilities of various sizes. Three buried tanks have been used to study deflagrations, accelerated flames, mitigation concepts, and the effects of aerosols. The effect of aluminum and iron oxide powdered aerosols on detonation of hydrogen mixtures has also been studied in a small 0.18-m^3 tank in conjunction with experiments in the 5-m^3 VGES tank at SNL. Four large horizontal tubes, as well as several smaller tubes, have been used for critical tube diameter and critical energy studies. The Flame Acceleration Measurement Experiments facility is a U-shaped channel. It was built with the intention to simulate geometries relevant to nuclear reactors and to study flame acceleration and transition to detonation. There is also a 0.46-m-diameter, 12.8-m-long heated tube for detonation studies in steam-hydrogen-air mixtures.

Experimental work has also been supported at McGill University in Montreal, Quebec, Canada. Tubes ranging in size from a few to 30 cm in diameter have been used to study flame acceleration, transition to detonation, and detonation propagation. Experiments have also been conducted in plastic bags to determine the initiation energy required for unconfined explosions.

The Fully Instrumented Test Site tank is 3.4 m high and 1.5 m in diameter and has been used to investigate the influence on hydrogen combustion of initial temperature, partial pressure of air in the tank, concentration of steam or carbon dioxide, and hydrogen concentration. This has resulted in a set of flammability data for hydrogen-air-steam mixtures, as well as hydrogen-air-carbon dioxide mixtures.

Some research has been aimed at hydrogen mitigation and prevention schemes. Because of the presence of water spray systems in reactor containments, experiments have been conducted to determine the effect of water sprays on hydrogen igniters. The influence of water droplets, as well as that of aerosols composed of aluminum or iron oxide, on the combustion of hydrogen-air mixtures has been studied. Because of the importance of reliable, deliberate ignition systems, work has proceeded on the development of a catalytic igniter which does not require an external source of power (Reactor Safety Research Quarterly Report October-December 1984, 1985b). Expenditures for FY86 for hydrogen mitigation are projected at $200,000.

Industry-Sponsored Programs

In addition to the research sponsored by the NuRC at Sandia Laboratories (including McGill University), the nuclear power industry embarked on research programs aimed at investigating hydrogen control and combustion during postulated severe accidents. During the period 1979-1980, Fenwal, Inc., and Westinghouse Corporation conducted a series of experiments sponsored by the Ice Condenser Utilities (Tennessee Valley Authority [TVA]), Duke Power and Light Company and American Electric Power Company, and EPRI. These experiments were conducted in a 3.8-m^3 sphere and demonstrated lean mixture (5 to 10 percent hydrogen) ignitability with glow plugs in the presence of steam and sprays (Liparulo et al., 1981). Data were also obtained on lean mixture burn fractions and peak pressures, whereas preliminary data were generated on equipment survivability and continuous injection burns. No attempt was made to simulate containment spray characteristics.

The Ice Condenser Utilities and EPRI sponsored a number of other investigations in 1981-1982. Tests were conducted at Atomic Energy of Canada Limited's Whiteshell Nuclear Research Establishment in a 6.3-m^3 sphere (Kumar et al., 1984; Tamm et al., 1982;). The ignitability of hydrogen and air mixtures by glow plugs and coils was investigated under conditions of high steam concentrations and fan-induced turbulence. Peak pressure and burn fraction data were collected at 100°C. The effect of turbulence induced by gratings and the effect of igniter location were also investigated. Flame acceleration from a sphere into a connecting pipe and vice versa were also studied. Factory Mutual Research Corporation (FMRC) studied the influence of water fogs on flammability in an 18-liter tube and arrived at conclusions with regard to the inerting of hydrogen-air mixtures as a function of fog density, drop size, and steam concentration (Zalosh and Bajpai, 1982a,b). The Westinghouse Hanford Company simulated hydrogen jet releases in lower compartments of ice-condenser containments, producing nearly uniform hydrogen concentrations (within 3 percent) outside the jet (Bloom et al., 1982, 1983). After jet flow is stopped, natural convection and blower-forced convection are important in diluting the hydrogen remaining in the jet region. Research with a 17.8-m^3 vertical cylinder was also performed at the Accurex Corporation. Premixed tests were conducted to study the effects of water sprays, fog, fans, and igniter location on hydrogen burn fraction and peak pressure. Continuous injection tests resulted in either repeated deflagrations or diffusion flames, depending on igniter location relative to release site and the presence of water sprays (Torok et al., 1982, 1983). Data were also collected on equipment response and operability during burns.

As described under the section on NuRC-supported research, the NTS studies incorporated combustion of premixed hydrogen-air. Continuous injection tests produced diffusion flames in almost all release configurations irrespective of fan or spray mixing and initial steam concentration. Data were also collected on equipment and cable operability and survivability (Haugh, in press).

The TVA sponsored tests by FMRC to examine the operation of Tayco glow coil igniters, used in TVA containments, at high water spray fluxes. Both shielded and unshielded coils were studied (Zalosh and Chaffee, 1984). EPRI and the BWR Mark III utilities (HCOG) provided funds for the Accurex Corporation to conduct tests in a 1/20th scale version of a Mark III containment which included spargers releasing hydrogen, a suppression pool, and igniters. Diffusion flames were observed to form above the suppression pool, and a vertical recirculating flow field was observed to form with warm gases rising at some positions and cooler gases descending at others (Brown et al., 1984). No combustion was observed at oxygen concentrations below 5 percent.

Recently, EPRI and HCOG have funded FMRC to conduct tests on a 1/4-scale model of a Mark III containment. Preliminary scoping test results have so far indicated that diffusion flames form at all hydrogen release rates after an ignitable hydrogen concentration forms at an igniter. Wall plumes were observed to form along the inner wall of the wet well, with highest temperatures measured near the inner wall. Wispy, weak flames occasionally formed away from the main flames. The full range of tests are scheduled for early 1986 and will continue through the end of the year.

Computer codes related to the generation and combustion of hydrogen during severe accidents have also been developed. See Chapter 3 for these codes.

3

MODELING TECHNIQUES

The objective of this chapter is to review models that have been developed for analysis of hydrogen transport and combustion as a result of hydrogen release in nuclear reactor containments. Some typical examples, and their evaluation using data from subscale tests, are described. Areas where additional model development is needed are also discussed.

Currently, there are two general approaches for modeling turbulent mixing processes: (1) lumped-parameter models, where specified volumes are assumed to be well-mixed and phenomenological relationships are used to describe transport and rate processes in the domain of interest; and (2) field models, where equations of motion and transport are solved over the domain of interest, with a variety of empirical approaches or approximations used to treat turbulence and transport properties. Both approaches have been applied to hydrogen in reactor containments. However, lumped-parameter models have received the most attention.

LUMPED-PARAMETER MODELS

There are two types of lumped-parameter models which have been used to analyze turbulent mixing within structures. The first type are lumped-volume models where specified volume elements are assumed to be well-mixed, with empirical relationships used to describe mixing between volume elements. The second type are zone models which invoke specific flow phenomena, such as plumes and stratified layers, using phenomenological analysis. Only lumped-volume models have been considered for reactor mixing analysis thus far. However, zone models offer a useful alternative and both methods will be considered in the following sections.

Lumped-Volume Models

Several lumped-volume models that have been developed for analysis of hydrogen mixing and combustion in reactor containments are summarized in

Table 3-1. The table identifies the organization which developed the model and provides references describing details and evaluation of the method. Lumped-volume models are popular since they require relatively short computation times and can be coded with minimal difficulty to treat complex geometries and scenarios. They differ greatly in detail and in the types of phenomena that can be incorporated. However, they all have in common the assumption of empirical flow resistances between well-mixed volume elements and use some type of network solver.

A typical lumped-volume code which has been widely used for nuclear reactor containment analysis in this country is called HECTR (Camp et al., 1982; Cummings et al., 1984). The lumped volumes are generally compartments within the containment, although some users arbitrarily subdivide compartments. The model satisfies global requirements for conservation of mass, energy, and momentum in each compartment. Flows between compartments include effects of pressure differences, buoyancy, and fans in a global manner with user-specified interconnection loss coefficients. The code includes models for hydrogen combustion (with empirical expressions for ignition, flame velocities, propagation between compartments, and completeness of reaction); radiative heat transfer (using a wide-band model); convective heat transfer (by natural and forced convection); wall condensation (using a laminar film condensation analysis); heat transfer to sprays (using a Lagrangian formulation with prescribed initial drop sizes); wall heat conduction (considering either lumped masses or slabs with internal temperature gradients); and ice condensers. Clearly, the list of phenomena considered by this model and others like it is very impressive. However, many of these features are drastic simplifications of actual phenomena due to the absence of needed fundamental knowledge and the requirement for moderate computation times. Critical user-selected parameters include intercompartment flow resistances and parameters relating to hydrogen combustion. Systematic sensitivity analysis of these parameters has not been reported; however, it is well known that predictions are strongly influenced by their selection.

There have been several investigations to evaluate aspects of lumped-volume codes (Cummings et al., 1983, 1984; Dingman et al., 1982; Fuls and Gunter, 1982; Haskin and Trebilcock, 1982; Wester and Camp, 1983). Most codes have provided reasonable correlations of global experimental observations; however, they all involve numerous adjustable parameters, whose values are generally not defined in evaluation reports. Thus, these evaluations are not definitive and the accuracy of the codes for configurations where extrapolation is necessary, such as to full-scale reactor containments, is questionable. They also require an experienced user who is familiar with proper parameter selection to achieve good results. Furthermore, all features of these models have not been systematically tested. Finally, the models work best under the assumption that fans and sprays are operating, helping to mix gases in

TABLE 3-1 Summary of Lumped-Volume Reactor Mixing Codes

Code	Organization	Reference
CLASIX, CLASIX-3	Westinghouse Offshore Power Systems	Fuls and Gunter (1982)
CONTEMPT-DG	Power Authority, State of New York	Deem and Rousseau (1982)
CONTEMPT-LI	Electric Power Research Institute (EPRI)	Deem and Rousseau (1982), cited
HECTR	Sandia National Laboratories	Camp et al. (1982)
HECTR-ES	Sandia National Laboratories	Kempka et al. (1982)
HYBRID	Public Services of Oklahoma	Zink (1981)
MAPHY	Japan	Fujimoto et al. (1982)
MAAP	Fauske & Associates	Baker et al. (1982)
MARCH	Battelle Columbus Labs	Wooten and Avci (1980)
RALOC, RALOC-MODI	GRS, Federal Republic of Germany	Jahn (1980)
RECAP	EPRI	Ritzman et al. (1980)
RELAP	Aerojet Nuclear Corp	Aerojet Nuclear Company (1976)

each compartment. Accuracy of the models is reduced in instances where outside agents are not assisting mixing and effects of stratification and buoyancy begin to dominate both fluid mixing and motion.

Zone Models

Zone models are generically similar to lumped-volume models since both divide the flow field into well-mixed regions. However, in zone models, these divisions are made on the basis of flow phenomena, and are recognized as regions of buoyant plumes, stratified layers within a compartment, door jets, etc., rather than by whole compartments, or arbitrary division of a particular compartment, as with lumped-volume methods. Consequently, zone models can be more effective for treating effects of stratification and buoyancy, which lumped-volume models do not predict very well, and still maintain performance similar to that of lumped-volume models for well-mixed conditions.

Zone models are widely used for the analysis of unwanted fires within structures. Table 3-2 is a summary of some representative zone models. Fire scenarios are very complex, and most of these models are limited to fires within a single room. However, multicompartment smoke transport models have been reported as well (Tanaka, 1980). The multicompartment models have been developed along the lines of available building ventilation codes used in the design of structures.

Single-room zone fire models generally divide the room into three zones, namely, the fire, a stratified hot ceiling layer, and a lower layer. Conservation relationships are written for these zones, allowing for flow resistances at room openings. Since stratification is important, there are generally simultaneous inflows and outflows at the openings. Needed flow and entrainment coefficients for these processes have been developed from auxiliary experiments, similar to the measurement and correlation of convection heat transfer coefficients. Most of these models use empirical correlations for flame spread rates, convective and radiative heat transfer, and the entrainment properties of the fire plume. Heat conduction in walls, floors, and ceilings is treated in a manner similar to that for the lumped-volume models.

Evaluation of zone models has been similar to that for lumped-volume reactor codes. However, for zone models, full-scale experiments are feasible and have been used (Cooper et al., 1985; Jones, 1983; Mitler, 1985; Mitler and Emmons, 1981). Since zone models tend to divide the problem along physical grounds, aspects of the analysis can also be tested at a small scale more convincingly by including flow coefficients for doors, entrainment of plumes and door jets, and radiation from fires and ceiling layers. Although additional evaluation and improvement is a continuing process (Cooper, 1981), there is a more systematic basis for development of the methodology than for lumped-volume models. Adopting zone-modeling principles for current lumped-volume codes would not involve a significant change in their fundamental properties. Consequently, the advantage of a more physically based zone-modeling approach which lends itself to systematic development could easily be incorporated into analysis of hydrogen mixing and combustion in reactor containments.

Table 3-2 Summary of Zone Codes[a]

Code	Organization	Reference
BCFM	National Bureau of Standards	Cooper et al. (1985)
CALTECH	California Institute of Technology	Zukoski and Kubota (1981)
COMPBRN	University of California, Los Angeles	Siu (1982, 1983)
DACFIR	University of Dayton	MacArthur (1981)
FAST	National Bureau of Standards	Tanaka (1983), Jones (1984)
HARVARD-5,6	Harvard University	Mitler and Emmons (1981), Mitler (1985)
NBS-II	National Bureau of Standards	Cooper (1981)
RFIRES Technology	Illinois Institute of (1980)	Pape et al.
—	Building Research Institute (Japan)	Tanaka (1980)

[a] Generally written to simulate fires in structures.

FIELD MODELS

Field models provide greater detail than lumped-parameter models, since the governing equations of conservation of mass, momentum, energy, and species are solved for incremental regions of the flow. The transport properties of the generally turbulent flows encountered in reactor containments are also represented. There are currently two categories of field models. Time-averaged analysis uses semiempirical approximations to represent the turbulence properties of the flows. Mathematical simulations, which solve the three-dimensional equations of motion in transient form, provide an exact (in principle) representation of the turbulent flow. Only time-averaged analysis has been considered for reactor mixing models thus far. Due to its computational requirements, numerical simulation is not feasible for analyzing the situation existing in an actual containment. However, simulation can still contribute to the development of more physically-based turbulence models. Therefore, both methods will be considered in the following sections.

Time-Averaged Models

Several time-averaged models developed for or applied to problems of hydrogen mixing and combustion in reactor containments are summarized in Table 3-3. The table identifies the organization which developed or adapted an existing model to the reactor containment problem. Details can be found in the associated references.

The computer code, Hydrogen Migration Studies (HMS), developed to describe hydrogen transport, is of particular interest and is currently under development by Travis (1982, 1985). It is based on the ICE algorithm of Harlow and Amsden (1971). This code is closely related to the CONCHAS-SPRAY and mixing code developed by Butler et al. (1980), which has also been adapted for containment problems (Cloutman et al., 1982; Cummings et al., 1984). The other codes listed in Table 3-3 are largely modifications of computational and turbulence-modeling efforts at Imperial College (Gosman and Pun, 1973; Launder and Spalding, 1972).

Since HMS continues to be developed to describe hydrogen transport in nuclear reactor containments, some of its current features will be described in more detail. HMS is designed to treat time-dependent, low-speed flow in three dimensions. In a broad sense, this code can yield numerical simulations of turbulent flow; however, the treatment of boundary conditions and interpretation results in time-averaged information. The time-dependent Navier-Stokes equations are solved along with transport equations for conservation of species and energy. Flow near surfaces is not resolved by the grid; therefore, the solution is matched to law-of-the-wall approximations for velocities, and the Reynolds analogy is used to provide heat and mass transport boundary conditions. Processes of radiation and wall heat conduction are also modeled (see original sources for details).

TABLE 3-3 Summary of Field Reactor Mixing Codes

Code	Organization	Reference
COBRA-NC	Battelle Northwest Laboratory	Thurgood (1982)
CONCHAS-SPRAY	Los Alamos National Laboratory	Cummings et al., (1984), Cloutman et al., (1982)
HMS	Sandia National Laboratories	Travis (1982)
IPSA	Cham, Inc.	Spalding (1977)
TEMPEST	Battelle Pacific Northwest Laboratory	Trent and Eyler (1982)

Turbulence properties are treated using a subgrid-scale model in the most recent version of HMS (Travis, 1985). The approach follows other recent work at Los Alamos National Laboratory (Amsden et al., 1985). This involves solving a modeled transport equation for turbulent kinetic energy (for turbulence having length scales too small to resolve by the computational mesh) using a prescribed mixing length based on the size of the mesh. The specific turbulence kinetic energy, q, and mixing length related to the mesh size of the numerical grid, L, are then used to compute a turbulent diffusivity, γ_t, from the following empirical expression:

$$\gamma_t = Lq^{1/2}/20.$$

The corresponding turbulent diffusivities of mass and heat are found by assuming turbulent Schmidt and Prandtl numbers equal to unity. Travis (1985) points out that this procedure reduces to an algebraic subgrid-scale model similar to those of Smagorinsky (1963) and Deardorff (1970, 1971) in regions where turbulence production and dissipation are equal.

This version of HMS also considers the combustion of hydrogen jets in air as a diffusion flame (Travis, 1985). The approach used follows contemporary work at Los Alamos National Laboratory as well (Amsden et al., 1985). This involves a global Arrhenius rate expression for combustion in a turbulent environment, neglecting effects of turbulent fluctuations, which is an approach similar to that of Fishburn and Pergament (1979). In this case, the flame is assumed to radiate a fixed fraction of the local rate of chemical energy release, neglecting reabsorption in other portions of the flow field (optically thin approximation), which is an approximation that has been used by workers at Factory Mutual Research Corporation for the analysis of flame radiation from fires (Tamanini, 1983; Ural and Zalosh, 1985).

The treatment of turbulence properties and hydrogen combustion in HMS departs significantly from contemporary methods used in time-averaged analysis of turbulent mixing and reaction processes (Alpert and Mathews, 1979; Bilger, 1977; Dibble et al., 1984; Drake et al. 1982, 1984; Gore et al., 1986; Launder and Spalding, 1972; Starner, 1983; Starner and Bilger, 1980, 1981). Since the HMS procedure has not been validated using available data for simple turbulent flows, its reliability is questionable. Turbulent transport properties are intrinsically linked to mesh size in HMS; thus, the mesh size is an implicit turbulence modeling parameter. When the model using a particular computational mesh is validated for particular cases, this can provide some capability for modest extrapolation. However, a physically realistic solution, if grid independence was achieved in the conventional sense (approaching the limit of small grid size), cannot be guaranteed; in fact, it is unlikely.

The diffusion flame analysis in HMS can be criticized on similar grounds. Existing measurements suggest that hydrogen-air diffusion flames are invariably at the fast-reaction, nonpremixed limit, except at points of flame attachment (Faeth and Samuelson, 1985). The conserved-scalar formalism has been shown to be effective for such conditions, particularly for the hydrogen-air diffusion flames of interest for nuclear containment problems (Bilger, 1977; Drake et al., 1982, 1984; Gore et al., 1986; Starner, 1983; Starner and Bilger, 1980, 1981). In view of this, the Arrhenius expressions used in HMS are not consistent with observed diffusion flame phenomena. Since turbulence is well-known to interact strongly with reaction processes, the relevance of these ideas to premixed flames is questionable as well.

The other codes listed in Table 3-3 incorporate a variety of turbulence-modeling methods, varying from constant eddy diffusivities to models employing higher order turbulence closure, e.g., the models referred to as k-e-g models (Launder and Spalding, 1972): these models use the conserved scalar formalism (Bilger, 1977). These methods are generally most successful for boundary-layer flows. Their application to complex compartments, with stratification, buoyancy, and premixed combustion and sprays, will undoubtedly generate very uncertain results. Establishing grid independence and numerical closure for computation in regimes as complex as nuclear reactor containments is a tedious and extremely costly process. Evidence that this has been done could not be found.

Some of the field models have been evaluated using existing data for hydrogen transport in containments (EPRI, 1983; Thurgood, 1982; Travis, 1982; Trent and Eyler, 1982). In view of earlier comments, however, these assessments are not convincing demonstrations of the general effectiveness of these methods. Rather, they establish capabilities of yielding representative results for particular scales and conditions. Extrapolation to full-scale systems or other circumstances, however, is questionable.

Turbulence Simulation

Turbulence satisfies the time-dependent, three-dimensional equations of motion and transport; therefore, exact solution for flow properties, without recourse to models, is feasible in principle. Results of such simulations can then be averaged over numerous realizations to obtain the statistically significant results normally used to describe turbulent phenomena (see Hsiao et al., 1984, for an example using two-dimensional simulation).

The difficulty with direct numerical simulation of turbulence is the large range of length scales involved for the high-flow Reynolds numbers of interest for most practical problems. Therefore, a fine grid in a large volume (or its equivalent for a Lagrangian computation) is required to resolve the flow. Allowing for the three-dimensional transient nature of turbulence requires a large number of space-time nodes. The result is that complete simulation of nuclear containments will probably not be feasible within the technological lifetime of the plants under consideration, in spite of anticipated advances of computational capabilities (Baum and Rehm, 1984).

Nevertheless, numerical simulation of turbulent processes is possible for simplified cases, such as low-Reynolds-number flows, and provides a valuable research tool to gain a better understanding of turbulent mixing. The strength of the approach is its ability to provide accurate predictions of quantities that are very difficult to measure, such as pressure-velocity correlations or multipoint correlations, among others. Thus, simulation is being actively pursued as a supplement to experiments to support the development of more empirical (but computationally tractable) methods.

Table 3-4 is a summary of some typical numerical simulation methods. The table provides the method used, the organization developing the method, and references describing the analysis and results. There are three general methods for carrying out these computations. The first is the random vortex or vortex dynamics method, which is particularly efficient for certain types of problems in two-dimensional (partial) simulations of turbulence. The second approach involves spatial and spectral methods, which currently are most convenient for treating processes within an enclosure. Finally, there are finite-difference methods. Each method has its proponents, and it is beyond the scope of the present study to discuss their relative merits. It is suggested, however, that these techniques could be applied to aspects of hydrogen reaction and transport in containments (e.g., jet mixing, premixed combustion, diffusion flames), to improve the physical basis for more approximate, but more phenomenologically complete, analysis.

CONCLUSIONS AND RECOMMENDATIONS

Lumped-Parameter Models

Lumped parameter models provide a viable approach for treating the complexities of hydrogen transport and combustion in containments. Substantial progress has been made toward developing codes of this type, with HECTR and its variants (Camp et al., 1982; Kempka et al., 1982) representing a current state-of-the-art code. The models have been evaluated to some extent using measurements from subscale systems. However, many of their features have not been evaluated directly. Furthermore, while evaluations have generally been favorable when executed by experienced users, there are many user-specified parameters; therefore, the extent to which these evaluations represent correlations or predictions is open to question. It is concluded that the general validity of the models for full-scale containments has not been adequately established. Finally, work thus far has shown that existing models are deficient in cases where mixing is not enhanced by external means, such as when fans and sprays are not operating.

Based on these observations, the implementation of the following recommendations would enhance the state-of-the-art of lumped-parameter models, improve confidence in their results, and make them more reliable for application to problems of hydrogen combustion.

- Model evaluation should continue, with the additional requirements that all user-specified parameters, and the scaling rules to be used for them, be fully documented as part of the evaluation. The goal of subsequent evaluations should be more generally valid guidelines for code use with demonstrated capabilities to treat hydrogen mixing and combustion in full-size containments.

TABLE 3-4 Summary of Numerical Simulations of Turbulent Mixing

Method	Organization	Reference
Random Vortex	University of California, Berkeley	Ghoniem et al. (1982), Ghoniem and Sherman (1985), Hsiao et al. (1984)
Random vortex (vortex dynamics)	Sandia National Laboratory, Livermore	Gibson et al. (1985)
Spectral	Flow Research Company	Riley and Metcalfe (1985)
Spectral	National Bureau of Standards	Baum et al. (1983), Baum and Rehm (1984)
Finite difference	Naval Research Laboratory	Boris et al. (1983)

- Lumped-parameter codes should be validated by undertaking comparison with measurements from a few large-scale experiments. These experiments could be carried out using inert gases in an actual containment or a structure of similar size. Comparison with data from the 1/4-scale tests would be useful as well.
- Future lumped-parameter models should make greater use of zone-modeling techniques since zone models offer attractive features for treating the hydrogen problem in containments, particularly when auxiliary mixing sources are absent. They are more physically based than the ad hoc subdivision of compartments into well-mixed volumes, and provide a formalism to design studies that address specific aspects of flow and mixing in structures, including plume entrainment or mixing in stratified layers.
- Coordination of National Bureau of Standards (NBS) and Nuclear Regulatory Commission (NuRC) efforts to develop zone models would be beneficial to both programs and should be pursued. The Center for Fire Research of the NBS is actively developing zone models of fires within structures. This technology is very similar to lumped-parameter modeling of hydrogen transport and combustion in containments.

Field Models

Field models cannot be as comprehensive as lumped-parameter models, in terms of phenomena considered, since they are more computationally intensive. However, they can provide more detailed analysis of the mechanisms of hydrogen mixing and combustion in containments and thereby help improve our understanding of the problem and assist in the development of empirical aspects of lumped-parameter models. Progress has been made in adapting existing codes to the containment problem, yielding the codes listed in Table 3-3 as the current state of this technology. HMS is still being actively developed for this purpose. The models have been evaluated to some extent, using a data base similar to that of the lumped-volume codes. While evaluations have been favorable, these models require many user-specified parameters, raising questions concerning their general usefulness when applied to full-scale containments by personnel not directly involved with model development. Numerical closure (grid independence and numerical convergence) has not been demonstrated adequately, raising questions whether these approaches can be accurately executed (aside from the limitations of their physical approximations) at reasonable cost with current computational facilities. Furthermore, the physical approximations used in these codes for turbulence properties and turbulent combustion have not included approaches which are state of the art in the field. Areas of probable deficiency include buoyancy/turbulence interactions, mixing of variable density flows, spray processes, and premixed turbulent combustion.

Based on these observations, the following recommendations would improve the state of the art of field models and confidence in their results.

- Development and evaluation of these methods should continue, with emphasis on the demonstration of grid-independent and user-independent results relevant to full-size containments.
- Field models should be used to model the structure of the flow within compartments based on the results of experiments in actual containments or similar multicompartment structures. These results could then be used to develop empirical parameters for the lumped-parameter models.
- Subelements of the field models should be developed using results from both detailed experiments and numerical simulations of turbulence. Improvements in these areas require that the limitations of the current experimental data base be overcome, as described for deflagrations in Chapter 4.
- The National Aeronautics and Space Administration (NASA)-Lewis Research Center is actively developing field models and methods for simulating turbulence under the HOST research program, as well as its basic in-house effort. This work includes sensitivity studies for numerical closure (grid independence) and turbulence modeling procedures for recirculating reacting flows, including sprays. The problems that this program has addressed are similar in some respects to flows in nuclear reactor containments. Coordination of NASA and NuRC efforts in this area would be beneficial to both programs and should be pursued.
- The Center for Fire Research at NBS is actively developing methods for numerical simulation of buoyant turbulent mixing in confined environments, which are similar to problems of hydrogen mixing in nuclear reactor containments. Coordination of NBS and NuRC efforts in this area would be beneficial to both programs and should be pursued.

4

DEFLAGRATION AND DIFFUSION FLAMES

To predict what may happen in a full-size reactor containment in which hydrogen injection and combustion take place, analytical and experimental models have been used to simulate containment conditions. Chapter 3 discussed theoretical modeling approaches applied to hydrogen mixing and combustion. This chapter focuses on interpreting recent experimental data regarding hydrogen deflagrations (premixed flames propagating at subsonic speeds) and diffusion flames. Theoretical and experimental results for detonations are considered in Chapter 5.

DEFLAGRATION SCALING

The primary data obtained in deflagration tests are peak pressures, percentage of hydrogen actually burned (burn fraction), effective flame speeds, and gas temperature or heat flux histories. Peak pressures are useful for containment integrity evaluations. Hydrogen burn fractions are useful for assessing hydrogen accumulation and consumption in hypothesized accidents with repeated injections. Effective flame speeds are used in containment system codes to calculate energy release rates and the resulting pressure and thermal loads. Gas temperature and/or heat flux histories are used to assess heat dissipation rates in the tests and postulated containment burns. They also provide a basis for determining thermal loads on critical safety equipment.

Hydrogen deflagration test data for reactor safety evaluations have been obtained in eight different test vessels varying in volume from 0.3 to 2,100 m^3. The question arises as to whether there is a reliable procedure to extrapolate these test data to full-scale containment volumes in the range of 35,000 to 60,000 m^3. The deflagration scaling question is particularly difficult in that the test vessels are not geometrically similar to the full-scale containments, nor do they include complications such as large internal equipment, structures, and compartments. Smaller equipment and structures have been included in some of the test programs, but not as geometrically similar, scaled representations of their counterparts in actual containments. Even if the test vessels were geometrically similar to full-scale containments, there are no direct scaling laws for the coupled turbulent combustion and heat transfer phenomena occurring in lean hydrogen-air-steam mixture deflagrations. Another limitation is the lack of quantification of turbulence levels and length scales both in the tests and in full-scale, containment-degraded core accident scenarios.

How can the test data be extrapolated without configuration similitude, scaling laws, and turbulence quantification? A rigorous extrapolation is not possible. Approximate extrapolations may be possible for scenarios involving initially quiescent gas mixtures in a relatively unobstructed containment compartment. However, the data are more useful for (1) calibrating and selecting input parameter values for computer codes that model turbulent, nonadiabatic deflagrations under actual containment conditions as well as test conditions and (2) providing additional physical insight into the relevant combustion and heat transfer processes. The following observations summarize the current status of parameter value selection and physical insights based on available deflagration data.

Adiabatic constant-volume calculations represent upper bounds for pressure rise from deflagrations in mixtures with 4 to 12 percent hydrogen by volume. For a given mixture composition, igniter location, and other given conditions, the data indicate that peak pressures in large vessels are likely to be closer to this upper bound than those from smaller test vessels. Figure 4-1 shows this effect in the comparison of peak pressures measured in the 16-m-diameter Nevada Test Site (NTS) sphere and those in 2.3- and 3.7-m-diameter spheres (Thompson et al., in press). The Three Mile Island Unit 2 (TMI-2) data point is also shown in Figure 4-1.

Peak pressure data are usually not scaled directly to full scale containment conditions. Instead, computer codes such as HECTR are used to incorporate configuration and heat transfer effects. Since these codes typically require hydrogen burn fraction and flame speed as input, the question of peak pressure scale-up using these codes becomes a question of scaling up burn fraction and flame speed data.

[illegible] fraction data are available for hydrogen concentrations between 4 and 8 percent by volume, but a comprehensive correlation incorporating all the relevant test data has not yet been developed. In the absence of such a correlation, burn fractions must be calculated from hypotheses about buoyant flame shapes, speeds, and quenching criteria. One difficult but important aspect of flame speed and quenching correlations is the effect of turbulence, which usually enhances combustion but at extreme levels, as defined by Al-Khishali et al. (1983), can quench near-limit hydrogen-air mixture flames.

Flame speed data compilations and envelope (upper bound)-type correlations are available. Berman and Cummings (1984) presented such correlations (with and without fan-induced turbulence) for vessels smaller than about 7 m^3, and Thompson et al. (in press) compared flame

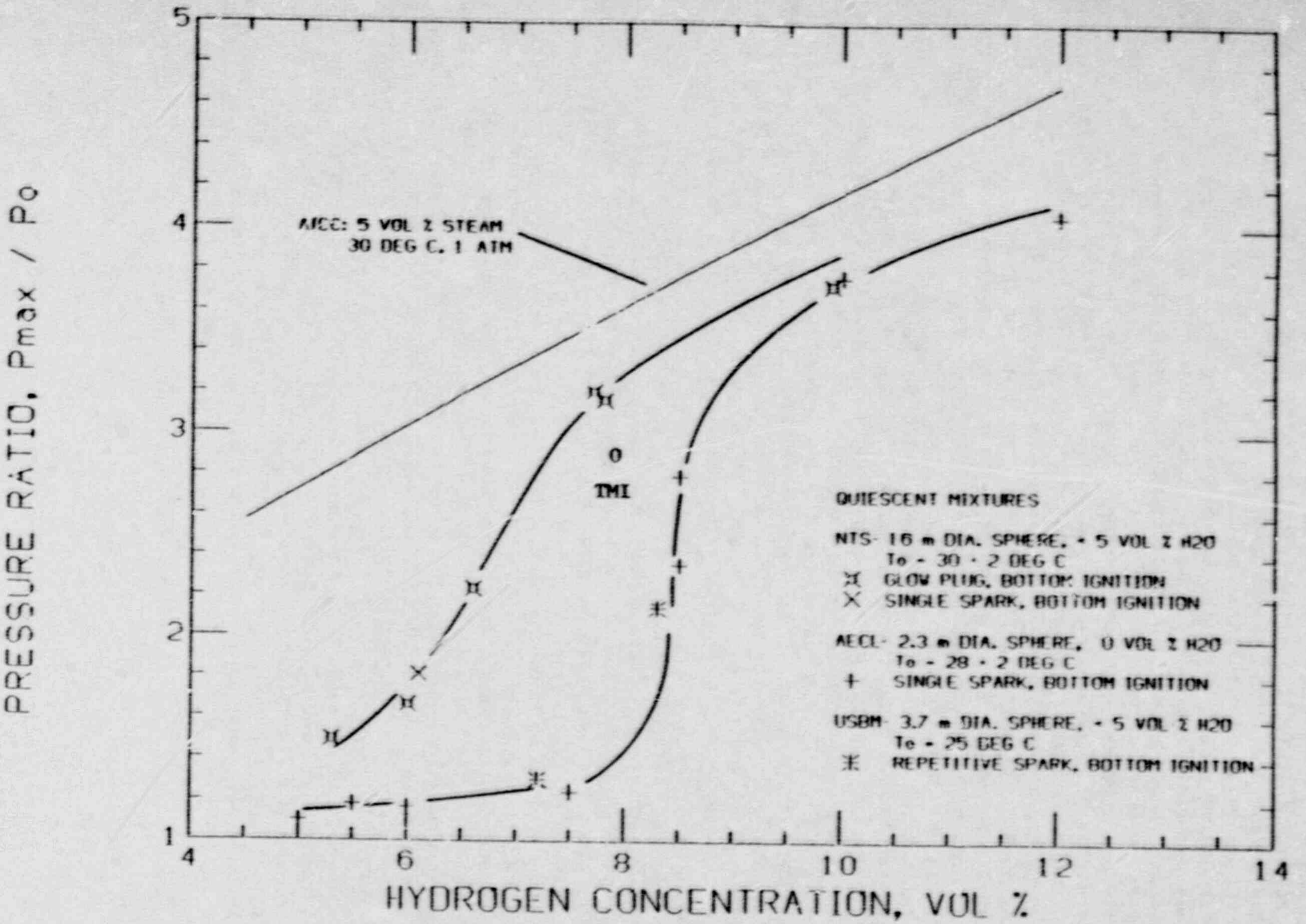

FIGURE 4-1 Effect of scale on pressure ratio for dry quiescent mixtures in spherical vessels. USBM: U.S. Bureau of Mines; AECL: Atomic Energy of Canada, Limited; AICC: Adiabatic Isochoric Combustion.

Source: Thompson et al., in press.

speed data obtained in the 2,100-m^3 Nevada Dewar (Figure 4-2) to the data from 5- and 6-m^3 vessels. The effective flame speed indicated in Figure 4-2 as pressure data has been defined as the distance the flame traversed divided by the pressure rise time during upward flame propagation. The comparison in Figure 4-2 for initially quiescent conditions indicates that upward flame speeds at hydrogen concentrations of 4 to 9 percent increase with vessel size (particularly with vessel vertical dimension), but there is no apparent scale effect at hydrogen concentrations of 10 to 13 percent. This suggests that scale effects are due to buoyancy.

Therefore, any extrapolation to full-scale containments should account for the higher rise velocities that buoyant fireballs might achieve in full-size containments. In addition, turbulence parameters associated with sprays and ventilated flows should be quantified and related to the corresponding turbulent flame speeds they would produce. Finally, application of flame speed data to multicompartmented containments is hampered by the lack of any data on flame acceleration associated with flame propagation between compartments.

Even if flame speeds can be extrapolated, the data are only as useful as the computational models used to determine combustion energy release rates. Flame speed data are used directly in the empirical lumped-parameter combustion models, such as HECTR and CLASIX (see Table 3-1). Combustion energy in these models is assumed to be released uniformly throughout the compartment at a constant rate determined by the flame speed and the distance between the ignition site and the most remote wall. In the more sophisticated models in which flame propagation is treated phenomenologically or via hydrodynamic and chemical kinetics, the flame speed is calculated (using other empirical parameters and algorithms) rather than specified as input. For these models, both video camera and thermocouple grid data on transient flame shapes (specifically, flame surface areas) are probably more useful than flame speed data.

Heat flux data during and following deflagrations have been obtained in the NTS Dewar tests and in several tests at Sandia National Laboratories. The data have been analyzed by Ratzel and Shepherd (1985) to identify the pertinent heat transfer mechanisms and associated scaling laws. Their analysis showed that appropriate scaling laws are available for every heat transfer mode except transient forced convection. Presumably, forced convection scaling should be directly related to flame speed scaling since flame speed is the relevant forced convection characteristic velocity.

In summary, then, deflagrations in lean hydrogen-air-steam mixtures are too complicated to allow direct scaling of any one test to full-size containment conditions. Computer codes with empirical models, or preferably phenomenological models, of combustion and heat transfer processes represent a more feasible scaling approach. Scaling laws are needed to extrapolate burn fraction, flame speed, and heat flux data to actual containment conditions. Some of the models contain these scaling relationships, but the more widely used empirical models rely on the user to provide the scaling and to insert appropriate burn fractions and

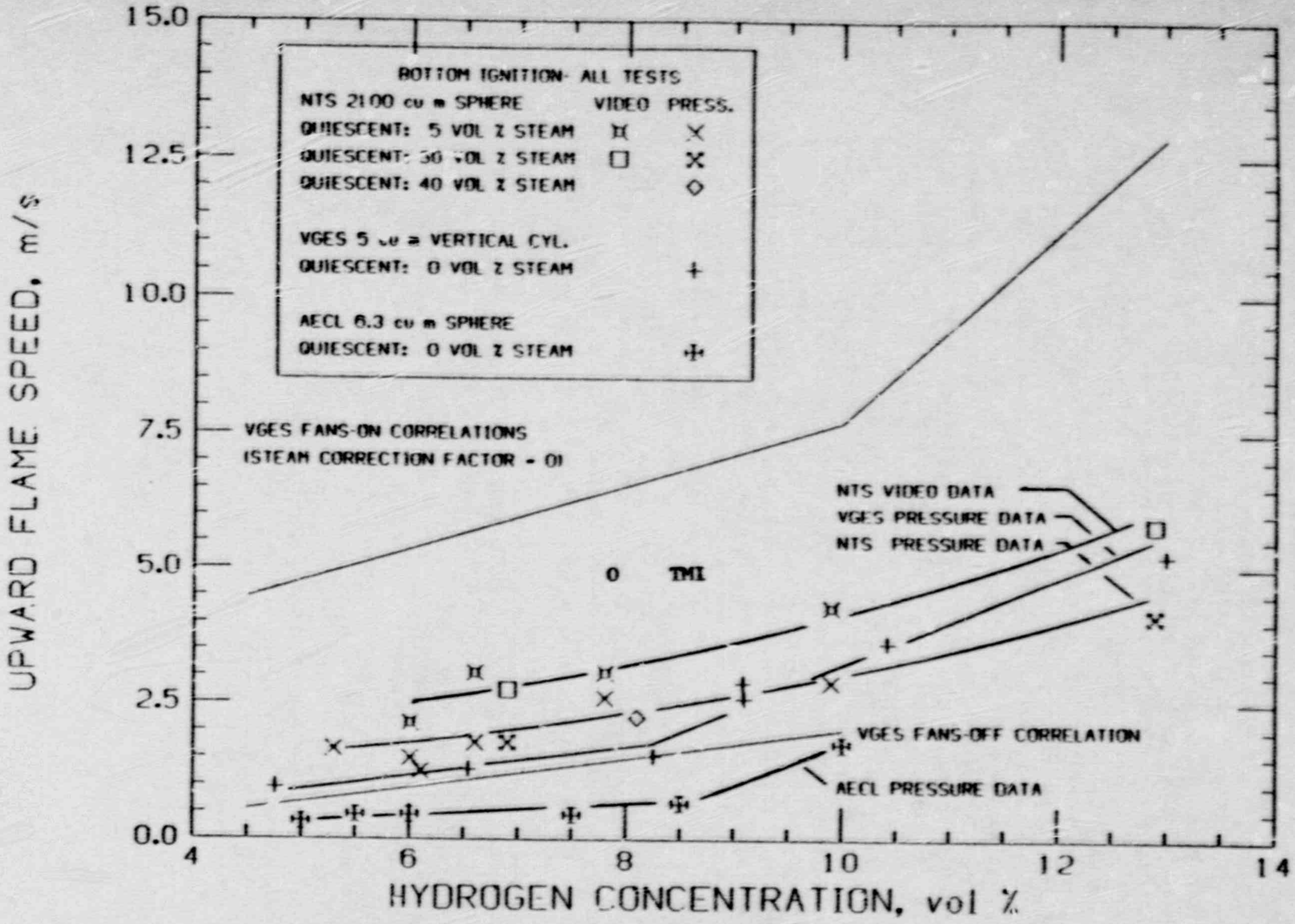

FIGURE 4-2 Comparison of effective upward flame speed data. VGES: Variable Geometry Experiment System.

Source: Thompson et al., in press.

flame speeds as input. One important limitation in carrying out this scaling either within or outside the codes is the lack of any fundamental quantification of turbulence effects associated with ventilated flows, containment sprays, and flame propagation around equipment and between compartments. Parametric calculations with conservative assumptions for these effects would be helpful in determining whether additional tests focusing on these effects are warranted.

DIFFUSION FLAME SCALING

A hydrogen release in the presence of preactivated igniters (situated above the release site) is expected to result in a diffusion flame. The concern in this scenario is the thermal load on critical safety equipment in the vicinity of the diffusion flame. Data needed to define these thermal loads include the convective and radiative heat flux distributions, and the location, size, and duration of the flames and thermal plumes. Interpretation of these data requires consideration of how hydrogen diffusion flame data can be scaled up to full-size containment conditions.

Several complications in the containment building release scenarios preclude the direct use of most diffusion flame data in the literature. These complications include (1) the presence of large walls and other structures in the vicinity of the flames, (2) complicated patterns of recirculating flow restricting air access to the combustion zone, (3) elevated ambient temperatures and steam concentrations, (4) gradually depleted ambient oxygen concentrations, (5) large mass fractions of steam released with hydrogen, and (6) effects of water sprays or forced air cooling. As noted in Chapter 2, experiments incorporating one or more of these complications have been conducted in the later stages of the industry- and Nuclear Regulatory Commission-sponsored hydrogen test programs.

Sandia National Laboratories (Shepherd, 1985b) has acquired hydrogen-steam jet flame data at high jet temperatures and steam fractions, but with hydrogen release rates limited to 0.14 g/s, i.e., three orders of magnitude smaller than the average value in a severe nuclear accident. Scaling relationships for flame length, blowoff velocity, and stagnation point heat flux have been presented along with the data. The flame length and heat flux scaling are based on extensive data and correlations in the literature, adjusted to account for steam dilution of both the jet and the containment atmosphere. Shepherd's (1985b) flame length correlation predicts flame length/diameter ratios 30 to 80 percent smaller than a similar correlation developed by Becker and Liang (1978). Kalghatgi (1984) has also developed a generalized jet flame length correlation based on data extending into the choked flow, underexpanded jet regime. Although the Kalghatgi (1984) correlation is of the same form as that of Becker and Liang (1978), it predicts flame lengths as much as 15 percent shorter for undiluted jets. Thus, the overall uncertainty in jet flame length predictability is 15 to 30 percent for undiluted jets and as much as 80 percent for steam-diluted jets with relatively low flame temperatures.

Jet flame lift-off distances and blowoff velocity scaling also have significant uncertainties. Shepherd (1985b) and Kalghatgi (1981) have different correlations, and it is not clear which, if any, is valid for large mass flow rates and orifice diameters on the order of those anticipated in reactor accident scenarios. Kalghatgi (1981) blowout data extend into the choked flow regime, but without any steam dilution, and with orifice diameters on the order of 1 mm. Both Kalghatgi (1981) and Shepherd (1985b) caution against extrapolation to much larger diameters in the choked flow regime. Use of an equivalent, fully expanded jet diameter as suggested by Birch et al. (1984) may suffice but has not been confirmed for large orifice diameters.

Both low- and high-speed diffusion flame data at elevated ambient temperatures and steam concentrations, including effects of oxygen depletion, were obtained as part of the NTS program. In addition to the usual pressure and temperature data, the NTS diffusion flame tests have produced some interesting flame lift-off and detachment observations. These lifted flames were observed when ignition occurred high in the vessel and the diffusion flame worked its way back to the release site, often pausing at scaffolding supports which acted as flame holders. Detached flames were also often observed toward the end of the burn in the form of wispy flames intermittently migrating upward, apparently toward areas with additional oxygen. This flame detachment phenomenon is a concern from an equipment survivability standpoint because it suggests that equipment distributed over large regions of the reactor building may be subjected to locally high thermal loads. Sandia National Laboratories has used lumped-parameter models to simulate the pressures and wall temperatures measured in these tests. However, apparently no quantitative analysis of the flame lengths, lift-off, and blowout observations has been attempted yet. This type of analysis is important in determining the need for additional jet flame data to ascertain the applicability of scaling relations to reactor accident scenarios.

Experiments simulating buoyant hydrogen diffusion flames in a boiling water reactor (BWR) Mark III containment have been a key part of the Hydrogen Control Owners Group program. One-twentieth-scale tests were run at the Acurex Corporation in 1982-1983, and 1/4-scale tests are under way now at Factory Mutual Research Corporation (FMRC). The scaling premise in these plant-specific simulations is that hydrogen release velocities and other relevant flow velocities are determined on the basis of Froude number equality. The rationale behind this Froude modeling approach is that buoyancy and flow inertia are the dominant forces governing both flow patterns and heat transfer rates and the corresponding thermal loads on critical equipment. Tamanini (1983) has provided a comprehensive discussion of Froude modeling as used in the design of the 1/4-scale Mark III test facility.

There are several important limitations to this application of Froude modeling. One limitation is that radiative heat fluxes measured in the 1/4-scale facility do not scale with the Froude number. Even if the temperature distribution in a scale model experiment were identical to that in a full-size containment, gas emissivities could differ substantially because of scale effects. This limitation can be overcome by calculating radiant heat fluxes in the full-scale analysis from the experimentally determined temperature and gas composition distributions instead of using the radiant heat flux data.

Another important limitation of Froude scaling is that convective heat transfer rates, which govern the rate of heat removal from the containment atmosphere, obey Reynolds number scaling rather than Froude scaling. Even if convective heat fluxes to critical equipment are calculated from temperature and velocity data rather than directly from convective heat flux data, there is concern that the cumulative effects of nonscaled heat sinks in the experiment may distort the experimental gas temperatures and velocities. Ural and Tamanini (1986) have analyzed this problem via analytical modeling (including comparisons of data with model calculations), and have concluded that the disproportionately higher wall heat fluxes in the 1/4-scale facility are approximately compensated for by the disproportionately reduced surface areas due to the absence of equipment and other structures. Thus, volume-average peak temperatures and pressures measured in the 1/4-scale tests should be roughly equal to, or slightly higher than, their full-scale equivalents. The analysis also suggests that peak temperatures in the plume directly above the flames are probably slightly cooler in the 1/4-scale facility (by 20°C to 40°C) than in the actual containment because of the absence of equipment in the flame itself.

Another inevitable consequence of the absence of minor equipment and structural details in the BWR Mark III 1/4-scale facility is that the local measurements of gas temperature and velocity should be averaged over length scales that are large compared to the length scales of the omitted equipment and structural details. If a finer resolution is needed for some particular equipment, additional analysis and/or heated wind tunnel tests may be necessary to account for wakes and other disturbances associated with the omitted equipment.

In summary, then, the applicability of hydrogen diffusion flame scaling in containment burn scenarios is being assessed by research program participants. Scaling relationships are available for flame lengths, temperature, and velocity distributions, for both jet flames and buoyant diffusion flames. However, preliminary data from the ongoing 1/4-scale facility tests suggest that the underwater hydrogen release causes flame heights to be significantly shorter (by almost one-half) than would be predicted on the basis of correlations in the literature (F. Tamanini, FMRC, personal communication). Additional work is also needed to assess flame length, lift-off, and detachment effects under full-scale containment conditions, particularly for underexpanded, steam-diluted hydrogen jet conditions. Analysis of these phenomena in the NTS continuous injection tests and in the 1/4-scale tests (where background burning occurred rather than coherent detached flames) should precede any new test program.

With regard to the 1/4-scale BWR Mark III tests, Froude scaling should not be expected to rigorously and precisely simulate convective and radiative heat fluxes, but the measured gas temperatures and velocities can be used to estimate thermal loads on major safety equipment. The two remaining conceptual questions are (1) how should the data be applied to small equipment in the immediate vicinity of nonsimulated equipment and structures, and (2) does the absence of some heat sinks and flow resistances in the experiments produce or prevent any cumulative effect on flame lift-off and extinguishment that would not occur in an actual containment?

INFLUENCE OF SUSPENDED WATER ON FLAMES

The presence of water sprays during a severe light-water reactor (LWR) accident leads to consideration of the effect of suspended water droplets on flames. Because laminar flames produce negligible dynamic pressure on any suspended water droplets, the mechanism of drop breakup is absent, as discussed in Chapter 5. In terms of either thermal interaction or chemical participation, water droplets are expected to have little influence on flames, as long as the water droplets are large, because the water evaporation rate is a controlling factor. Since the evaporation rate depends on the ratio of droplet surface area to volume, it can easily be seen why large drops are ineffectual. This has been confirmed by the investigation of Marx et al. (1983). Zalosh and Bajpai (1982a) give further support to this conclusion. In their experimental arrangement, they found that the lower flammability limit (LFL) is marginally changed by droplets on the order of 100 μm, whereas droplets on the order of 20 μm raised the LFL from 4 percent hydrogen to 7.2 percent hydrogen. However, there is an order of magnitude of uncertainty in the fog concentrations required for the specified increases in the LFL (Westinghouse Electric Corporation, 1982; Zalosh and Bajpai, 1982a). Some evaluations of dense fog formation for postulated degraded core accidents have been conducted (Westinghouse Electric Corporation 1982), but there is a large uncertainty in the results of this analysis because of the absence of relevant experimental data.

Water droplets, however, have been known to influence the behavior of the flames by inducing turbulence which can lead to faster flames. It is not clear, however, whether such flames could lead to detonation.

As to the isochoric (constant volume under adiabatic conditions) pressure attainable for hydrogen combustion in the presence of water, it is found that generally, because of the imbalance between the effect of the heat of vaporization and that due to the increase in the gaseous mass, the pressure during combustion would almost always be lower than that of burning the dry mixture. By the same token the overall temperature would also be reduced (I.A. Zlochower, U.S. Bureau of Mines, Pittsburgh, Pennsylvania, and Adel Sarofim, Massachusetts Institute of Technology, Cambridge, Mass., personal communication). Thus, water sprays can alleviate structural and thermal damage.

CONCLUSIONS AND RECOMMENDATIONS

Deflagrations

The following conclusions are based on the above discussion regarding deflagrations.

- Although lean hydrogen-air mixture deflagrations are too complicated to allow direct extrapolation of subscale tests to full-size containments, the data are useful for (1) identifying scaling trends, (2) computer code validation, calibration, and input parameter selection, and (3) providing physical insights into relevant combustion and heat transfer phenomena.
- Peak pressures in lean hydrogen-air mixture deflagrations are likely to be higher (and closer to the adiabatic, constant volume pressure) in actual containments than in subscale tests. Prediction of peak pressures in actual containments is tantamount, via use of computer codes, to predicting hydrogen burn fraction and flame speeds.
- Although flame speed and burn fraction data compilations are available, there is no systematic, quantitative procedure to account for turbulence, geometry, and scale effects in actual - containments. The development of such a procedure is hampered by the scarcity of data on flame propagation around equipment and between compartments and on turbulence intensities and length scales associated with containment sprays and ventilated flows.

In view of these conclusions, the following recommendations are offered regarding deflagrations.

- Parametric calculations should be conducted for turbulence effects associated with containment sprays, ventilated flows, and flame propagation around equipment and between compartments. Results of these calculations using conservative estimates of turbulence parameters and/or burn fraction and flame speed will determine whether additional tests focusing on these effects are warranted.
- Hydrogen burn fraction and flame speed correlations, quantitatively including turbulence, scale, and geometry effects, should be developed accounting for recent data such as that in the NTS Dewar. If these correlations are not developed, then improved models should be used in which burn fraction and flame speed are computed within the model.

Diffusion Flames

The following conclusions are based on the above discussion regarding diffusion flames.

- Scaling relationships are available for both buoyant and jet diffusion flame lengths, as well as for temperature and velocity distributions. These relationships are useful in identifying the extent of the regions subject to thermal loading. The uncertainties in these scaling relationships (as much as 80 percent for weak, steam-diluted jet flames) may be important from the standpoint of equipment survivability.
- Scaling relationships for both jet flame and buoyant diffusion flame lift-off distances and blowoff velocities also have

significant uncertainties in the range of the large mass flow rates and release diameters hypothesized in containment accident scenarios. These flame lift-off and detachment phenomena, which have been observed in both the NTS experiments and in several Mark III 1/20- and 1/4-scale tests, may lead to possible thermal damage to equipment in remote regions of the containment, as well as to equipment in the vicinity of the release site.

- Froude scaling cannot rigorously simulate convective and radiative heat fluxes in containment accident scenarios involving diffusion flames. However, measured gas temperatures and velocities can be used, along with quantitative analyses of departures from Froude scaling, to estimate thermal loads on major safety equipment.
- The spatial resolution to be expected from Froude scaling extrapolation of temperature and velocity data is limited by the length scale of the small equipment and structures present in actual containments but omitted in the tests.

In view of these conclusions, the following recommendations are offered regarding diffusion flames.

- Conservative calculations of thermal loads on key safety equipment due to jet diffusion flames should be conducted to determine whether the uncertainties in the flame length and temperature/velocity field scaling relationships is acceptable or whether additional data are needed.
- Additional testing and analysis should be conducted to develop flame lift-off, blowoff, and relocation criteria relevant to containment accident scenarios.
- If a spatial resolution finer than that provided by the current Mark III 1/4-scale tests is needed, additional analyses and/or tests may be needed to account for wakes and other disturbances associated with omitted small equipment and structures.

Suspended Water Droplets

With regard to the nature of suspended water droplets formed, it is concluded that:

- There is considerable uncertainty in droplet size and fog density resulting from fog formation in containment during postulated severe LWR accidents.

The basic conclusions related to the effect of water droplets on flames are as follows.

- Large water droplet containment sprays can increase flame speeds in lean hydrogen-air mixtures and cause peak pressures to be closer to the adiabatic, constant volume values. However, these sprays also enhance cooling of the burned gases and therefore cause pressures and temperatures to decrease more rapidly to precombustion levels. Thus, depending on the relative safety margins for pressure loads and thermal loads, the sprays can be either beneficial or detrimental during premixed combustion. They are definitely beneficial for postcombustion cooling and for the diffusion flames anticipated with deliberate ignition.

- Droplets on the order of 20 μm or less in diameter can significantly raise the lower flammability limit for hydrogen combustion and, as noted above, can raise the threshold of ignition to as high as 7.2 percent hydrogen. However, it is not clear whether such fogs would form in a containment atmosphere under conditions postulated for an accident scenario. The presence of such fogs would delay the onset of hydrogen ignition by igniters (see Chapter 6) but should also mitigate the effects of hydrogen combustion. Experimental confirmation of the extent of these mitigating effects would be desirable if they are neccessary to maintain containment integrity.

5

DETONATION ASPECTS

BACKGROUND

As was indicated previously, the generation of hydrogen during a severe accident to a nuclear power plant and the subsequent entry of the hydrogen into the containment could result in combustion, either accidently or deliberately. For premixed conditions the combustion could occur in one of two modes: as a deflagration or as a detonation. In the deflagration mode, combustion takes place in a relatively leisurely manner and the flame front moves at low subsonic speeds. On the other hand, the detonative mode is characterized by supersonic wave propagation. The deflagration mode was discussed in Chapter 4. In this chapter, detonation is discussed as it relates to the mitigation problem, recent research on hydrogen-air-diluent mixtures, and implications for reactor containments.

The study of detonation waves dates back to the late nineteenth century, when Bertholet and Vieille (1881) and Mallard and Le Chatelier (1881) identified the supersonic nature of these waves and indicated that they constitute a mode of combustion distinct from slow deflagration. Shortly thereafter, Chapman (1899) and Jouguet (1905, 1906), working independently and using a gas dynamic approach, confirmed this observation. In addition, they independently recognized that the burned gas behind the wave travels at the local speed of sound relative to the wave. Waves possessing this unique property are called Chapman-Jouguet (CJ) waves, after their discoverers. World War II provided further impetus to the study of detonations, as a result of which Zeldovich (1940) in Russia, Von Neumann (1942) in the United States, and Doring and Burckhardt (1944) in Germany again independently described detonation as a shock followed by an inviscid reaction zone which is terminated by a sonic plane. The structure of the detonation wave was known to be experimentally different from the one-dimensional description under certain conditions near the so-called composition limits. Nonetheless, it is remarkable that the theory predicts the propagation velocity and the pressure with a good degree of accuracy solely on the basis of the heat release during combustion and hydrodynamic considerations. With the advent of the digital computer, the calculation of the properties of CJ detonations, wherein equilibrium conditions or frozen composition are assumed at the sonic plane, has become a relatively quick and easy task. Among other computer programs, one devised at the National Aeronautics and Space Administration (NASA) by Gordon and McBride (1976) has become useful for such calculations. Figure 5-1 shows the CJ detonation velocity (V_D) and Mach number (M) as functions of the equivalence ratio (ϕ), and percent hydrogen (H_2) in hydrogen-air mixtures for equilibrium conditions behind the front. The equivalence ratio (ϕ) is the ratio of the actual hydrogen air ratio to that of a stoichiometric hydrogen-air ratio.

From a nuclear plant accident standpoint, one of the concerns about detonation is the possibility of development of transient pressures that are much higher than those obtainable in a constant volume (isochoric) combustion. A comparison of the transient pressures that can develop is shown in Figure 5-2. It can be seen that the detonation pressure spike is about twice the isochoric pressure. It is clear that even in a 10 percent hydrogen mixture the detonation pressure will exceed the static design pressure, which is much lower than the failure pressure, of present-day containment vessels. Structural analysis could determine whether such a transient pressure spike would lead to containment failure.

It is also important to note that under certain conditions the pressures involved are those obtained from an adiabatic shock corresponding to the detonation Mach number. Such pressures are about twice the detonation pressures (Adamson and Morrison, 1958). Further, wave reflections from the walls can result in pressure amplification of over four times the detonation pressure, or eight times the isochoric pressure. The report by Delichatsios et al. (1982) on the pressure spikes that can be developed from detonative combustion shows one method of evaluating the pressure amplification. Thus, detonations at levels of hydrogen close to the lean flammability limit may pose a serious threat to the integrity of the containment, though the true measure of the threat is the impulsive strain resulting from the transient pressure as the detonation wave strikes the structure.

In the last 20 to 30 years, it has been recognized on the basis of experimental evidence that the structure of the detonation wave is not one dimensional but is cellular in shape due to interaction of the incident wave with some transverse waves resulting from instability of the wave (Strehlow, 1984). This structure arises from the trajectory of the triple point generated from the interaction of the incident wave, the transverse wave, and the resultant Mach stem. It is well known that for a given oxidizer-fuel combination, the higher the CJ Mach number (i.e., the closer the mixture is to the stoichiometric ratio), the smaller the cell size. The cellular structure implies pockets with much higher pressures than that calculated from the one dimensional model. These pressures are very localized and of relatively brief duration, but it is not evident how much greater a threat they pose than the CJ pressures until additional structural analysis is conducted.

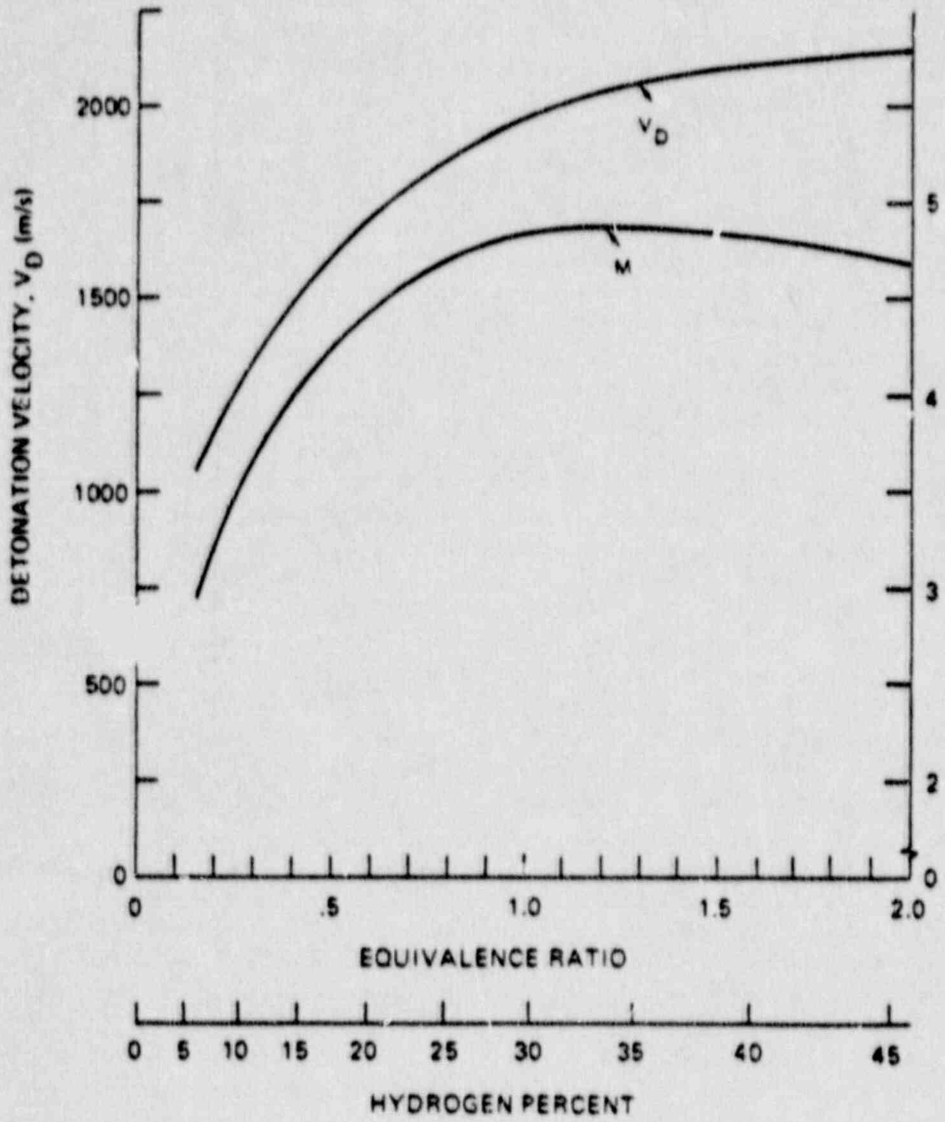

FIGURE 5-1 Detonation velocity and Mach number as a function of hydrogen concentration in dry air.

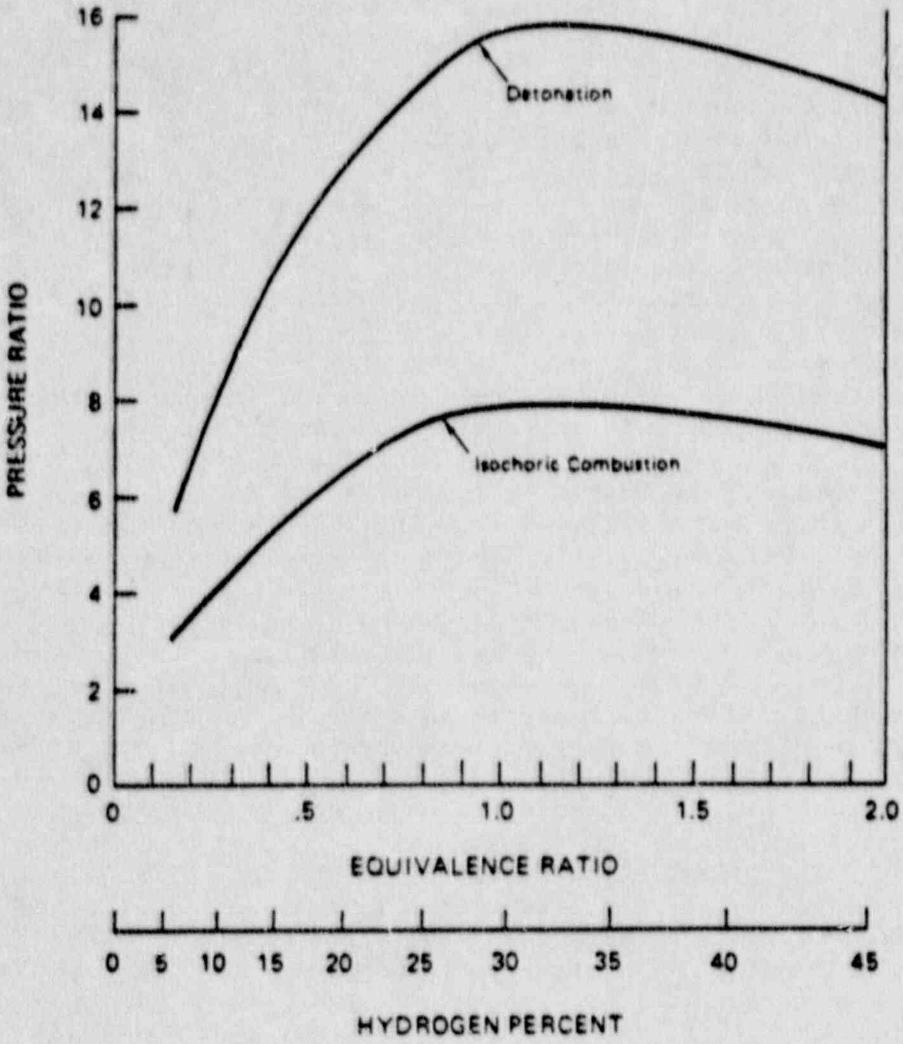

FIGURE 5-2 The ratio of final to initial pressure for detonation and isochoric combustion as a function of hydrogen concentration in dry air.

The heating effect of the detonation could also impair performance of equipment in the detonation path. It can be shown, however, that detonation temperatures are only slightly higher than the isochoric temperature for the same mixture. Therefore, any precautionary measures taken to protect equipment from heating by a deflagration should be adequate for detonation as well.

INITIATION OF DETONATION

There are mainly two methods by which a detonation can be developed in a detonable mixture. One is direct initiation and the other is flame acceleration. In direct initiation, a rapid deposition of energy in the gas is necessary, e.g., a high-energy spark or a high explosive. The blast wave developed must be of high enough strength at a certain critical radius to induce detonation, the critical radius being dependent on the mixture ratio (Lee, 1972, 1977; Lee et al., 1966). Generally, the initiation energy needed is low for a stoichiometric mixture, but it increases rapidly with leanness or richness of the mixture. The phenomenon is now well enough known and understood that the minimum energy requirement for direct initiation can be predicted accurately (Guirao et al., 1982). Experimental (Lee and Matsui, 1976) and theoretical (Abouseif and Toong, 1982; Dabora, 1982) work on the relation between initiation energy and rate of energy deposition also has been done. Near the lean limit of detonation (lowest value measured to date is about 13 percent hydrogen in dry air), the energy requirement for direct initiation is theoretically estimated to be over 14 MJ. Estimates based on the extrapolation of experimental data yield values of 2.5 MJ. It is unlikely that such high initiation energies would be released sufficiently rapidly in a containment vessel, to cause detonation to be initiated at hydrogen concentrations on the order of 13 percent or less.

The other method by which a detonation can be developed is by flame initiation and acceleration. Flame acceleration can occur due to turbulence, changes in geometry, obstacles, and wall roughness. This is the most likely method by which a detonation might develop in a suitably high concentration of hydrogen from a nuclear plant accident. The deflagration to detonation transition (DDT) phenomenon in a tube with constant area is well described by Oppenheim (1965). It is interesting that, for a given mixture, it has been found (Oppenheim, 1965) that neither DDT time nor distance can be correlated to any physical parameters of the system. Thus, a prediction of how far down a tube or at what time a DDT will occur is not possible. However, the ratio of distance to time is found to be a well-behaved function of the Reynolds number.

Another method for development of detonation is akin to knock in spark ignition engines. In the course of flame development and partial propagation, the unburnt mixture is compressed, with a corresponding increase in temperature, rendering the mixture more sensitive and thus easier to detonate. If there is a hot spot (Kailasanath and Oran, 1983) or an igniter in the unburned field a detonation could occur. Thus, a knowledge of the composition limits at elevated pressures and temperatures is necessary for detonation risk assessment.

LEAN DETONATION LIMITS

The current strategy for hydrogen burn mitigation is designed to avoid detonative combustion. It is therefore very important that the lean detonation limit be known with a high degree of certainty. It is reasoned that the rich limit is only of academic interest since, in an accidental release of hydrogen into a containment building, the air-hydrogen mixture would have to pass through a range of detonable compositions (near stoichiometric, which would be beyond mitigation) before it could reach the rich limit.

The recent work at Sandia National Laboratories, McGill University, and other places on hydrogen-air detonations as related to reactor safety is summarized by Berman (1985). The results of the large-scale experiments described lead to the conclusion that in terms of the geometry, turbulence, obstruction, venting, etc., it is virtually impossible to predict the combination of conditions that should be avoided to prevent detonation from occurring, as long as the mixture is intrinsically detonable. Hence, an evaluation of the intrinsic limit must be made.

Up until the 1950s, it was widely accepted that the lean detonability limit for hydrogen-air was about 18 percent hydrogen, on the basis of experiments of Breton (1936) and Lafitte (1938). The work of Kogarko and Zeldovich (1948) with different tube sizes showed that geometry affects limits to a significant degree. These experiments showed that mixtures near 15 percent hydrogen could be detonated in a 30-cm-diameter tube. More recently, Lee et al. (1984) have shown that flame acceleration in an obstacle-filled tube is a function of both composition and tube size. The larger the tube, the lower the hydrogen concentration required to achieve flame acceleration. Quasi detonation regimes (i.e., propagation at speeds higher than sound velocity but at less than the CJ velocity) could be detected in an 18 percent hydrogen mixture when the tube diameter was 30 cm and in a 26 percent hydrogen mixture in a 5-cm-diameter tube, further confirming the size effect. Results presented to the committee during its visit to Sandia National Laboratories indicated a detonation limit down to 13 percent hydrogen in the absence of steam. Unfortunately, no tests have been performed on a scale comparable to a nuclear reactor. The limit for such a scale must therefore be inferred from currently available tests or analyses.

An impressive amount of data (Tieszen et al., 1985) on detonation cell size has been generated. Many researchers have attempted to correlate the cell size with induction length calculable from basic principles. The induction length is the distance behind the detonation front at which the bulk of heat release takes place. The most recent attempt at correlation was performed by Shepherd (1985a). After using the currently accepted hydrogen-oxygen (H_2-O_2) reaction mechanism (see Table 5-1, reactions 1 to 19) and trying several criteria for induction lengths, he found that the most successful correlation could be obtained when the induction length is defined as the location where the Mach number of the reaction products reaches a value of 0.75 behind the detonation front. The cell size λ is found to be equal to A_2 l_2, where l_2 is the induction length and A_2 is a multiplicative

TABLE 5-1 Chemical Reactions Involved in a Hydrogen-Oxygen Reaction Mechanism

Reaction	A	β	E
1. $H_2 + O_2 \rightleftharpoons OH + OH$	1.70×10^{13}	0.00	47780.
2. $OH + H_2 \rightleftharpoons H_2O + H$	1.17×10^{9}	1.30	3626.
3. $H + O_2 \rightleftharpoons OH + O$	5.13×10^{16}	-0.82	16507.
4. $O + H_2 \rightleftharpoons OH + H$	1.80×10^{10}	1.00	8826.
5. $H + O_2 + M \rightleftharpoons HO_2 + M$	2.10×10^{18}	-1.00	0.
6. $H + O_2 + O_2 \rightleftharpoons HO_2 + O_2$	6.70×10^{19}	-1.42	0.
7. $H + O_2 + N_2 \rightleftharpoons HO_2 + N_2$	6.70×10^{19}	-1.42	0.
8. $OH + HO_2 \rightleftharpoons H_2O + O_2$	5.00×10^{13}	0.00	1000.
9. $H + HO_2 \rightleftharpoons OH + OH$	2.50×10^{14}	0.00	1900.
10. $O + HO_2 \rightleftharpoons O_2 + OH$	4.80×10^{13}	0.00	1000.
11. $OH + OH \rightleftharpoons O + H_2O$	6.00×10^{8}	1.30	0.
12. $H_2 + M \rightleftharpoons H + H + M$	2.23×10^{12}	0.50	92600.
13. $O_2 + M \rightleftharpoons O + O + M$	1.85×10^{11}	0.50	95560.
14. $H + OH + M \rightleftharpoons H_2O + M$	7.50×10^{23}	-2.60	0.
15. $H + HO_2 \rightleftharpoons H_2 + O_2$	2.50×10^{13}	0.00	700.
16. $HO_2 + HO_2 \rightleftharpoons H_2O_2 + O_2$	2.00×10^{12}	0.00	0.
17. $H_2O_2 + M \rightleftharpoons OH + OH + M$	1.30×10^{17}	0.00	45500.
18. $H_2O_2 + H \rightleftharpoons HO_2 + H_2$	1.60×10^{12}	0.00	3800.
19. $H_2O_2 + OH \rightleftharpoons H_2O + HO_2$	1.00×10^{13}	0.00	1800.
20. $HO_2 + CO \rightleftharpoons CO_2 + OH$	5.80×10^{13}	0.00	22934.
21. $CO + O + M \rightleftharpoons CO_2 + M$	3.20×10^{13}	0.00	-4200.
22. $CO + OH \rightleftharpoons CO_2 + H$	1.51×10^{7}	1.30	-758.
23. $CO + O_2 \rightleftharpoons CO_2 + O$	1.60×10^{13}	0.00	41000.

Reaction rate coefficients are in the form $k_f = AT^n \exp - E/RT$. Units are moles, cubic centimeters, seconds, Kelvins and calories/mole. Third body efficiencies: $k_5(H_2O) = 21k_5(Ar)$; $k_5(H_2) = 3.3k_5(Ar)$; $k_5(CO_2) = 5k_5(Ar)$; $k_5(CO) = 2k_5(Ar)$; $k_{12}(H_2O) = 6k_{12}(Ar)$; $k_{12}(H) = 2k_{12}(Ar)$; $k_{12}(H_2) = 3k_{12}(Ar)$; $k_{14}(H_2O) = 20k_{14}(Ar)$. E: activation energy; M: any non-identified molecule; R: gas constant; T: temperature. A and B constants for a given reaction.

Source: Shepherd (1985a).

factor equal to 21 for a stoichiometric mixture. Ideally, the factor A_2 would be expected to be constant, but unfortunately this does not appear to be the case. It changes as a function of hydrogen concentration because dominant reactions, and thus appropriate activation energies, are different. Figure 5-3 shows the value of A_2 as a function of equivalence ratio (ϕ) as obtained by Shepherd (1985a,b). It is to be noted that as the equivalence ratio decreases from 0.6 to 0.4, the value of A_2 changes from 35 to 5. Inasmuch as no cell measurements exist below $\phi = 0.4$, the value of A_2 below 14.4 percent hydrogen ($\phi = 0.4$) is not known.

Figure 5-4, provided by Shepherd (personal communication, Sandia National Laboratories, Albuquerque, New Mexico) shows the calculated induction length (l_2) in the lean regime. It can be seen that as the percentage of hydrogen decreases there is a continuous increase in the induction length. It was noted by Shepherd (personal communication) that since no dramatic change in l_2 occurs as composition is altered, no intrinsic limit could be found. Therefore, detonation limits must be considered in the context of composition and container size.

Guirao et al. (1982) indicate that the threshold tube diameter (d_t) that can sustain a detonation is that for which $d_t = \lambda/2$ and that for an unconfined cloud a minimum cloud diameter (d_s) of $d_s = 6.5\ \lambda$ is necessary for detonation. On the basis of Figures 5-3 and 5-4 and the above criteria, Table 5-2 is presented. It is assumed that $A_2 = 5$ and remains constant for hydrogen concentrations lower than 14.4 percent.

A typical reactor containment structure of concern has a diameter of about 50 m. From Table 5-2 it can be seen that depending on whether the containment volume is considered as a tube or an unconfined space, a mixture with 9 to 11 percent hydrogen <u>might be detonable</u>. Since it is felt that the containment is more nearly an unconfined space than a tube, the higher end of the range may be more likely. It is to be noted that if A_2 actually decreases below a value of 5, even lower percentages of hydrogen in air could [illegible]onable. Based on this and because of the lack of experiments [illegible]le comparable to that of a nuclear plant, prudence would call [illegible]uring that any mitigation strategy should avoid the attainment of hydrogen levels greater than 9 to 11 percent.

At this point it is worthwhile to mention that the effect of size should not be minimized. In a recent field experiment, Moen et al. (1985) have noticed that a 5 percent acetylene-air mixture, with an equivalence ratio of 0.626, detonated by virtue of shock wave development. The mixture was ignited by a flame in a 2-m-diameter, 3.5-m-long, cylindrical plastic bag. The detonation started at the end furthest from the initiating jet, leading to the conclusion that in a large-size container the probability of instabilities leading to detonation can be greater.

Effect of Temperature

In the above discussion, it was assumed that the mixture is originally at standard temperature and pressure. Small variations in pressure

TABLE 5-2 Cell Size and Threshold Diameters for Hydrogen-Air Mixtures in the Lean Regime

Mole % H_2	Equivalence Ratio	Induction Length l_2 (m)	A_2	Cell Size (m)	Threshold Tube Diameter d_t (m)	Minimum Cloud Diameter d_s (m)
8	0.207	62	5 (assumed)	310	155.	2,000
9	0.235	15	5 (assumed)	75	37.5	487.5
10	0.264	4	5 (assumed)	20	10.	130
11	0.294	1	5 (assumed)	5	2.5	32.5
12	0.325	0.5	5 (assumed)	2.5	1.25	16.26
13	0.356	0.2	5 (assumed)	1	0.5	6.5
14.4	0.4	0.06	5 (measured)	0.30	0.15	1.96

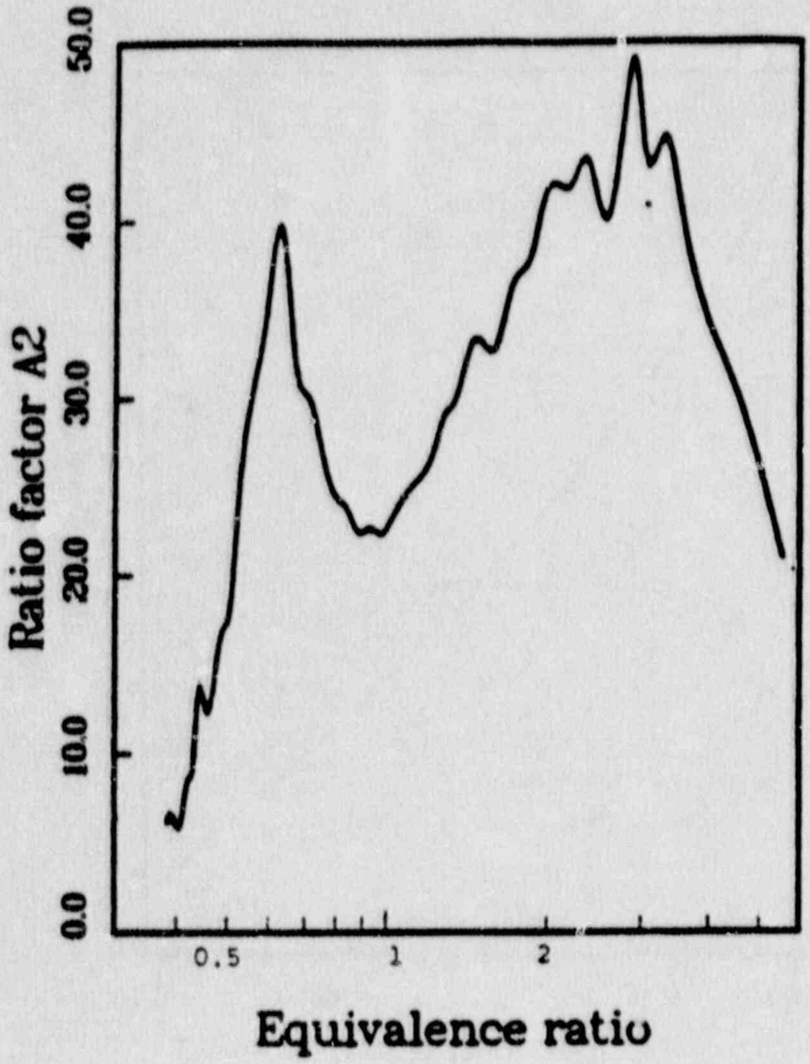

FIGURE 5-3 ~~The~~ multiplicative factor (A_2) for calculating cell size as a function of the equivalence ratio.

Source: Shepherd (1985a).

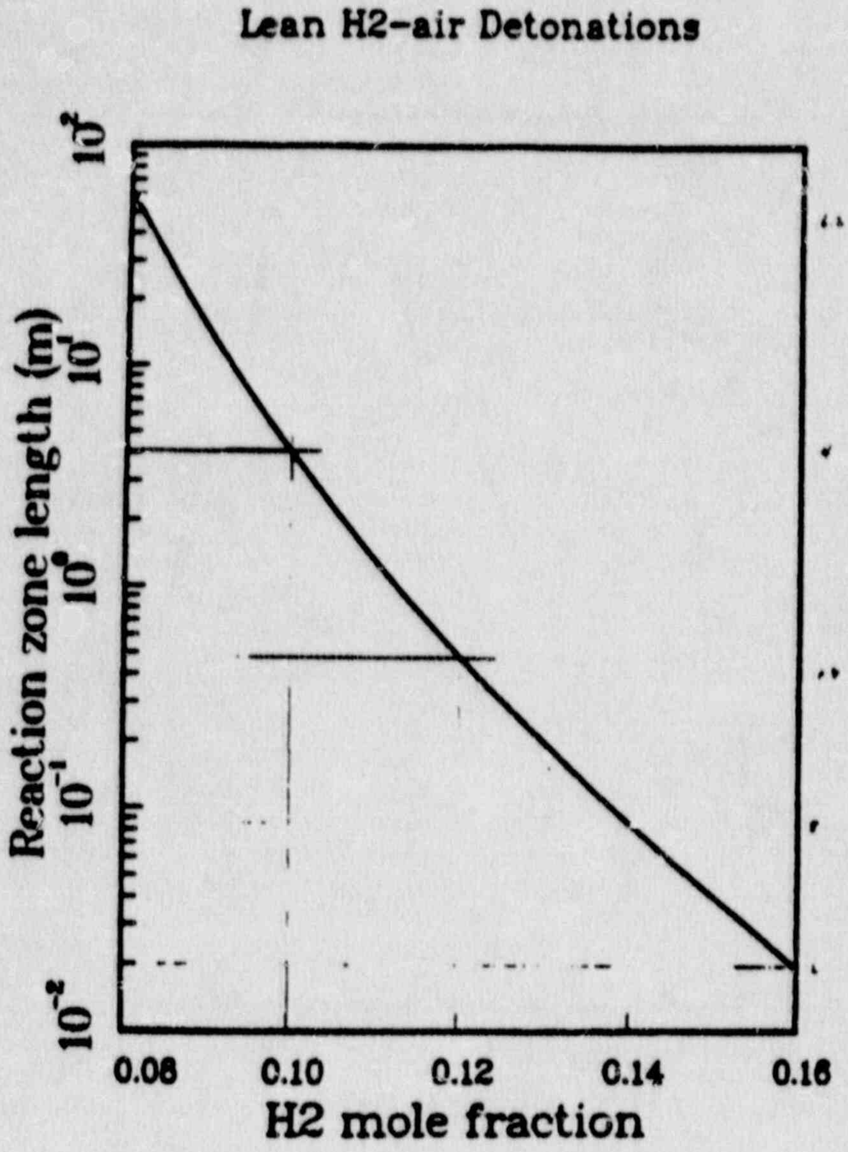

FIGURE 5-4 Reaction zone length as a function of hydrogen mole fraction.

Source: J.E. Shepherd (personal communication).

(i.e., ± 10 percent atmospheric pressure) would have practically no effect on the detonation limit. However, temperature can influence the lean limit. From data reported by Shepherd (1985a), the measured and predicted cell sizes at $\Phi = 0.4$ are 0.2 and 0.15 m, respectively, at a temperature of 373°K. These values are to be compared to a measured cell size of 0.3 m at 298°K at the same equivalence ratio and the same density. Thus, as might be expected, increased temperatures render a given mixture more sensitive. The logical conclusion then, is that at elevated temperatures, hydrogen-air mixtures at concentrations even lower than 9 to 11 percent hydrogen could become detonable. However, elevated temperature is not expected to occur without the presence of steam which, by itself, acts as a diluent (see next section). By the same token a lower than normal temperature, if it could be maintained, would move the lean limit upward.

Effect of Diluents (Water and Carbon Dioxide)

The research group at Sandia National Laboratories has investigated the effect of two possible diluents on detonation, namely, water in the form of steam and carbon dioxide (CO_2). They used a heated detonation tube facility, which is a tube 43 cm in diameter by 13 m in length, that can be heated to over 100°C to study the effect of steam. The same facility was used to obtain data on the effect on CO_2 at room temperature.

In the case of water (H_2O) vapor it is noted that at room temperature the saturation pressure is about 3 kPa, which means that at standard pressure only 3 percent vapor dilution can be obtained. Thus, the experiments at the higher temperatures were necessary to obtain higher dilution levels. The results of the experiments indicate that the cell size increases by a factor of about 5, 25, and 125 for 10, 20, and 30 percent, respectively, of water vapor dilution.

Similar trends of increased cell size were obtained with CO_2 dilution at room temperature when reactions 20 to 23 of Table 5-1 were included. For the same percentage of dilution, CO_2 appears as effective as water vapor in increasing the cell size (i.e., lowering the detonation sensitivity) at dilution levels below 10 percent, but more effective than water vapor at the higher dilution levels. The analysis by Shepherd (1985a) attributes both thermal and chemical effects for water but mostly a thermal effect for CO_2. Whatever the reason is, however, dilution does diminish the sensitivity and if an extrapolation could be ventured, a 20 percent dilution of the hydrogen-air mixture by either CO_2 (e.g., 20 percent CO_2 and 80 percent air by volume) or H_2O vapor changes the lean detonation limit in a reactor containment to around 13 percent hydrogen (in air-hydrogen mixtures, see Table 5-2). This is, of course, a tentative conclusion that must be verified by actual experiments.

INFLUENCE OF WATER DROPLETS ON DETONATIONS

In contrast to extensive studies of sprays in fires, there appears to be a dearth of experimental data on the effect of water spray on detonations. The most recent work regarding detonation seems to be that of Carlson et al. (1973). These authors observed the behavior of hydrogen-air detonations in a tube 40.6 cm in diameter by 12 m in length, with and without a spray. In the case of spray, which they characterize as 500- μm-diameter spray, they found that no detonation could be sustained in a 20 to 24 percent hydrogen-air mixture, whereas in a 28 percent hydrogen-air mixture detonation was possible. Unfortunately, it is not possible to ascertain all of the water spray characteristics from the data given in the report, and more information along these lines would be very useful. Nevertheless, it is apparent that a detonation can be suppressed by a spray.

It can be reasoned that the effectiveness of a spray depends on the droplet size, the size distribution, and the loading factor. A spray in the form of fog (drop size in the micron range) is expected to influence detonation in the same manner as the vapor. Since no data on drop size distribution or loading factor was given by Carlson et al. (1973), it is conceivable that the noted detonation suppression is due mainly to the small-size drops present in the spray.

The effect of large-drop-size sprays (diameters greater than 50 μm) can be inferred from studies on two-phase detonations (Dabora et al., 1967, 1968, 1969), hybrid detonations (Pierce and Nicholls, 1974), and droplet breakup by shock waves in dilute and dense sprays (Fox and Dabora, 1973; Ranger and Nicholls, 1969). In the case of two-phase detonations, where the fuel is in the form of a spray and the oxidizer is gaseous, it has been found that the drops ignite and take part in the exothermic reaction only after they are mechanically broken up into smaller droplets by the convective flow induced by the shock front of the detonation wave. Thus, drop breakup time becomes an important parameter that affects the overall reaction time. Breakup studies of single drops (Ranger and Nicholls, 1969), have shown that the nondimensional breakup time (T_b), as defined below, is reasonably constant, having a value of about 5:

$$T_b = (\rho_g/\rho_1)^{1/2} U_2 t_b/D_o,$$

where ρ_g is gas density, ρ_1 is liquid density, U_2 = velocity of the gas with respect to the drop, t_b is breakup time, and D_o is original diameter of the drop.

The breakup time for droplets in sprays is found to be shorter than that of isolated drops (Fox and Dabora, 1973) by a factor which is dependent on the spacing to diameter ratio, the latter being a function of the loading factor. However, the following reasoning should not be affected by this refinement of the breakup time.

In two-phase detonations, participation of the droplets in the reaction has been found to occur after the elapse of 1/3 of the breakup time (Pierce et al., 1975). Also, in the case of hybrid detonations in mixtures of hydrogen-oxygen and a hydrocarbon spray, it was found that participation of the droplet in the exothermic reaction becomes effective only when the hydrogen-oxygen mixture is below an equivalence ratio of 0.5. At a higher equivalence ratio, where the gas phase reaction time is short, no influence of the drop on detonation propagation was noticed.

Taking all of the above information into consideration, one would expect, then, that if the induction length (l_2) in a detonation is shorter than the distance traveled by the wave during 1/3 the breakup time, the influence of the droplet would be negligible. Under the conditions prevailing behind detonation fronts in hydrogen-air mixtures, this distance is about 60 D_o. Thus, for significant water droplet participation in the reaction to influence the fate of the detonation, the following must hold:

$$D_o < l_2/60.$$

For mixtures at $\Phi = 0.6$ and 0.4, l_2 is 0.15 and 6 cm, respectively, so that the maximum drop diameters for reaction influence are then 25 and 1,000 μm, respectively. This approximate analysis seems to be consistent with the trends observed by Carlson et al., (1973). Also, it is apparent that sprays with drops on the order of 1 mm in diameter should be effective at equivalence ratios below 0.4. Such a conclusion, however, must be checked by a more-refined analysis and a systematic experimental program.

IMPLICATIONS AS TO DETONATIONS IN REACTOR ACCIDENTS

Current licensing practice addresses the possibility of hydrogen detonation by requiring systems or features that make the likelihood of a detonation acceptably low. Depending on the type of containment, this is done through inerting, igniters, or dilution. None of these approaches can be considered as 100 percent effective because, as with all systems, they have a finite chance of failing to perform as intended. For example, current rules permit containments that have been made inert to be returned to normal for 1 day after startup and 1 day before shutdown (a few percent of the operating time), and of course, a normal atmosphere is permitted during shutdown. Clearly, igniters have some small probability of failure, and nonuniform concentrations of hydrogen might lead to detonable concentrations in limited regions of large-volume containments.

To date, several dozen full-scale risk analyses have been performed on U.S. nuclear power stations. Almost all these studies suggest that the median probability of a serious core-damaging event is about 10^{-4}/plant/yr or less. This is consistent with the proposed safety goal of the U.S. Nuclear Regulatory Commission (NuRC). Accidents of this type would, of course, almost surely generate significant amounts of hydrogen.

Detonations in Inert Containments

The boiling water reactor (BWR) Mark I and II containments are required to be made inert because of their small volume. Current rules permit them to be returned to normal roughly 1 percent of the operating time so the probability per year of having a detonable mixture in the containment is roughly about 10^{-6}. This assumes that the probability of a hydrogen generating accident is the same during these periods as during normal operation. Since there is a finite chance that the hydrogen would burn rather than detonate, the probability of hydrogen detonation is estimated to be less than 10^{-6}/yr. If hydrogen generated by a severe core damage accident were to detonate in a small-volume BWR containment, then a catastrophic rupture of the containment might occur. This could produce a category 1 release (see Table 2-2). As can be seen from Table 2-2, such releases were estimated in the Reactor Safety Study (RSS) (NuRC, 1975) to have a median probability of 10^{-6}/yr from other causes. Thus, the total likelihood of release category 1 would be increased by less than a factor of 2. In fact, in the RSS the major public risk was associated with category 2 releases, which are 6 times more likely than category 1. Since the consequences of a category 2 release are nearly the same as those of a category 1 release, the contribution to risk to the public from hydrogen detonation in small-volume BWRs would be less than one-tenth of the total risk.

Detonations in Medium-Volume Containments

In medium-volume pressure supression containments, BWR Mark III, and pressurized water reactor (PWR) Ice Condensers, current licensing practice requires the use of ignition sources to cause hydrogen to burn before concentrations reach detonable levels. For this strategy to be successful, there must be an acceptably high probability that the igniters will ignite the mixture before it can reach a detonable concentration. Since the exact point of release of hydrogen into the containment cannot be known, each containment space is required to have at least two igniters, while larger spaces have more. Two separate power sources are used so that half of the igniters in any given space are powered from an electrical source different from that of the other half.

There has been concern that the operation of containment sprays might impede the successful operation of the igniters currently being used. Tests have shown that this could be a problem with bare igniters, which has led to the requirement that, where appropriate, the igniters must be protected by spray shields. Experiments have shown that igniters will cause ignition in the presence of heavy sprays when protected by these shields (see Chapter 6).

In many of the risk analyses one of the important contributors to the risk of core damage are sequences initiated by loss of all alternating current (AC) power. In such sequences the igniters, which are powered by station AC, would not be operating. Possible solutions to this problem include a separate independent power supply for the igniters or the use of catalytic igniters which require no external power.

It is always possible to postulate nonuniform mixing that might produce detonable concentrations over limited volumes. Among other factors, the seriousness of this concern depends upon the rate of hydrogen release into the containment. As indicated earlier, except for loss of station power sequences, both the MARCH and the MAAP codes predict this rate to average 0.1 kg/s or less with occasional spikes of 10 times that value. This would suggest that the conditional probability, given core melt, of suddenly releasing into the containment a large fraction of the hydrogen generated is small. Since analysis includes the core melt probability as 10^{-4}/plant/yr, the absolute probability would be substantially less than this. To reduce the likelihood of collecting high concentrations of hydrogen in containment spaces, a large number (greater than 60) of igniters is required. Sequences like station blackout (TMLB'), with sudden large releases of hydrogen and steam, are of special concern. Both the MARCH and the MAAP codes calculate that the steam release in these accident sequences will prevent hydrogen burning in the containment (Pickard, Lowe, and Garick, Inc., 1983). If the value of the Zr-H_2O reaction is assumed to be 100 percent in some cases, the amount of water vapor may not prevent detonation. This is why a resolution of the differences in the calculations of hydrogen release is needed.

There has been concern that igniters might produce detonations by the mechanism of flame acceleration discussed above. However, numerous tests at the Nevada Test Site and the 1/4-scale facility operated by Factory Mutual Research Corporation have shown no evidence of flame acceleration at concentrations up to 13 percent. It should be noted that these tests are performed in the absence of osbtacles which are known to cause flame acceleration.

Detonations in Large Dry Containments

Large dry containments used for some PWRs depend upon dilution by the containment atmosphere to reduce the hydrogen concentration. In containments of 56,000 m^3 (2 million ft^3) or larger, if the hydrogen produced by a 75 percent metal-water reaction is well mixed it will produce a hydrogen concentration of about 10 percent or less in dry air. Experiments to date indicate that the lower limit for detonation is about 13 percent, and on this basis the containments have been licensed. The recently developed theory relating lower detonability limit to cell size suggests that the detonability limit may be somewhat lower (9 to 11 percent in large volumes).

It is likely that under some realistic conditions the containment atmosphere will not be uniformly mixed in a postulated accident, leading to regions where a detonable mixture exists. It is also known that the detonability limit goes down as the temperature increases. Countering these concerns to some extent is the effect of water vapor, which raises the lower detonability limit. These issues are discussed below.

All the reactor accidents that would generate significant hydrogen require that the water be lost from the primary system. In most of the accident sequences this water would be lost to the containment through safety valves or breaks. In a few sequences (V sequences in PWRs: see Table 2-1) the water would be lost through a break outside the containment. In this latter type of accident, any hydrogen generated would also be released outside of the containment. Thus, in any accidents in which hydrogen would be released into the containment, there must of necessity be a major loss of hot primary system water to the containment before the hydrogen release. The large amount of water at about 300°C (572°F) released in these events ensures that the relative humidity of the containment will initially be essentially 100 percent. There is also a significant probability that a fog will be present. How much water dilution this will provide to the hydrogen-air mixture depends upon the temperature and pressure of the containment. The lower dilutions will occur at lower temperatures. The exact temperature following the accident would depend upon the accident sequence. The RSS (Appendix VIII therein) states that after a few minutes of operation of the sprays the containment will be about 110°C, and after about 1 h of spray operation it will be about 55°C. The vapor pressure of water at 55°C is 120 mm of Hg, or the atmosphere is about 13 percent water vapor. From the previous discussion this would suggest a cell size about a factor 10 larger than that of a hydrogen-air mixture. From Table 5-2, at 13 percent hydrogen this would give about 65 m for d_s. Thus, it appears that even this small amount of water vapor increases the detonable concentration above the 12 to 13 percent range. Eventually, as the containment cools, the detonable concentration would fall. After this amount of time, however, the fission product aerosols in the containment atmosphere would have been removed by the sprays and/or natural deposition. If the sprays failed to work, then the temperature would remain high and the amount of water vapor would be much higher, offering much more protection against detonation. As the temperature increases, the cell size increases much more due to the increase in the vapor pressure of water than it decreases due to the rise of temperature.

In the case of containments having fan coolers, the above assumption of 100 percent relative humidity may not be valid because the coolers are effective dehumidifiers. For example, at the time of the burn at Three Mile Island Unit-2, the estimated water vapor fraction was 3.5 percent (Henry, Fauske and Associates, Chicago, Ill., personal communication) due to the operation of the fan coolers. In the larger dry containments where the maximum hydrogen concentration is only 8 percent, there is still a reasonable margin of safety. However, in the smaller containments where the maximum hydrogen concentration may be 10 percent, the margin of safety will be reduced.

Thus, although the lower limit of detonation of hydrogen-air mixtures may be as low as 9 to 11 percent in large containments, in water-hydrogen-air mixtures of the type that must be present following a hydrogen-producing accident, the value is greater than 13 percent in many cases. Consequently, for the case of uniform mixing in which the maximum hydrogen concentration is 10 percent or less and in which the relative humidity is 10 percent or greater, the possibility of a detonation is remote. However, nonuniform mixing could lead to detonable concentrations in local regions within the containment as discussed later in this chapter.

Detonations in Subatmospheric Containments

Subatmospheric containments are a special case because their volume is only 50,400 m^3 (1.8 million ft^3) and their operating pressure is about 2/3 of an atmosphere. Thus they have less air so less hydrogen is needed to reach a given concentration. At a 75 percent metal-water reaction, the hydrogen concentration is about 15 percent. At this concentration the cell size is about 0.3 m (Shepherd, 1985a), so that for the case of 20 percent water vapor the value of d_s is 47 m. Therefore, these assumptions imply that for a situation with less than 20 percent water vapor, the possibility of hydrogen detonation cannot be dismissed. Current MARCH code calculations give an upper limit for the Zr-water reaction of 60 percent. If correct, this would give a maximum hydrogen concentration of 12 percent. Assuming a 10 percent water vapor dilution, since these containments do not have fan coolers, would give a value of 80 m for d_s. Although such factors may reduce the probability of a detonation, the margin of safety is much less than in the other cases cited above.

Because of the smaller safety margin, it seems appropriate to consider the effects of a detonation on the containment for this case. The RSS considered hydrogen detonation in a subatmospheric containment and concluded that it would not fail. However, this calculation included only the impulse to the containment of the initial pressure spike. No reflections or other effects were considered. Codes such as CSQ (Byers, 1982) and that developed by Delichatsios et al. (1982) using the random choice method are available for calculating detonation loads. These codes have been applied to the analysis of large dry containments, but no such analysis for the subatmospheric case has been identified. If such an analysis concludes that the containment will not fail, it would restore a substantial safety margin. However, if such an analysis concludes the containment will fail, it will be a matter for serious concern and action.

Local Limited Detonations

In the large dry containments nearly uniform mixing of the hydrogen is required to ensure that a detonable concentration is not reached. Since many scenarios envisage nearly pure hydrogen being released into the containment, it is clear that in some regions there would exist detonable concentrations. Some of the spaces beneath the reactor floor might contain detonable concentrations, at least during the period that hydrogen is being released. Limits in situations like this would be hard to assess and define. This is due to the fact that the problem is multidimensional, making it impossible to know a priori exact condition scenarios with any degree of certainty. Thus, the NuRC strategy of more emphasis on prevention rather than mitigation is appropriate.

It is important that the containment and key safety systems survive limited detonations in any of these spaces. Thermal damage is expected to be no worse than for deflagrations or diffusion flames. The area of concern is mechanical damage from overpressure caused by the shock wave.

Experts testifying before the committee felt that structures and heavy equipment were not likely to be damaged by the shock waves. However, electronics and electrical equipment might be damaged by the shock waves. Another area of concern expressed related to tiedowns of equipment. Because of the distinct possibility of limited detonations, the area of possible damage by shock waves from limited detonations to equipment and structures requires further study.

CONCLUSIONS AND RECOMMENDATIONS

Based on the above discussion the following conclusions are arrived at with respect to conditions for detonation and its implications for reactor containments.

- The estimated energy and power density required for direct initiation of detonation near but above the lean detonation limit are very high. Near this lean limit, it is unlikely that high enough energy or power would be available to cause <u>direct detonation</u> in a containment vessel environment. However, this does not rule out the possible occurrence of detonation through the mechanism of flame acceleration.
- Detonation temperatures are only slightly higher than the isochoric temperature for the same mixture. Any precautionary measures taken to preserve the equipment in the case of a deflagration should be adequate for detonation thermal loading as well. However, as addressed in the recommendations, further consideration of the effects of detonation pressures on equipment is needed.
- The lean composition limit of dry hydrogen-air mixtures is expected to decrease as the size of a containment increases. It is estimated that in a reactor space of diameter on the order of 50 m, a 9 to 11 percent hydrogen-air mixture might be detonable. Increasing temperature renders a given mixture more sensitive so that hydrogen-air mixtures at elevated temperatures might detonate at concentrations lower than 9 to 11 percent.
- The presence of water vapor or carbon dioxide decreases the sensitivity of a mixture to detonation. It is estimated that a 20 percent dilution by either carbon dioxide or water vapor raises the lower bound to the lean detonation limit in a reactor containment to around 13 percent hydrogen.
- Water sprays have the potential of reducing the probability of detonation. Of interest here is that mixtures at hydrogen concentrations of 14.4 percent or less can be quenched by sprays with 1-mm-diameter drop sizes, and as the hydrogen to air ratio

decreases even coarser sprays can be effective. More refined analysis and a systematic experimental program would substantiate this conclusion.

- The effect of sprays on detonation is not taken into account in regulatory analysis and may in many accident scenarios provide a significant margin of conservatism.
- Current procedures of making the containment inert for protection against hydrogen detonation in small-volume BWR containments are satisfactory.
- For accident scenarios in which they operate as intended, igniters are a reasonable way to reduce the probability of a large-scale detonation in medium-volume containments.
- Although the lower limit of detonation of dry hydrogen-air mixtures may be as low as 9 to 11 percent in large containments, in water-hydrogen-air mixtures of the type that must be present in most large-volume containments following a hydrogen-producing accident, the value is greater than 13 percent. Thus, for the case of uniform mixing in which the maximum hydrogen concentration is 10 percent or less, the possibility of detonation would be remote. However, consideraton should be given to cases of nonuniform mixing, as noted in the recommendation below.

Based on the above discussion and conclusions the following recommendations are put forth.

- Work should be conducted to develop igniter systems to improve the reliability of ignition for station blackout scenarios. The work on catalytic igniters seems promising (also see Chapter 6).
- A reanalysis of the likelihood of failure of a subatmospheric containment structure under detonation loads should be performed and used as a basis for deciding what, if any, further actions are needed.
- Because of the distinct possibility of limited or localized detonations in large dry containments, the topic of possible damage to equipment and structures, including containment, by shock waves from limited detonations requires further evaluation.
- The possibility of detonation should be examined for each large dry containment having fan coolers, to determine if a satisfactory safety margin exists.

6

IGNITION, IGNITERS, AND SPRAY OPERATION

The conditions under which ignition occurs in hydrogen-air mixtures are important in determining whether combustion will occur either accidentally or deliberately. One of the tasks of the committee (see Preface) was to determine the conditions under which autoignition of a hydrogen jet into an ambient atmosphere might occur. Furthermore, the committee thought it necessary to address some aspects of deliberate ignition strategies and the use of containment sprays. Consequently, this chapter focuses on autoignition; methods of deliberate ignition, namely, igniters; and the influence of containment sprays.

AUTOIGNITION

Background

Auto- or self-ignition means the initiation of a self-sustained exothermic process of combustion at a given pressure and temperature. The term is de facto a misnomer, as is its synonym: spontaneous ignition. For the process to be started, the medium must be brought to a certain threshold temperature. Below this temperature, after a preliminary period of development, manifested by the generation of radicals, the process is extinguished. Moreover, in contrast to spontaneity, in the course of its development the process goes through a number of stages, of which the induction period of the initial generation of radicals, followed by the stage of a quasiequilibrium radical pool, are of crucial importance to the outcome. Thus the phenomenon under question should be called simply thermal ignition, in contrast to thermochemical ignition that is initiated by bringing the reactive medium not only to an elevated temperature but also seeding it with a certain amount of active radicals.

The subject of ignition has a rich and distinguished literary background. Its critical properties, known as explosion limits--another misnomer--have been studied extensively and exposed notably in most textbooks on combustion and chemical kinetics (Benson, 1960; Glassman, 1977; Lewis and von Elbe, 1961; Sokolik, 1960; Strehlow, 1984; and Zeldovich et al., 1980)

As far as has been ascertained, the fundamental aspects of ignition were first formulated by Van't Hoff (1896). A classical solution has been provided by Semenov (1935), who subsequently expanded this subject by extensive studies of chain reaction theory (Semenov, 1943, 1944a,b, 1958, 1959). As a consequence of the major emphasis he placed on the chemical kinetic aspects, in his theory the dissipative effects of diffusion and conduction were neglected.

Thereupon, following the pioneering studies of Frank-Kamenetskii (1967), an impressive amount of effort has been spent on the establishment of the role of transport phenomena in the process of ignition. The temperature and concentration gradients, not considered by Semenov, became then of essential significance (Gray and Lee, 1967; Hicks, 1954; Kindelan and Williams, 1975; Linan and Williams, 1970; Merzhanov and Averson, 1971). This was associated, moreover, with investigations of the so-called hot-spot ignition which is of particular, but not exclusive, relevance to condensed explosives. Under such circumstances, the geometry of the system under study was of critical importance, as lucidly exposed by Boddington et al. (1971). Most of the subsequent investigations of gaseous ignition followed the same trend, as exemplified by the publications of Kassoy and associates (Clarke et al., 1984; Kassoy and Poland, 1980, 1981; Poland et al., 1982).

In contrast to the latter, careful consideration of chemical kinetic effects, with transport processes taken into account only in the form of a loss to the surroundings rather than being involved in the evolution of the process, led to the establishment of deterministic thermochemical criteria in the form of a unified thermokinetic theory developed by Gray and Yang (1965) and Gray and Lee (1967) with particular relevance to photochemical ignition. The state of the art in this methodology was reviewed by Berlad (1973), with particular reference to thermal explosion limits for the hydrogen-oxygen system adopted here for illustration of our method of approach.

In the same vein, Foo and Yang (1973) investigated subsequently the surface effects leading to quadratic branching and the thermal process of self-heating that occur in the oxidation of hydrogen. This ushered in the analytical studies of Kordylewski (1979), who first elucidated the bifurcation aspects of critical conditions for thermal ignition and then (Kordylewski and Scott, 1984) explored the combined action of chain branching and self-heating in the vicinity of the second and third thermal ignition limits for the hydrogen-oxygen system. At the same time a similar method of approach has been used by Guirguis et al. (1981) in the study of methane-air mixtures.

Process

The problem of ignition is conveniently formulated in terms of an exothermic center (Borisov, 1974; Oppenheim, 1985; Van Tiggelen, 1969), a system consisting of a kernel undergoing the process of an exothermic chemical reaction and of surroundings absorbing the energy it emits. The latter is expressed in terms of the relaxation time, (τ), the time constant of temperature decay that would take place in the absence of the exothermic process. Such a system is governed by a set of chemical kinetic rate equations determining the chemical source and of the energy equation specifying the thermal source.

The solution yields time-resolved concentration and temperature profiles of ignition, starting from initial conditions specified in terms of a given thermochemical state of the reacting system.

As an example, Figure 6-1 presents the variation of species concentration and temperature obtained for a stoichiometric hydrogen-oxygen mixture initially at a temperature of $774^{o}K$ or $775^{o}K$, a pressure of 6 atm, and a thermal relaxation time of $\tau = 1$ s. Concentrations, expressed in terms of mass fractions, are plotted in logarithmic scales, while the scale for temperature is linear. Solution for the higher initial temperature is presented by continuous lines, whereas that for the lower, by broken lines. For the sake of simplicity, only concentration profiles of the chain carriers-- H, O, and OH radicals--are shown.

As can be seen, a small difference in initial temperature can exert a profound influence upon the result. In one case one obtains ignition manifested by a rapid increase in temperature, referred to as the "Frank-Kamenetskii thermal explosion." In the other case one has extinction, following an initial buildup in radical concentration, while the temperature remains virtually unchanged until, instead of rising, it falls.

The two initial temperatures furnish the upper and lower bounds to what can be quite properly referred to as the ignition temperature-- the threshold between ignition and extinction. By repeating the same procedure as that yielding Figure 6-1 over a range of pressures, one can determine the variation of this threshold as a function of initial temperatures and pressures.

Such plots corresponding to thermal relaxation times $\tau = 1$ s and 30 s are presented in Figure 6-2. Displayed there also are the classical, experimentally established, thermal ignition limits, usually referred to in the literature by the misnomer "explosion limits" (Lewis and von Elbe, 1961).

The curves have a characteristic shape of an inverted S. They are considered thus as comprised of three branches. At low pressures, the first limit is ascribed to the influence of quenching by the wall. At intermediate pressures, the second limit is accredited to the onset of chain branching. At high pressures, the third limit is rationalized in terms of heat conduction losses.

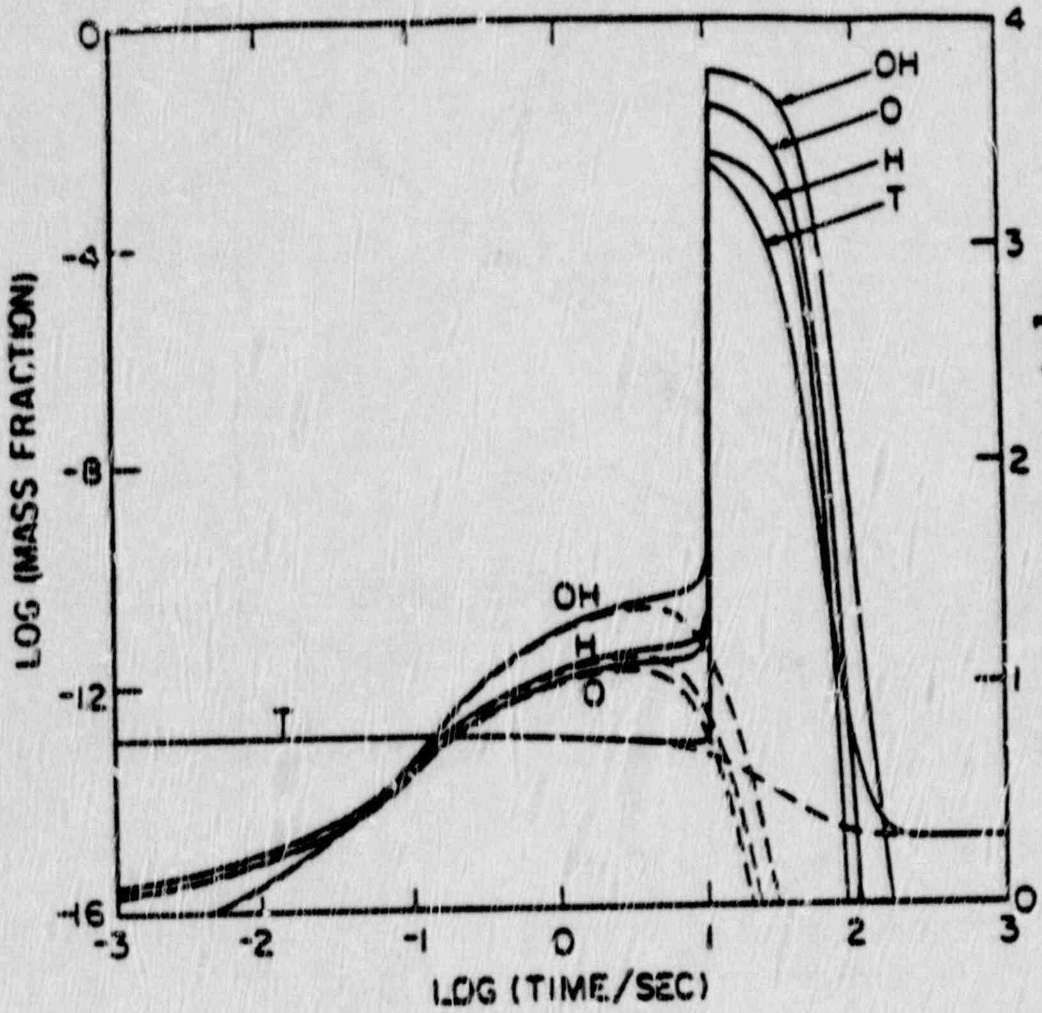

FIGURE 6-1 Temperature and chain carrier concentration profiles in a stoichiometric hydrogen-oxygen mixture, initially at a temperature of 774° (broken lines) or 775°K (solid lines) and pressure of 6 atm with a thermal relaxation time of 1 s.

Source: Oppenheim (1985)

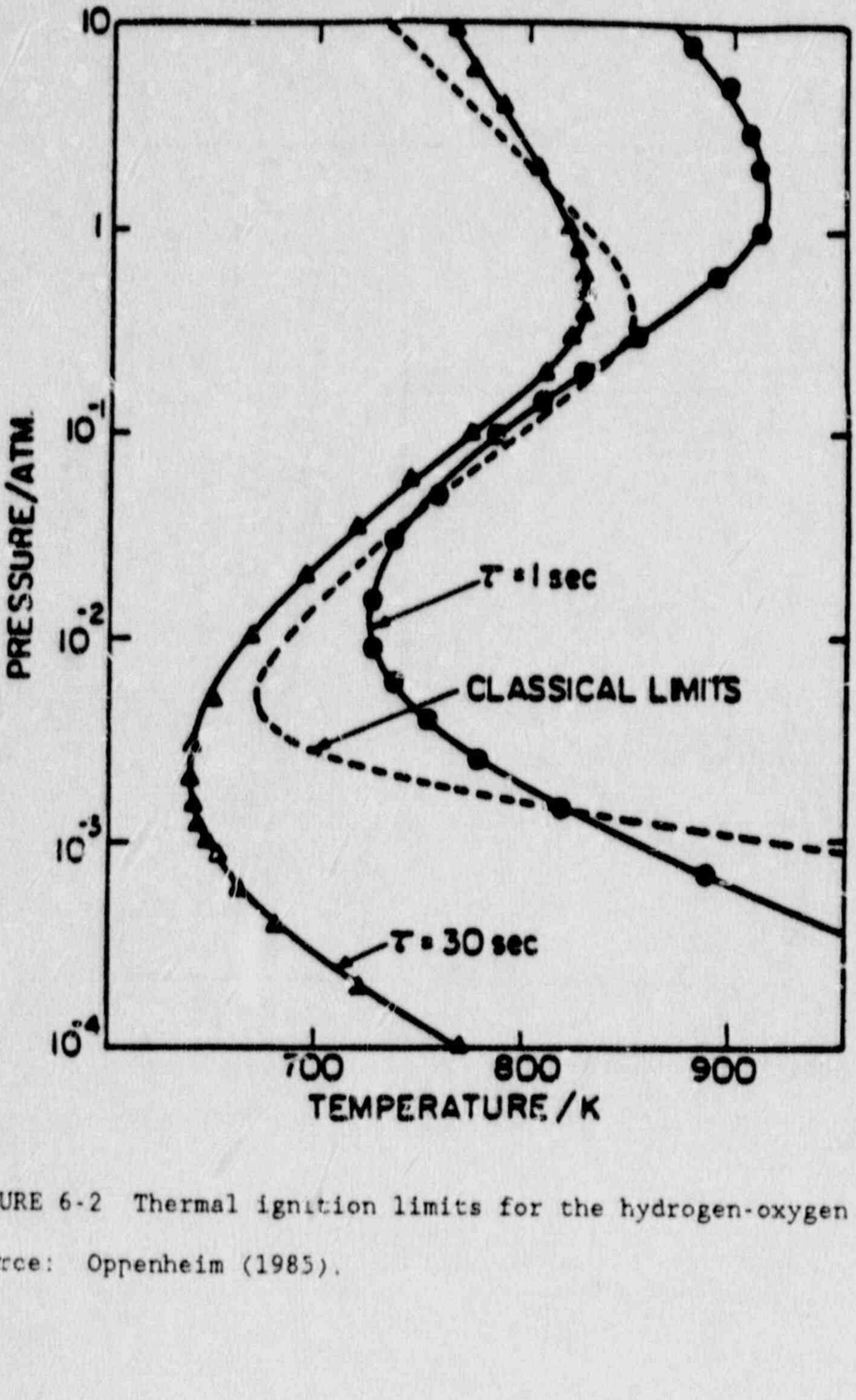

FIGURE 6-2 Thermal ignition limits for the hydrogen-oxygen system.

Source: Oppenheim (1985).

Getting all three in a comprehensive manner as a locus of a constant thermal relaxation time is a noteworthy outcome (Oppenheim, 1985). The agreement between the results of numerical analysis and the classical limits manifested by Figure 6-2 provides an interesting demonstration that the thermal relaxation time may vary over a wide range without a marked effect on the ignition limits.

The most informative way to express the solution is in the form of an integral curve on a (N + 1)-dimensional phase space--a space whose coordinates are the concentrations of all the chemical species (N being their total number) participating in the reaction and the temperature. The time is eliminated by taking advantage of the autonomous nature of governing equations. In the phase space, time appears thus only as a running coordinate marking the progression of points representing sequential states of the system along an integral curve.

As an example a projection of the phase space solution on the plane of the temperature and the hydrogen atom concentration is presented in Figure 6-3. Families of integral curves displayed there correspond to two cases of initial conditions: on the left those of thermal ignition, and on the right those of thermochemical ignition corresponding to an initial mass fraction of hydrogen atoms of 0.001. In each case one has a set of integral curves for ignition and for no ignition. As is apparent in Figure 6-3, this temperature is significantly lower for thermochemical ignition than for a purely thermal ignition.

The thermal curves exemplified by curves 1 and 2, with the arrows showing the direction of time, indicate that if we start at a given temperature corresponding to curve 1, ignition would be possible as manifested by the increase in temperature. At a slightly lower temperature (curve 2) a decrease in temperature takes place and thermal ignition becomes impossible.

In the case of the thermochemical ignition, curves 3 and 4 illustrate what can happen. In curve 3, the starting temperature is low, it increases with time, stays constant for a while, and then declines, again resulting in no ignition. In contrast to this, curve 4, with a somewhat higher initial temperature, behaves similarly to curve 3 except that it eventually shows an increase in temperature, which means that ignition has ensued.

One is thus led to the conclusion that the presence of active radicals in relatively minute concentrations may have a profound influence in autoignition. The particular hydrogen atom concentration of 0.001 in Figure 6-3 could be easily attained in a hydrogen-air mixture with fresh products of combustion provided by a flame or a catalytic igniter.

Clearly, there are many possible sources of ignition in the containment other than autoignition. These include sparks from electrical equipment and hot wires, and static electricity. It seems very likely that a combustible mixture cannot remain very long without being ignited, as happened in our only example, Three Mile Island Unit 2.

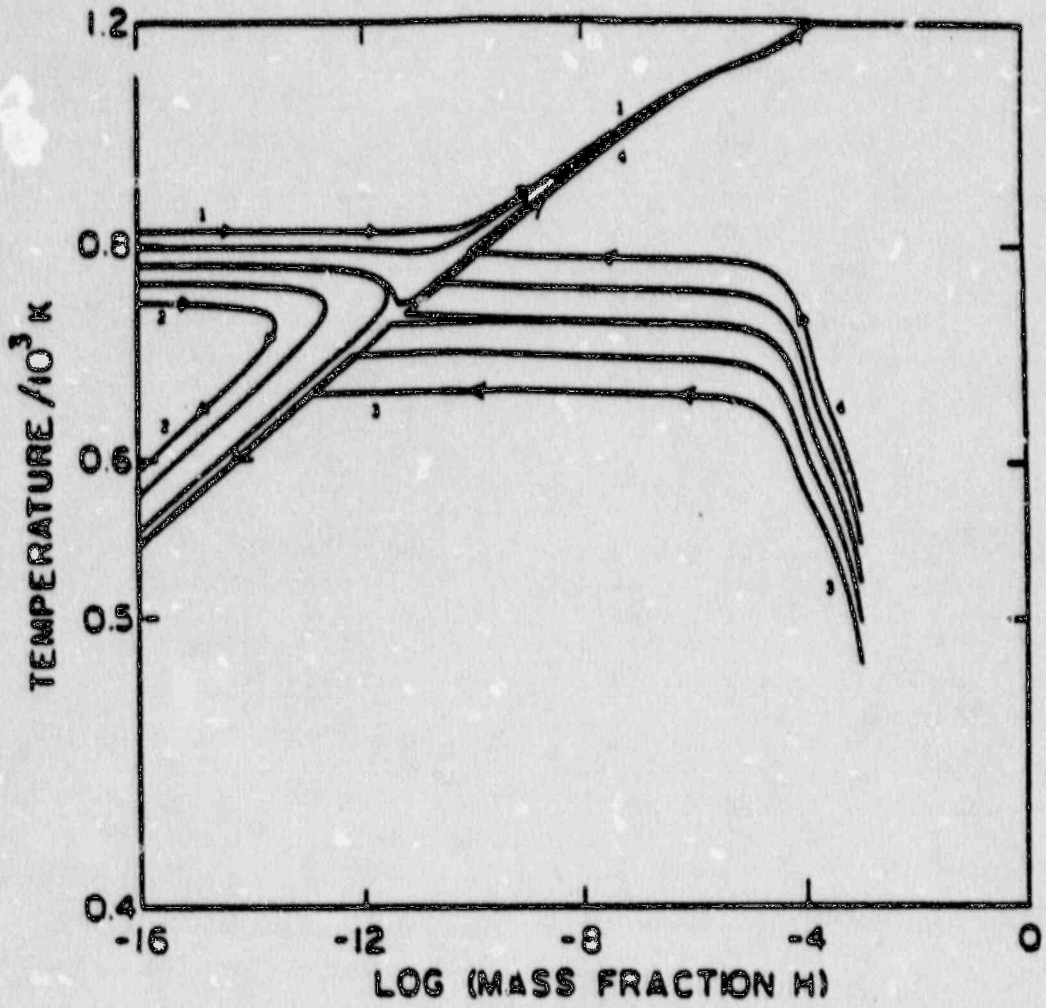

FIGURE 6-3 Projection of the phase space upon the plane of temperature and hydrogen atom concentrations displaying integral curves in the vicinity of the first thermal ignition limit for the hydrogen-oxygen system at a pressure of 6 atm.

Source: Oppenheim (1985).

IGNITERS

For present purposes, ignition is defined as the process of supplying sufficient heat or chemically reactive species to a combustible mixture of gases to produce self-sustaining flames. Igniters may appropriately be classified as thermal (e.g., spark plug or glow plug), thermochemical (e.g., pilot flame), or catalytic. For thermal ignition, minimum energy requirements have been studied extensively and can be predicted theoretically. On the other hand, thermochemical ignition, which provides reactive chemical species as well as kinetic energy, is more complicated, and modeling ignition requires a complex analysis of the reaction kinetics and transport. Some success has been achieved in theoretical analysis, but the performance of a particular thermochemical igniter cannot be accurately predicted, and therefore experimentation must guide any evaluation.

The effectiveness of an igniter is often evaluated through the resultant flame speed and the peak pressure of the burning mixture in a closed vessel. Such measurements are often made for near stoichiometric mixtures, a practice which may not be appropriate for evaluating an igniter for the lean limit mixtures of present interest. For a combustible mixture whose composition is on the threshold of the lean flammability limit, ignition may produce only slow oscillatory combustion, possibly requiring frequent reignition, possibly at different locations. For such conditions, different criteria on effectiveness are required to evaluate an igniter. For the ignition of a lean hydrogen-air mixture at conditions postulated for a loss of coolant accident (LOCA), desirable igniter properties also include consideration of performance in the presence of water vapor or microfog, reliability of operation during central station blackout scenarios (noted in Chapter 5), and designs to provide large effective ignition volumes. The types of igniters to be considered are included in Table 6-1.

There have been several comparative studies of the relative merits of different igniters (Boston et al., 1984; Laderman and Oppenheim, 1962; Oppenheim, 1985) where combustion efficiency (burning velocity, peak pressure) of the ignited mixture is used as the comparison index. The purely thermal igniters can be considered less effective than the thermochemical ones solely on the basis of the energy requirements. For the thermal igniters, the geometrical configuration and aerodynamics are often critical. A glow plug can be considered less effective than a spark plug because (a) it cannot transfer its energy in a rapid pulse and (b) it will not generate turbulence in a quiescent mixture. Thus, to reach ignition of a lean limit mixture, a glow plug would have to transfer more energy to the combustible mixture than the other igniters discussed. (The term soft ignition has been used to characterize glow plugs to distinguish them from the hard ignition of exploding wires. This latter type of igniter will not be included in this discussion, nor will the term soft ignition be used.)

TABLE 6-1 Description of Different Kinds of Igniters

Type of Igniter	Comments
Spark igniters[a] (arc or glow discharge)	Mechanism is by transfer of thermal and sometimes thermochemical energy; ignition is aided if blast wave generates turbulence.
Surface igniters (hot wires or glow plugs)	Transfer of thermal energy, configuration, and flow are important.
Pilot flames	Usually a small stable diffusion flame which provides free radicals as well as heat for ignition.
Plasma jet igniter[b]	Usually a small arc discharge which generates free atoms, radicals, and electrons (more effective if discharge is in a fuel gas and hydrogen atoms are generated).
Catalytic igniter	Under development (produces free radicals similar to a pilot flame but at lower temperature; does not require electric power).

[a] See, for example, Maly (1980).
[b] See, for example, Orrin et al. (1981) and Mittinti and Dabora (1984).

A potential disadvantage of a deliberate ignition strategy is that, for some mixtures, improvements in the ignition process will likely result in improved completeness of combustion and increased overpressure in the containment. Arguments such as these are probably responsible for some ambivalence in the commitment to a deliberate ignition strategy. If deliberate ignition is the approach, the most effective igniters are appropriate to achieve ignition at the lowest possible hydrogen concentration. Inefficient igniters, partial inerting, and the use of water microfogs run counter to this approach. Water sprays with characteristic drop diameters on the order of several hundred micrometers should not affect gas mixture ignitability provided that igniters are shielded from direct spray impingement and cooling. On the other hand, small droplets produced by fog formation can potentially increase the hydrogen concentration required before igniters initiate combustion. Even though the ignitability threshold may increase, the heat sink effect associated with these small droplets should produce lower pressure than the equivalent dry hydrogen-air mixture (see Chapter 4 on suspended water droplet discussion).

The present Nuclear Regulatory Commission policy is to use glow plugs or hot coils as the igniters in the deliberate ignition strategy based on their simplicity of operation (only requiring electric power) and their compatability with other instrumentation (no electrical noise from sparks). Glow plugs have been evaluated extensively at simulated LOCA conditions for reliability, endurance, and ignition performance. Tests conducted by Fenwall Inc., (Dalzell, 1980), sponsored by Tennessee Valley Authority, Duke Power, American Electric Power Company, and Westinghouse, and those conducted at Whiteshell Nuclear Research Establishment (Pamm et al., 1984) have indicated the following:

1. The igniters will initiate combustion for hydrogen concentrations of 5 to 8 percent, but all the hydrogen will not be consumed.
2. Operation of sprays has little effect on the ability of shielded thermal igniters to initiate combustion. At low hydrogen concentrations of 5 to 8 percent, water spray promotes more complete hydrogen combustion because of induced turbulence
3. Steam concentrations of up to 40 percent by volume do not affect the ability of the igniter to initiate combustion, nor does the steam dramatically suppress peak pressures generated by a burn.
4. For hydrogen concentrations of 10 to 12 percent in the presence of sufficient oxygen, all hydrogen present in the atmosphere will burn.
5. The igniter can initiate hydrogen burning under transient conditions of continuous injection of hydrogen and steam unless the mixture is outside its flammability limits.

The possibility of using platinum catalytic igniters for lean hydrogen-air mixtures offers interesting advantages over the use of glow plugs (Thorne et al., 1985). For one thing, the catalytic igniter requires no additional power source. Thus, in the case of a total power failure accompanying a loss of coolant accident, it would continue to operate. In addition, the catalytic igniter appears to be highly reactive and is thus capable of igniting hydrogen-air mixtures at concentrations below 5 percent hydrogen and in the presence of water vapor. Tests on a catalytic igniter are still under way at Sandia National Laboratories, and Lawrence Livermore National Laboratory, and have demonstrated an insensitivity to high temperature, humidity, water spray, and gas flow velocity, as well as the capability of repeated operation in the event of further hydrogen buildup. Recently a wet-proofed platinum/Teflon-coated catalytic substrate was shown to be an effective igniter in the presence of liquid water.

On the other hand, catalytic igniters have some specific disadvantages such as the long time constants for catalytic ignition and the possibility of long-term poisoning or deactivation of the catalyst. The importance of these potential shortcomings can only be determined by additional analysis and some experimental work on catalytic igniters.

The original purpose of the containment sprays was to reduce containment pressure and to remove radioactive aerosols from the containment atmosphere. As noted in the various sections of this report, sprays can also have impacts on some aspects of hydrogen combustion. The presence of spray droplets can raise the detonability limit. However, sprays also have the potential for increasing turbulence, which may enhance flame acceleration. Currently, the sprays are initiated by containment overpressure. It would appear that there may be conditions in addition to excess pressure that would be aided by spray activation.

CONCLUSIONS AND RECOMMENDATIONS

Ignition and Igniters

- Strictly speaking, ignition is the initiation of a self-sustained exothermic process of combustion. Actually, it can be accomplished either by a purely thermal action, due to high temperature only, or as a thermochemical process, that is, one involving both an elevated temperature and active radicals.
- The temperature threshold between ignition and extinction defines an ignition temperature. Since the addition of active radicals acts as a thermal substitute, the thermal ignition temperature is, for a given chemical system, as a rule higher than its thermochemical equivalent.
- Gas dynamic effects alone are inadequate for ignition. The only way they can be effective is by contributing toward the attainment of the ignition threshold on either the thermal or thermochemical side of the critical radical concentration barrier--an attractor in the phase space for ignition (see curve 1 or 4 in Figure 6-3).
- Ignition may or may not lead to the formation of a flame. In a self-sustained detonation wave, for example, flameless ignition is induced periodically by the gas dynamic action of shock interactions, of which the most prominent are collisions between triple point, or Mach, intersections. If a deflagration flame is formed, it can be extinguished by being overly stretched or blown off. However, in contrast to ignition, the formation of a flame, or inflammation, is a process governed by fluid mechanic

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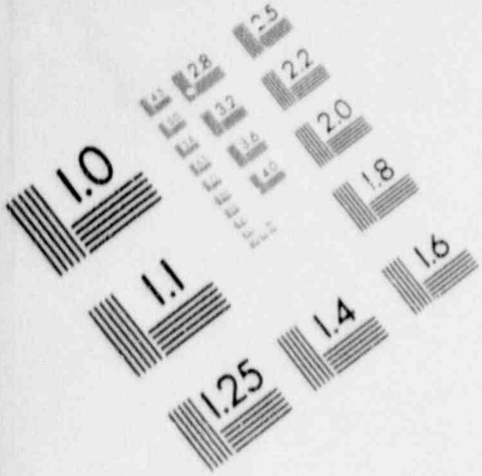

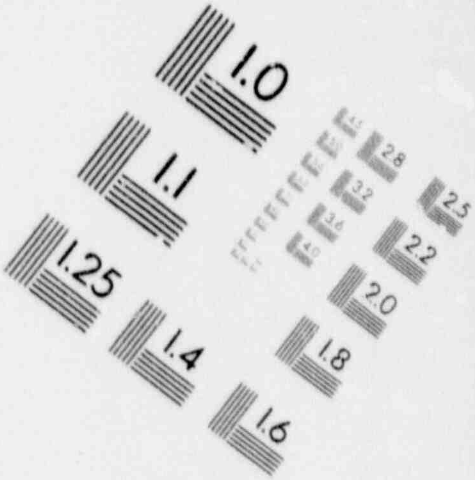

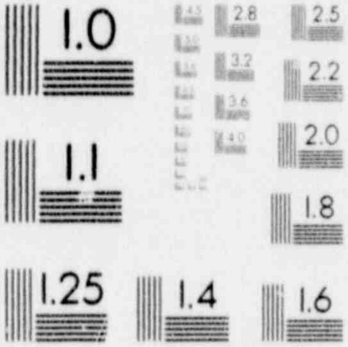

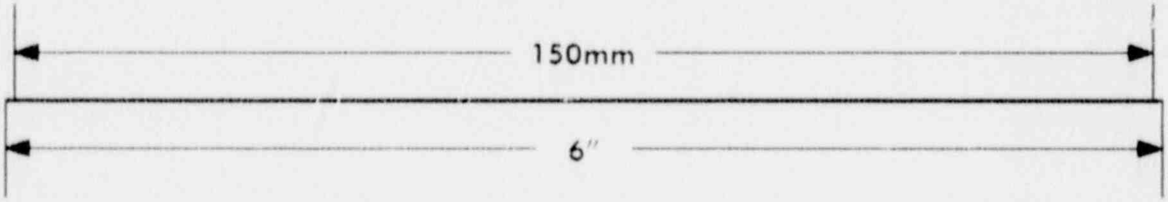

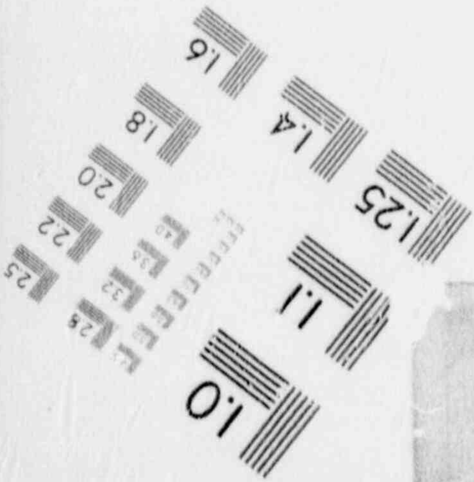

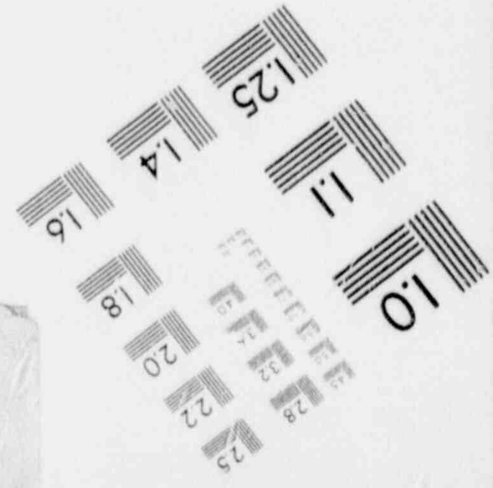

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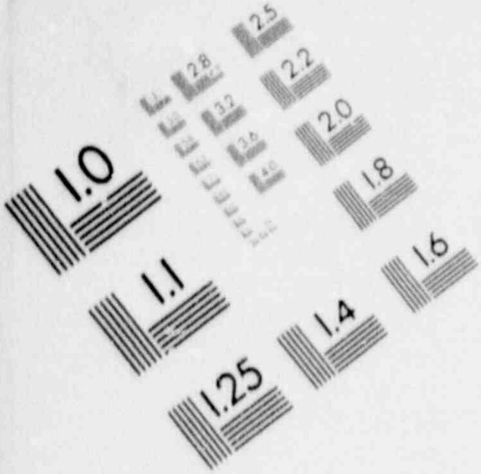

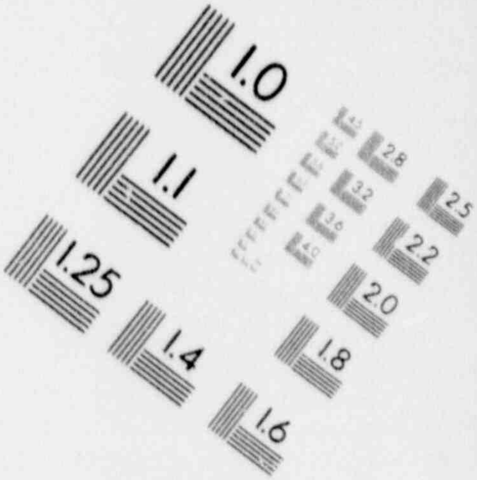

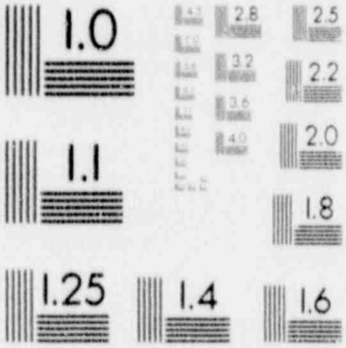

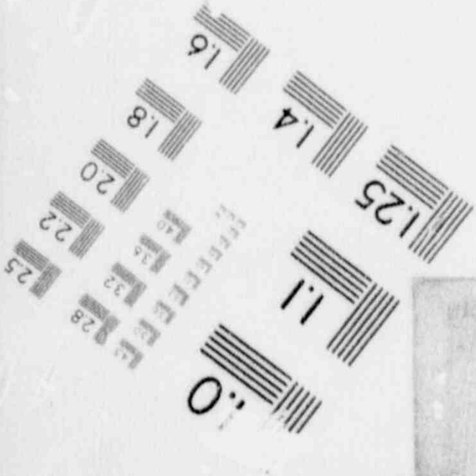

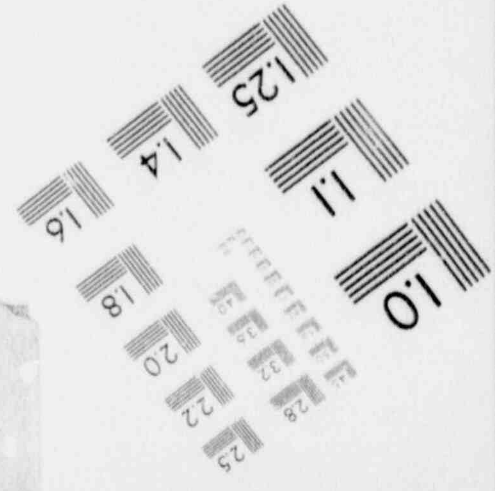

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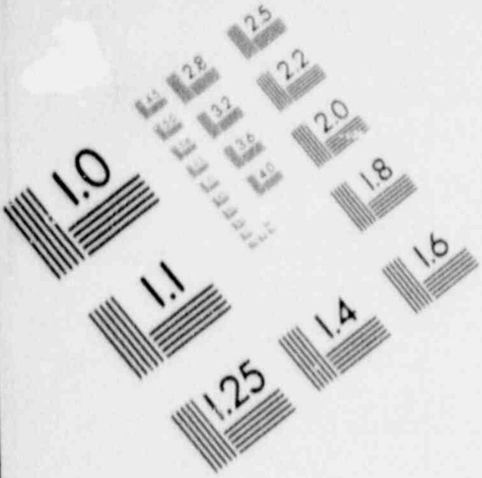

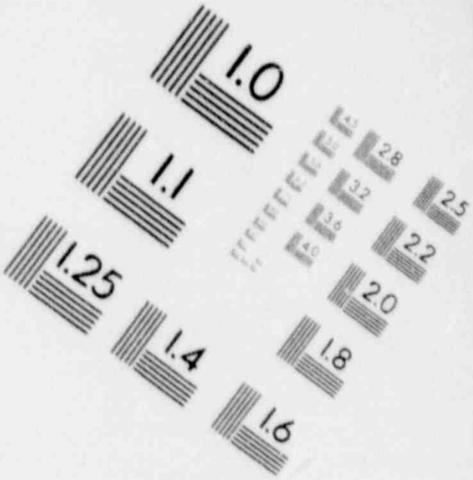

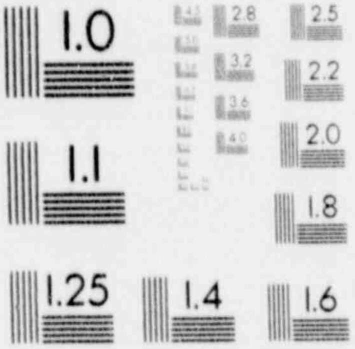

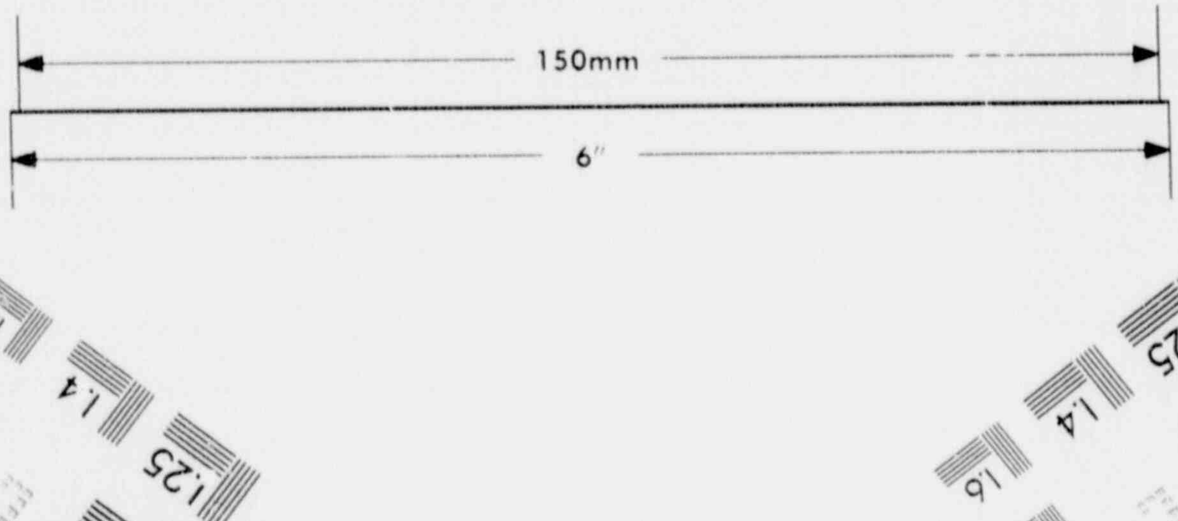

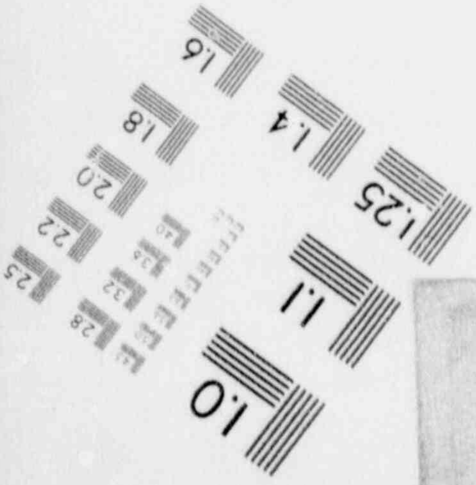

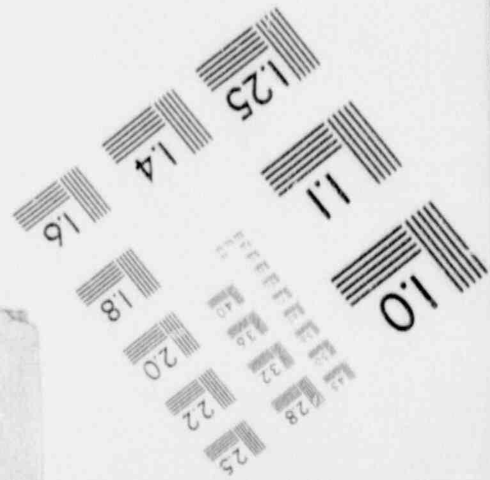

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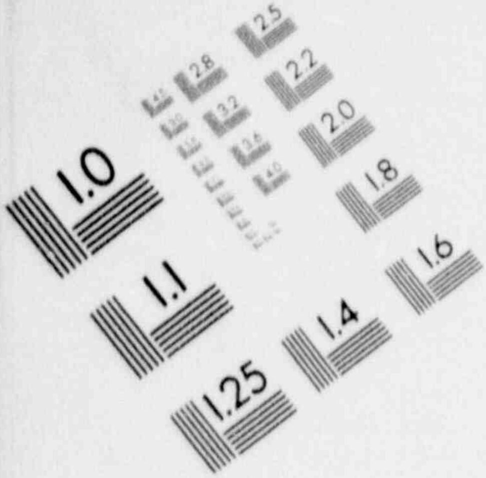

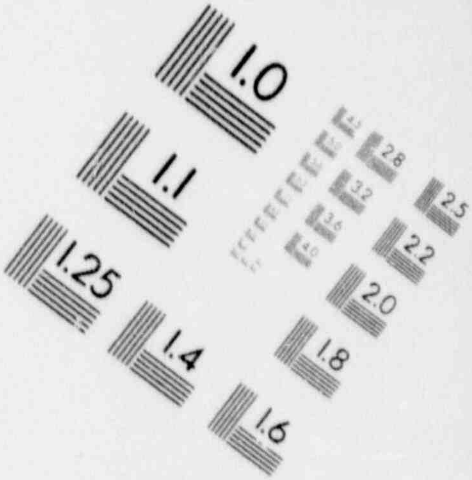

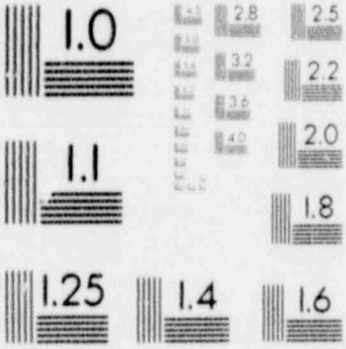

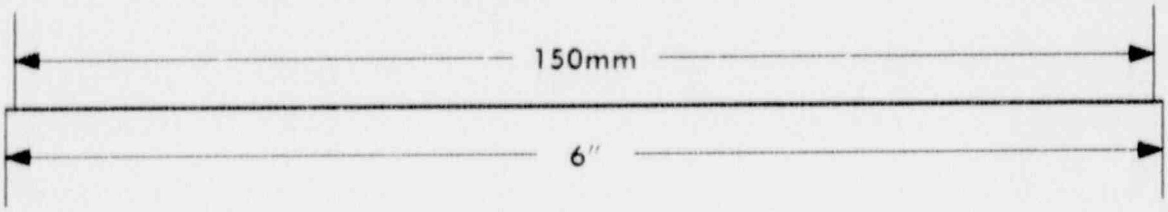

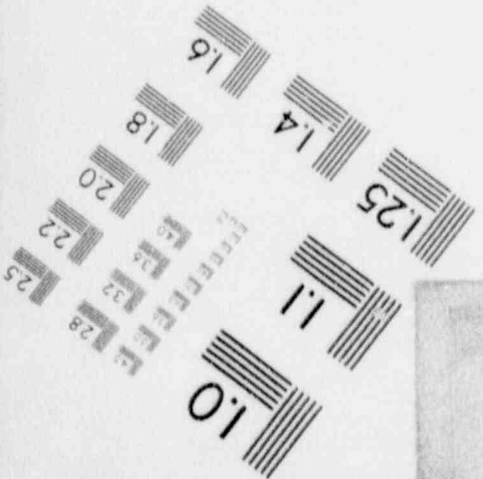

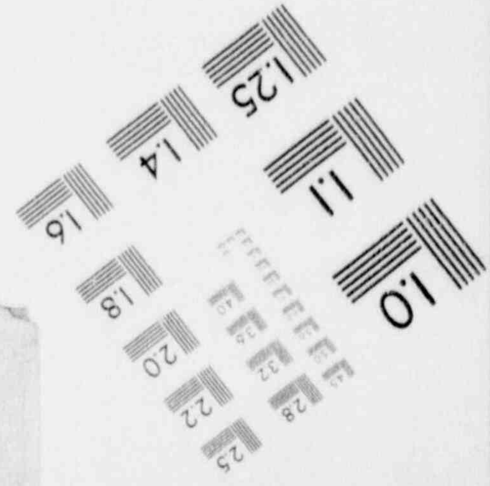

phenomena, and consequently, its threshold cannot be specified in a similarly straightforward manner as that for ignition.

- By inference it follows that initiation and sustenance of a flame in a gaseous fuel jet issuing into an oxidizing atmosphere is a phenomenon dependent on fluid mechanic features of the field it generates, associated with mixing and diffusion, on top of the thermochemical processes of ignition, so that its threshold cannot be described in simple terms of a go-no go event. As in any fluid mechanically dominated system, its occurrence besides the natural requirement to have to settle down at the stoichiometric contour, is so dependent on initial and boundary conditions that demanding its description to be specified in absolute terms of a correlation formula is an essentially ill-posed problem.
- Tests indicate that shielded igniters will operate reliably under conditions anticipated in nuclear reactor accidents except for total loss of power.

The following recommendation regarding ignition and igniters is made.

- As discussed in Chapter 5 on detonation, methods for improving the reliability of igniter systems for station blackout scenarios is desirable. One such possible method would be with the use of catalytic igniters or other ignition sources not dependent on outside sources of power such as individual battery-powered igniters. Because of their potential value for enhancing reliability, it is recommended that additional development of catalytic igniters be undertaken.

Operation of Sprays

With regard to the influence of sprays on containment conditions, the following conclusion is drawn.

- The original intention of containment sprays was to reduce containment pressure and remove radioactive aerosols from the containment atmosphere. Since sprays also affect hydrogen combustion (also see Chapter 4), it appears that there may be conditions in addition to these original ones that would be aided by spray activation.

Based on the above conclusion the following recommendation is made.

- It is recommended that analysis be conducted to establish if sprays should be initiated for conditions other than containment overpressure.

APPENDIX A

STATEMENT OF TASK

1. Scale-up
   a. Evaluate experimental data from various test facilities with respect to the following questions:
      (i) How typical are the combustion mechanisms in small enclosures as compared with full-size containments?
      (ii) How well can they be scaled to full-size containments?
   b. Evaluate the ability to scale the instrument temperatures obtained from small-scale tests through analytic codes to the temperatures predicted for full-size reactor containments.
2. Completeness
   Evaluate Sandia National Laboratory's program and the programs sponsored by industry with respect to the question of whether all important areas have been properly covered.
3. Detonation
   a. Comment on the need for extending experimental work to include effects of detonation on equipment, recognizing that most work to date has concentrated on deflagration, in view of the difficulty of detonation work and the low probability ascribed to such an event.
   b. Provide an independent assessment of the following research: Recent research by the Sandia National Laboratory has established lower limiting concentrations of hydrogen (approximately 13.5 percent) in air which would support a detonation. Furthermore, additional testing with steam in the heated detonation tube facility has provided results indicating that steam addition to hydrogen-air mixtures had little effect on the detonability of mixtures.
4. Jet Flames
   Develop inferences and comment on the quality of the inferences with respect to the following question: What are the conditions under which autoignition of jet flames might occur, for release of a steam-hydrogen or hydrogen jet into an ambient mixture?

5. <u>Suspended Water</u>

   Evaluate the influence of suspended water droplets on hydrogen combustion in a hydrogen-nitrogen-oxygen-steam mixture with respect to the following questions:

   a. What is the influence of suspended water as a function of droplet size and volumetric density on the limiting concentrations for hydrogen deflagrations and detonations?

   b. What is the nature of suspended water formed as a result of bulk condensation of steam in the subject mixtures? What are initial droplet sizes and what are the effects of coagulation?

APPENDIX B

REPORT CONCLUSIONS AND RECOMMENDATIONS

For reference purposes, all the conclusions and recommendations in the main body of the report are summarized in Table B-1 in this appendix according to subject category.

TABLE B-1 Report Conclusions and Recommendations

Subject	Conclusions	Recommendations
Hydrogen Control	Regulatory requirements have been established by the Nuclear Regulatory Commission (NuRC) for ensuring that a hydrogen detonation after a severe nuclear plant accident is not likely to be the cause of containment failure. The committee further concludes that for most accident sequences these requirements generally reflect an adequate margin of conservatism. None of these approaches completely eliminates the possibility of a detonation since, for example, during shutdown and during the startup period for boiling water reactors (BWRs) the containment is not made inert. Clearly, since the igniters require electricity, if power is lost the igniters will fail. In large dry containments nonuniform mixing may pose a problem. Thus, all that these approaches can do is reduce the probability of a hydrogen-caused containment failure. The goal of these mitigative features, then, is to attempt to ensure that containment failure by hydrogen burning or detonation will be acceptably low. The committee also concludes that the applied research programs that have been sponsored by the NuRC and the nuclear industry have provided a credible basis for the adequacy of the control measures. If the margin of conservatism is to be reduced in the future, additional research will be needed. This should be basic research, leading to more	

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Hydrogen control (continued)	fundamental understanding of the distribution of hydrogen in a containment and the combustion process in its various forms. Research of this kind can be used as a basis for analytical methods resting on first principles, which can be used for more confident calculations of the features of threats to the containment.	
Lumped-parameter models	Lumped-parameter models provide a viable, engineering approach for treating the complexities of hydrogen transport and combustion in containments. However, many of their features have not been evaluated directly so that their general validity for full-scale containments has not been adequately established. Furthermore, existing models are deficient in cases where mixing is not enhanced by external means, such as when fans and sprays are not operating.	Model evaluation should continue with the additional requirements that all user-specified parameters, and the scaling rules to be used for them, be fully documented as part of the evaluation. The goal of subsequent evaluations should be more generally valid guidelines for code use with demonstrated capabilities to treat hydrogen mixing and combustion in full-size containments. Lumped-parameter codes should be validated by undertaking comparison with measurements from a few large-scale experiments. These experiments could be carried out using inert gases in an actual containment or a structure of similar size. Comparison with data from tests at the 1/4-scale facility would be useful in this regard.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Lumped-parameter models (continued)		Future lumped-parameter models should make greater use of zone-modeling techniques since zone models offer attractive features for treating the hydrogen problem in containments, particularly when auxiliary mixing sources are absent. They are more physically based than ad hoc subdivision of compartments into well-mixed volumes and provide a formalism to design studies addressing specific aspects of flow and mixing in structures, including plume entrainment or mixing in stratified layers. Coordination of National Bureau of Standards (NBS) and NuRC efforts in this area would be beneficial to both programs and should be pursued. The Center for Fire Research at NBS is actively developing zone models of fires within structures. This technology is very similar to lumped-parameter modeling of hydrogen transport and combustion in containments.
Field models	Although field models cannot include as many phenomena as lumped-parameter models because of computational intractability, they can be used for detailed analysis of specific phenomena.	Development and evaluation of field model methods should continue with emphasis on the demonstration of grid-independent and user-independent results relevant to full-size containments.

TABLE B-1 Report Conclusions and Recommendations (<u>Continued</u>)

Subject	Conclusions	Recommendations
Field models (<u>continued</u>)	Field models can be used for detailed study of the flow field within compartments. Results can be used to parameterize coefficients in the lumped-parameter codes.	Field models should be used to model the structure of the flow within compartments based on the results of experiments in actual containments or similar multicompartment structures. These results could then be used to develop empirical parameters for the lumped-parameter models. Subelements of the field models should be developed using results from both detailed experiments and numerical simulations of turbulence. Improvements in these areas require that one overcome the limitations of the current experimental data base as described for deflagrations in Chapter 4. The National Aeronautic and Space Administration (NASA)-Lewis Research Center is actively developing field models and methods for simulating turbulence under the HOST research program as well as its basic

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Field models (continued)		in-house effort. This work includes sensitivity studies for numerical closure (grid independence) and turbulence modeling procedures for recirculating reacting flows including sprays. The problems that this program has addressed are similar in some respects to the nuclear reactor containments. Coordination of NASA and NuRC efforts in this area would be beneficial to both programs and should be pursued. The Center for Fire Research at NBS is actively developing methods for numerical simulation of buoyant turbulent mixing in confined environments, which are similar to problems of hydrogen mixing in nuclear reactor containments. Coordination of NBS and NuRC efforts in this area would be beneficial to both programs and should be pursued.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Deflagrations	Although lean hydrogen-air mixture deflagrations are too complicated to allow direct extrapolation of subscale tests to full-size containments, the data are useful for (1) identifying scaling trends; (2) computer code validation, calibration, and input parameter selection; and (3) providing physical insights into relevant combustion and heat transfer phenomena. Peak pressures in lean hydrogen-air mixture deflagrations are likely to be higher (and closer to the adiabatic, constant-volume pressure) in actual containments than in subscale tests. Prediction of peak pressures in actual containments is tantamount, via use of computer codes, to predicting hydrogen burn fraction and flame speeds. Although flame speed and burn fraction data compilations are available, there is no systematic, quantitative procedure to account for turbulence, geometry, and scale effects in actual containments. The development of such a procedure is hampered by the scarcity of data on flame propagation around equipment and between compartments, and on turbulence intensities and length scales associated with containment sprays and ventilated flows.	Parametric calculations should be conducted for turbulence effects associated with containment sprays, ventilated flows, and flame propagation around equipment and between compartments. Results of these calculations using conservative estimates of turbulence parameters and/or burn fraction and flame speed will determine whether additional tests focusing on these effects are warranted. Hydrogen burn fraction and flame speed correlations, quantitatively including turbulence, scale, and geometry effects, should be developed accounting for recent data such as those in the Nevada Test Site (NTS) Dewar.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Diffusion flames	Scaling relationships are available for both buoyant and jet diffusion flame lengths, as well as for temperature and velocity distributions. These relationships are useful in identifying the extent of the regions subject to thermal loading. It is not clear yet whether the uncertainties in these scaling relationships (as much as 80 percent for weak steam-diluted jet flames) are critical from the standpoint of equipment survivability. Scaling relationships for both jet flame and buoyant diffusion flame lift-off distances and blowoff velocities also have significant uncertainties in the range of the large mass flow rates and release diameters hypothesized in containment accident scenarios. These flame lift-off and detachment phenomena, which have been observed in both the NTS experiments and in several Mark III 1/20- and 1/4-scale tests, may lead to possible thermal damage to equipment in remote regions of the containment as well as to equipment in the vicinity of the release site.	Conservative calculations of thermal loads on key safety equipment due to jet diffusion flames should be conducted to determine whether the uncertainties in the flame length and temperature/velocity field scaling relationships are acceptable or whether additional data are needed. Additional testing and analysis should be conducted to develop flame lift-off, blowoff, and relocation criteria relevant to containment accident scenarios. If a spatial resolution finer than that provided by the current Mark III 1/4-scale tests is needed, additional analyses and/or tests may be needed to account for wakes and other disturbances associated with omitted small equipment and structures.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Diffusion flames (continued)	Froude scaling cannot rigorously simulate convective and radiative heat fluxes in containment accident scenarios involving diffusion flames. However, measured gas temperatures and velocities can be used, along with quantitative analyses of departures from Froude scaling, to estimate thermal loads on major safety equipment.	
	The spatial resolution to be expected from Froude scaling extrapolation of temperature and velocity data is limited by the length scale of the small equipment and structures present in actual containments but omitted in the tests.	

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Detonation aspects	The estimated energy and power density required for direct initiation of detonation near but above the lean detonation limit are very high. It is unlikely that initiation of direct detonation near this limit would occur in a containment vessel environment. Detonation temperatures are only slightly higher than the isochoric temperature for the same mixture. Any precautionary measures taken to preserve the equipment in the case of a deflagration should be adequate for detonation thermal loading as well. However, further consideration of the effects of detonation pressures on equipment is needed. The lean composition limit of dry hydrogen-air mixtures is expected to decrease as the size of a containment increases. It is estimated that in a reactor space of diameter on the order of 50 m, a 9 to 11 percent hydrogen-air mixture might be detonable. Increasing temperature renders a given mixture more sensitive so that hydrogen-air mixtures at elevated temperatures might detonate at concentrations lower than 9 to 11 percent. The presence of water vapor or carbon dioxide decreases the sensitivity of a mixture to detonation. It is estimated	A reanalysis of the likelihood of subatmospheric containment failure under detonation loads should be performed and used as a basis for deciding what, if any, further actions are needed. Because of the distinct possibility of limited or localized detonations, the area of possible damage to equipment and structures, including containment, by shock waves from limited detonations requires further evaluation. The possibility of detonation should be examined for each large dry containment having fan coolers to determine if a satisfactory safety margin exists.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Detonation aspects (continued)	that a 20 percent dilution by either carbon dioxide or water vapor raises the lean detonation limit in a reactor containment to around 13 percent hydrogen. Water sprays have the potential of reducing the probability of detonation. Of interest here is that mixtures at hydrogen concentrations of 14.4 percent or less can be quenched by sprays with 1-mm-diameter drop sizes, and as the hydrogen to air ratio decreases even coarser sprays can be effective. More refined analysis and a systematic experimental program would substantiate this conclusion. The effect of sprays on detonation is not taken into account in regulatory analysis and may in many accident scenarios provide a significant margin of conservatism. Current procedures of inerting for protection against hydrogen detonation in small-volume BWR containments is satisfactory. For accident scenarios in which they operate as intended, igniters are a reasonable way to reduce the probability of a large-scale detonation in medium-volume containments.	

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Detonation aspects (continued)	Although the lower limit of detonation of dry hydrogen-air mixtures may be as low as 9 to 11 percent in large containments, in water-hydrogen-air mixtures of the type that must be present in most large-volume containments following a hydrogen-producing accident, the value is greater than 13 percent. Thus, for the case of uniform mixing in which the maximum hydrogen concentration is 10 percent or less, the possibility of detonation in these cases is remote. However, consideration should be given to cases of nonuniform mixing.	
Ignition and igniters	Strictly speaking, ignition is the initiation of a self-sustained exothermic process of combustion. Actually, it can be accomplished either by a purely thermal action, due to high temperature only or as a thermochemical process, that is, one involving both an elevated temperature and active radicals. The temperature threshold between ignition and extinction defines an ignition temperature. Since the addition of active radicals acts as a thermal substitute, the thermal ignition temperature is, for a given	As discussed in Chapter 5 on detonation, methods for improving the reliability of igniter systems for station blackout scenarios is desirable. One such possible method would be with the use of catalytic igniters or other ignition sources not dependent on external power sources such as individually battery-operated igniters. Because of their potential value for enhancing reliability, it is recommended that additional development of catalytic igniters be undertaken, as well as other methods for enhancing reliability until the most desirable method can be chosen.

TABLE B-1 Report Conclusions and Recommendations (<u>Continued</u>)

Subject	Conclusions	Recommendations
Ignition and igniters (<u>continued</u>)	chemical system, as a rule higher than its thermochemical equivalent. Gas dynamic effects alone are inadequate for ignition. The only way they can be effective is by contributing toward the attainment of the ignition threshold on either the thermal or thermochemical side of the critical radical concentration barrier--an attractor in the phase space for ignition. Ignition may or may not lead to the formation of a flame. In a self-sustained detonation wave, for example, flameless ignition is induced periodically by the gas dynamic action of shock interactions, of which the most prominent are collisions between triple point, or Mach, intersections. If a deflagration flame is formed, it can be extinguished by being overly stretched or blown off. However, in contrast to ignition the formation of a flame, or inflammation, is a process governed by fluid mechanic phenomena, and consequently, its threshold cannot be specified in a similarly straightforward manner as that for ignition.	

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Ignition and igniters (continued)	By inference it follows that initiation and sustenance of a flame in a gaseous fuel jet issuing into an oxidizing atmosphere is a phenomenon dependent on fluid mechanic features of the field it generates, associated with mixing and diffusion, on top of the thermochemical processes of ignition, so that its threshold cannot be described in simple terms of a go-no go event. As in any fluid mechanically dominated system, its occurrence, besides the natural requirement to have to settle down at the stoichiometric contour, is so dependent on initial and boundary conditions that demanding its description to be specified in absolute terms of a correlation formula is an essentially ill-posed problem. Tests indicate that shielded igniters will operate reliably under all conditions anticipated in nuclear accidents except for total loss of power.	
Influence of suspended water droplets	Large-water-droplet containment sprays increase flame speeds in lean hydrogen-air mixtures and cause peak pressures to be closer to the adiabatic, constant-volume values. However, these sprays also enhance cooling of the burned gases and therefore cause pressures and temperatures to decrease more rapidly	

TABLE B-1 Report Conclusions and Recommendations (<u>Continued</u>)

Subject	Conclusions	Recommendations
Influence of suspended water droplets	to precombustion levels. Thus, depending on the relative safety margins for pressure loads and thermal loads, the sprays can be either beneficial or detrimental during permixed combustion. They are definitely beneficial for postcombustion cooling and for the diffusion flames anticipated with deliberate ignition. Water sprays have the potential of reducing the probability of detonation. Of interest here is that mixtures at hydrogen concentrations of 14.4 percent or less can be quenched by sprays with 1-mm-diameter drop sizes, and as the hydrogen to air ratio decreases even coarser sprays can be effective. Droplets on the order of 20 μm or less in diameter can significantly raise the lower flammability limit for hydrogen combustion. However, it is not clear whether such fogs would form in a containment atmosphere under conditions postulated for an accident scenario. The presence of such fogs would delay the onset of hydrogen ignition by igniters (see Chapter 6) but should also mitigate the effects of hydrogen combustion. Experimental confirmation of the extent of these mitigating effects would be desirable if they are necessary to maintain containment integrity.	

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Nature of suspended water droplets (continued)	There is considerable uncertainty in droplet size and fog density resulting from fog formation in containment during postulated severe light-water reactor (LWR) accidents.	
Operation of sprays	The original intention of containment sprays was to reduce containment pressure and remove radioactive aerosols from the containment atmosphere. Since sprays also affect hydrogen combustion (also see Chapter 4), it appears that there may be conditions in addition to these original ones that would be aided by spray activation.	As addressed in Chapters 4 and 6, there appear to be conditions in addition to excess pressure that would be aided by spray activation. It is therefore recommended that analysis be conducted to establish if sprays should be initiated for conditions other than containment overpressure.
Documentation of hydrogen accidents	The committee recognized the dearth of informaton regarding hydrogen explosions in industrial accidents.	It is important that the NuRC continues to keep track of any past and future accidents involving hydrogen such as occurred or might occur in its production, use, or handling. These accidents should be studied on a continuing basis with the aim of finding any possible similarity between them and what may occur in a reactor accident. This information could be used by NuRC for making decisions regarding hydrogen-related mitigation procedures in the future.

TABLE B-1 Report Conclusions and Recommendations (Continued)

Subject	Conclusions	Recommendations
Alternative means of hydrogen control	Although beyond the charge of the present committee, a study to investigate means of hydrogen control in comparison to igniters would be worthwhile.	A careful analysis of the benefits and liabilities of alternative hydrogen-control systems in comparison to igniters should be conducted.
Proposed committee on modeling techniques	A critical assessment of modeling techniques would be worthwhile.	A committee of experts should be formed to conduct a critical assessment of modeling techniques used and/or under development as well as consider their future use and development. In particular, this assessment should focus on numerical fluid mechanics applied to transient flow problems involving turbulence.

APPENDIX C
MINORITY REPORT: COMMENTS ON THE HAZARD OF HYDROGEN COMBUSTION IN A NUCLEAR POWER PLANT

A. K. Oppenheim

INTRODUCTION

These comments are based on the premise that, in essence, the principal task of our committee was twofold in nature:

(1) appraisal of the technological merit of past work, and (2) advice on future work.

One should bear in mind that of major concern in this respect is nothing else but the minimization of hazard.

Unfortunately, the emphasis of the whole program was misplaced right from the outset. Too much attention was devoted to the question of whether a detonation wave can develop or not, and too little was devoted to the real hazard, the actual damage that hydrogen combustion may cause.

Fortunately, as a consequence of a significant effort, conducted throughout the world for a quarter of a century, starting from the mid-1950s, the mechanism of the development of detonation waves and their structure are today known sufficiently well to provide practically all the information one may need not only on the evolution but also on the abatement of this process (Oppenheim, 1985). In a nutshell, the view one should have consequently upon the flame acceleration leading to the onset of detonation is that it is an essentially transient event whose evolution is extremely sensitive to initial and boundary conditions. As a typically nonlinear process, it is earmarked by the property that minute variations in these conditions have a significant influence on the outcome. Moreover, in establishing the limit, it is not only the critical energy that is of importance but also the rate at which it is deposited in the reacting medium, i.e., the critical power. Thus, even if problems associated with initial and boundary conditions are properly handled, the minimum one requires to express the limit is a line on the plane of specific energy and specific power, where it would appear as a hyperbola, so that at higher powers less energy would be required to enter the domain of hazard. Under such circumstances simple scaling laws are obviously out of the question, and the essential objective of scaling, specified as one of the major tasks of the committee, appears to have been ill-posed. It is not the information on the scaling-up of data one should ask for but information on the actual mechanism of the process, a relatively easy task in view of the abundance of knowledge acquired as a consequence of the quarter-of-a-century, worldwide program of studies that has been recorded, in particular, in the Proceedings of the International Colloquia on Dynamics of Explosions and Reactive Systems, in addition to the vast scientific literature on the subject.

As far as the potential for damage is concerned, it is, however, the energy content alone that matters, irrespectively of whether the detonation may be developed or not. After all, one should not overlook the fact that all the detonation parameters, such as its velocity of propagation or pressure jump across its front, are functions of energy rather than power. The practical way of dealing with the potential hazard of hydrogen combustion is then to do all one can to prevent the accumulation of an appreciable amount of hydrogen in the oxidizing atmosphere. Waiting until it is sufficiently large and well-mixed to be set off by a passive ignitor, such as a glow plug, is certainly not very smart.

In what follows, salient features of the pragmatic aspects of the problem are presented. This is followed by a discussion of the fundamental aspects and concluded with a list of recommendations.

PRAGMATIC ASPECTS

In the following, two strategies available to deal with the potential hazard posed by accidental discharge of hydrogen from a nuclear reactor are considered: (1) elimination of hydrogen by deliberate burning, and (2) neutralization of oxygen by total or partial inerting.

Burning

This strategy occupied, in effect, exclusively the attention of the whole program, as well as of the committee, with consequent diminution, if not outright rejection, of all other considerations.

To make matters worse, the solution universally adopted and accepted by the committee, the glow coil igniter, is the least effective in mitigating the hazard and the most likely to exacerbate its consequences. The main reason for it is its essential nature as a passive ignition source. It cannot become operative until the local concentration of hydrogen in air at the point of ignition reaches the low inflammation limit of 4 percent. The probability that hydrogen is then at a much higher concentration level in the surroundings is much too high for comfort. In fact, the tests performed by Factory Mutual Research Corporation indicate that it was 100 percent where the diffusion flame was observed.

The likelihood of aggravating the situation under such circumstances is, in my opinion, sufficiently high to question the whole rationality of this technique.

If getting rid of hydrogen by burning is deemed necessary, one should resort to an active ignition source, such as a pilot flame. For the purpose at hand, such a flame could be maintained in a small combustion chamber, preceded by a compressor fan capable of inhaling a significant volume of air and backed up by an expander and cooler. A system like this would constitute, in effect, a miniature gas turbine, except that it would require power to drive the fan. This could be provided either by the electrical supply system or, to deal with potential black out, it could be furnished by compressed gas or water. If hydrogen is used as fuel, the exhaust gases may be condensed so that the system could operate for a long time without causing any increase of pressure in the containment. If one wishes, the effectiveness of the combustor could be enhanced by the use of catalytic surfaces.

The cost of the development, production, and installation of such devices cannot be, under any circumstances, considered prohibitive.

Inerting

The concept of inerting was, in my opinion, much too readily discarded. Here, the most promising concept is the principle of partial inerting (dilution). According to the essential premise of deliberate burning that received such overwhelming approval, a hydrogen fire is evidently considered an acceptable risk--an essentially questionable decision. The only hazardous event, then, that by all means must be avoided is detonation. In this case, the extent of required inerting is just that which would be sufficient to prevent the transition to detonation. For this purpose one does not have to eliminate all the oxygen from the atmosphere beyond the inflammation limit of 4 percent--tantamount to complete inerting--but only enough to make sure that a self-sustained detonation wave could not develop.

One way in which such an atmosphere could be created is by the use of a suitable diluent, such as carbon dioxide. Its effects were studied experimentally at McGill University and at Sandia National Laboratories several years ago, and the results were published last year at the Tenth International Colloquium on Dynamics of Explosions and Reactive Systems in Berkeley. In an earlier version, they were presented at the Twelfth Water Reactor Safety Research Information Meeting (Sherman, 1984).

Figure C-1 presents the essential result, in the form of a plot of cell sizes (λ), of detonation waves for different concentrations of CO_2 in air. The minimum for any fixed concentration is at the stoichiometric hydrogen-air mixture. Figure C-2 shows that λ^{-1} for such mixtures is a linear function of the CO_2 concentration, intersecting the $\lambda^{-1} = 0$ axis at a point where the mole fraction of CO_2 is 17 percent.

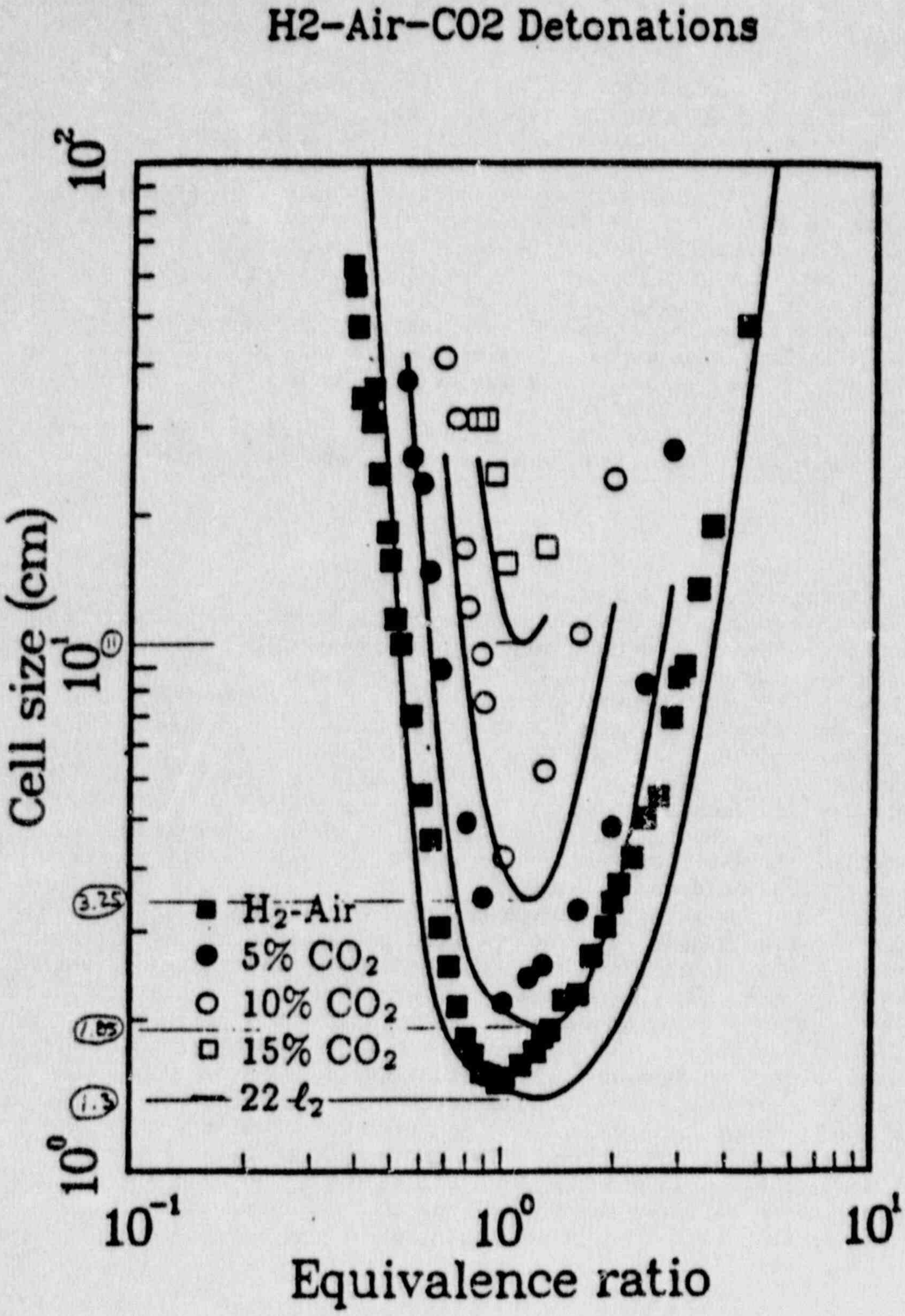

FIGURE C-1 Cell sizes in hydrogen-air-carbon dioxide detonations.

Source: Sherman (1984).

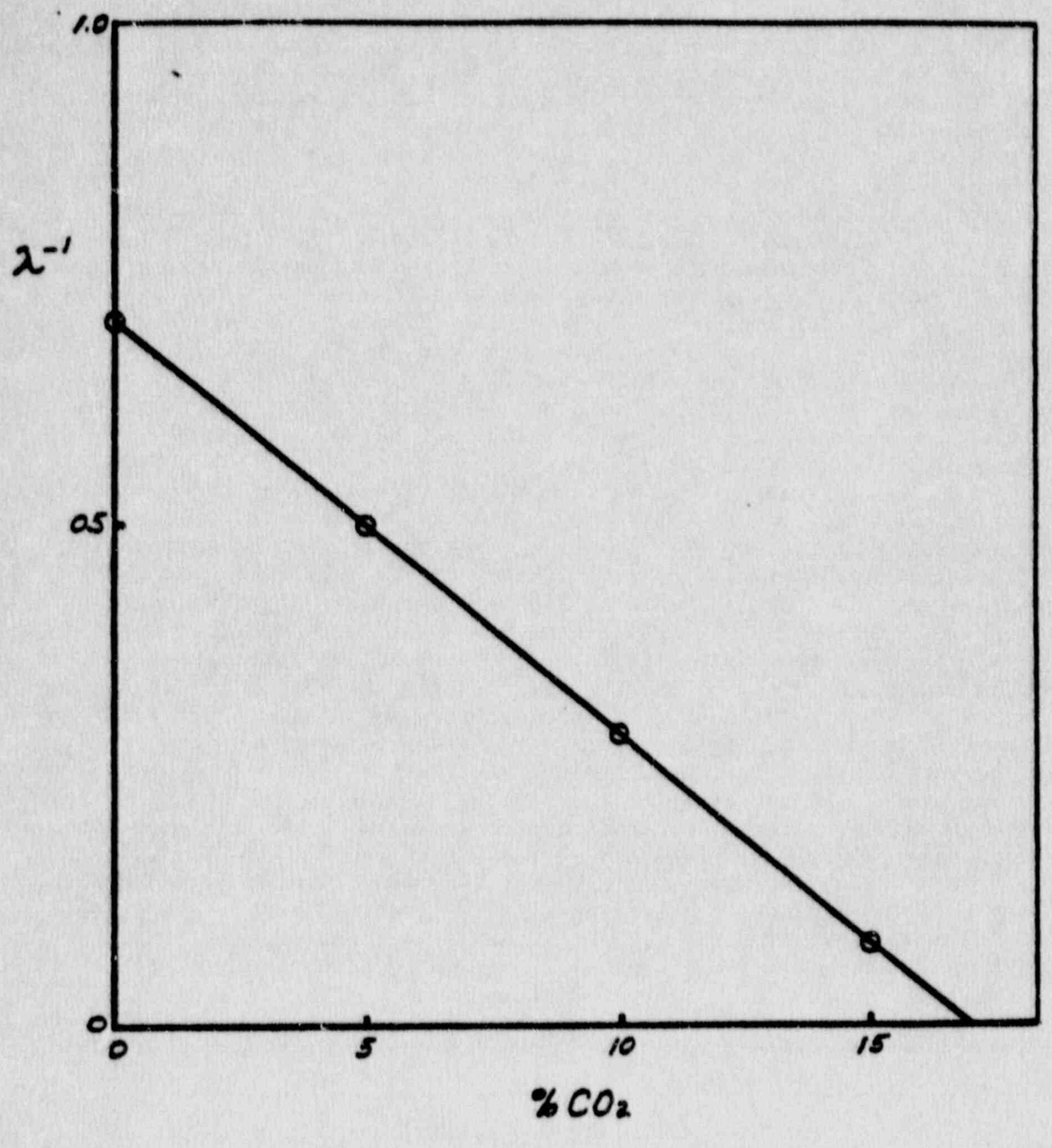

FIGURE C-2 Reciprocal of minimum cell sizes as a function of the molar fraction of CO_2.

On this basis one can conclude that detonation cannot be attained if the mole fraction of CO_2 is, say, 20 percent. The cost of the gas and all auxiliary equipment, such as pumps to partially evacuate the enclosure, and of the facilities and supplies to maintain the desired concentration of CO_2 cannot possibly be considered to be exorbitant. Moreover, it should be noted that CO_2 can be easily fabricated in situ by a suitable clean combustor, that is, one provided with a proper chemical processing system and operated so that the exhaust products are pollutant-free. Should an engine be adopted for this purpose, it could drive an exhauster to maintain an atmospheric or, even better, subatmospheric pressure in the containment.

The CO_2-diluted atmosphere should be maintained in the containment all the time that the nuclear reactor is in operation. The maintenance crew would be required then to use oxygen masks and carry small gas tanks, but that could not possibly cause any impediment. It should be also noted as demonstrated by Figure C-3, a photocopy of a page from the last edition of the classic book by Lewis and von Elbe (1961), that dilution by CO_2 at a level of 20 percent has a negligible influence upon the low inflammation limit of hydrogen in air. Consequently, the use of CO_2 as a diluent does not preclude deliberate burning of hydrogen, should that be deemed desirable.

As to future studies, one may consider the need for an independent experimental verification of the critical concentration of CO_2 at the detonability limit. At the same time one may consider the advisability of confirming the results of such a study by the measurement of the strong ignition limit (Oppenheim, 1985), a parameter that, in contrast to the cell size of an already established self-sustained detonation wave, manifests the salient feature of the essentially transient process of an explosion-in-explosion that triggers the transition to detonation.

The possibility of having the atmosphere made totally inert by the use of CO_2 and/or N_2, thus extending to large containments the technology already instituted for smaller reactors, should not be overlooked. The fact that one thereby obtains complete protection from fire as well as detonation should be recognized as an exceptional asset --one that cannot be annihilated by reasons of economy or impediment. In spite of my best efforts, I have not been able to find any evidence of a thorough engineering study of this technology, let alone a disproof of its applicability to large containments. I cannot imagine that the cost of a relatively small engine driving an exhauster to maintain subatmospheric pressure in the containment and, at the same time, provide inert gas to maintain a sufficiently low O_2 concentration could be economically unfeasible.

FUNDAMENTAL ASPECTS

All the phenomena of primary concern to the task of the committee are dominated by the turbulent flow conditions under which they occur. Proper appreciation of the essential features of turbulence is therefore indispensable for the assessment of their effects. Fortunately, fundamental knowledge of turbulent flow and combustion dynamics has

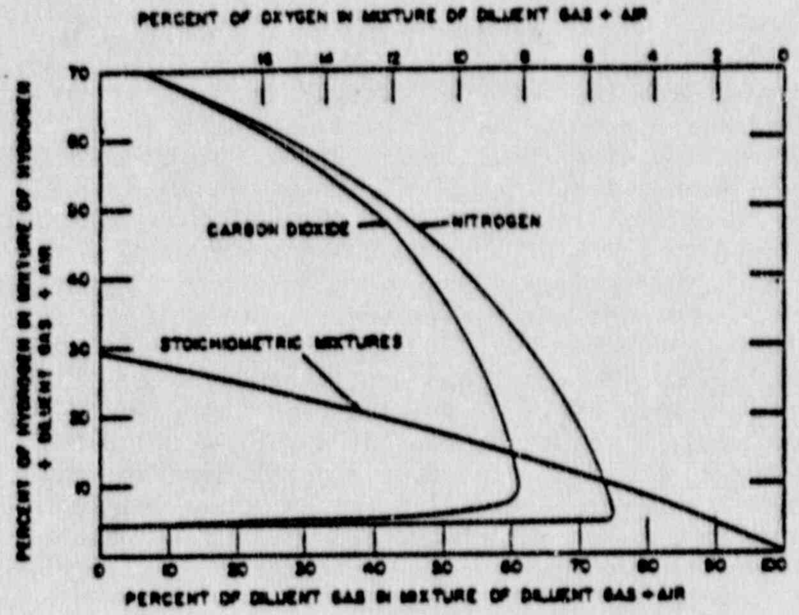

FIGURE C-3 Limits of inflammability of hydrogen in air diluted with CO_2 and N_2.

Source: Lewis and von Elbe (1961).

been advanced significantly over the last decade; unfortunately, this knowledge has not yet been disseminated sufficiently well for the realization of its benefits.

The major purpose of this section, then, is to present highlights of modern concepts on turbulent flow and their effects upon flame acceleration that may lead to the development of detonation. It should be noted that this topic is quite wide, so that it cannot be covered in a short note without vast oversimplifications. By the same token, citation of the impressive literary background on which it is based has to be, for the sake of brevity, omitted (Oppenheim, 1985).

Turbulent Flow

Traditionally, turbulent flow has been treated as a phenomenon associated intimately with fluctuations around an average. That is how it appeared, indeed, to experimenters since the founding of this branch of science in the pioneering study of Osborne Reynolds. It is for this reason that its theory was essentially statistical, manifesting the predominant concern over its apparently chaotic nature. At the same time its physical effects largely have been considered the major cause of energy dissipation. The stochastic theory was in this respect most satisfactory.

Over the last decade it became apparent that turbulence has the attribute of coherence, whereby it has the capability of concentrating rather than just dissipating--a feature providing a completely different, in effect opposite, view upon this phenomenon than realized so far. Effects that were thought of before as characteristic of the breakdown of laminar flow (e.g., the Von Karman vortex street behind a rod, the Kelvin-Helmholz vortex generation at the interface between fluids of different densities, the Tollmien-Schlichting collapse of laminar boundary layer, the Taylor instability in Couette flow, to mention just a few) were found now to occur in their equivalent form under fully developed turbulent flow conditions. However, in the latter case, instead of being on the threshold of laminar and turbulent flow in the parameter space, they were found to be at the boundary between turbulent and inviscid regions in the physical space.

The concomitant switch from the viscous to the inviscid aspect of fluid mechanics has a profound effect upon the interpretive and predictive analysis of turbulent flow phenomena. In particular, it brings to the fore basic flaws in most of the computational techniques used today.

They are two major factors contributing to this state of affairs namely, (1) presumptuous algorithms, and (2) premature averaging. They briefly are elucidated here.

<u>Presumptuous</u> <u>algorithms</u> are causing more confusion than providing elucidation for turbulent flow phenomena. To assess the gravity of the situation that they create, a remark on algorithms in popular practice is in order. At the risk of a gigantic oversimplification, computational techniques currently used for the analysis of flow phenomena may be divided into two categories: lumped-parameter and finite-difference.

Lumped-parameter analysis is based on the postulate that the flow system can be considered as a composite of a set of suitably interconnected subsystems. This reduces the problem, specified essentially in terms of partial differential equations, into a set of ordinary differential equations--a transformation associated inherently with misinterpretation of the effect of boundary conditions. Although this simplistic approach may be adequate for many practical problems of a steady-state nature, it is definitely inappropriate for the typically transient, highly time-dependent phenomena of an accidental nature, especially when escalation is of particular interest. The major reason for this is that one excludes them from consideration of the most essential feature of the Navier-Stokes equations, namely, their elliptic character whereby any local variation has an immediate effect upon the whole field. In a lumped-parameter network, on the contrary, local effects propagate through the field at finite speeds governed by impedances of branches and capacitances of nodes.

Finite-difference analysis is, as a rule, associated with the effects of numerical viscosity which is detrimental to the attainment of a solution for a slightly viscous flow, as is most characteristically the case in turbulent combustion. Numerical viscosity is introduced intrinsically with the specification of the finite difference technique when the question is posed as to what the value of an unknown is at a given point and time. In the finite difference solution of Navier-Stokes equations, such a question invokes interpolation whose effects are diffused throughout the field as if it were induced by viscosity. The computational error in the solution is consequently proportional to the Reynolds number, imposing a serious drawback upon such techniques for the analysis of the essentially high Reynolds number phenomena of turbulent combustion.

Premature averaging is the salient feature of the vast majority of turbulent combustion theories in vogue today. Its consequences are particularly detrimental to the analysis of transient turbulent flow phenomena. The source of trouble lies in averaging the equations right at the outset, rather than seeking the average of the solutions upon their final evaluation. This was reiterated recently by Chorin (1985) more or less as follows.

It is quite unsafe to average the equations in the hope that the solution of the averaged equations is related to the average solution of true equations. In general, the combustion in an averaged flow field is very different from the average combustion in an unaveraged flow system. In dealing with large fluctuations, and a reacting turbulent flow certainly is full of them, theories based on averaging are likely to be wholly unreliable. Furthermore, the problem of constructing realizable closures is unresolved, whereas, to make matters worse, the averages that one obtains from averaged equations may fail to be the averages of any functions whatsoever, let alone the averages of real solutions of the equations one is trying to solve.

As a consequence of the presumptuous algorithms and premature averaging, most of the computational techniques used today exert an inhibiting effect upon the constructive features of turbulence, that is, aspects which are of particular relevance to the escalation of the combustion process leading to the onset of explosive detonation.

Both these flaws of conventional techniques are obviated by the Langrangian particle techniques pioneered by Chorin's (1985) random vortex method. Their major attribute is the severance of dependence upon an a priori prescribed spatial grid and the capability of treating unaveraged variables. Their drawback is the increased amount of computational effort required for the solution, limiting their applicability to relatively simple cases. The net gain obtained by their use is then in getting a better grasp of the mechanism of the constructive effects of turbulence, exhibited by the formation of the large-scale vortex structure, and its consequences, rather than in the extrapolation or scaling-up of experimental data.

One should realize that the solution of the equations of motion provides, in effect, information on the consequences of the initial and boundary conditions. Thus, once a solution is obtained, the conventional nondimensional scaling parameters, such as the Reynolds numbers, can be applied only if the initiation of the process and the geometry of the enclosure are the same--a conclusion that is of relatively little practical value for the individual that may overexpeditiously wish to have a more general scaling law, preferably in scalar form, as is usually the case.

Flame Acceleration

The flame front in a flow field acts, in essence, as an interface, a boundary between the burnt and unburnt gases. Its propagation mechanism consists of the following four components:

1. advection by the flow field,
2. self-advancement in the direction normal to its surface at a so-called normal burning speed--the eigenvalue of the system,
3. action as a velocity source brought about by the expansion due to the exothermicity of the combustion process, and
4. production of vorticity as a consequence of the baroclinic effect.

It is by virtue of the last two components that the flame exerts a feedback upon the flow field, contributing toward its growth. At the same time the flame gets stretched by being pulled apart along its frontal surface by the flow field in which it resides.

In turbulent combustion, the acceleration of the process is due to the generation, growth, and shedding of large-scale vortices. The flame front tends to acquire the role of a contact boundary, stretched to the limit of its endurance at a contour of a large-scale vortex. Its acceleration is then caused primarily by the volumetric expansion of the vortex due to the exothermic process taking place inside of it, while the residence time of reacting particles is enhanced by the recirculation that it induces, with both effects having a profound influence upon the escalation of the combustion process.

Development of Detonation

Since the 1950s there has been over 25 year of effort spent by a multitude of scientific groups scattered all over the world (in the Soviet Union, West Germany, France, England, Canada, United States, and Japan) on the study of the development and structure of detonation waves. Although this effort was based on a distinguished background of knowledge, founded by such great men of science as Le Chatelier, Rankine, von Neumann, and Zeldovich, to mention just a few, a good deal of it was initially directed to provide straightforward answers to questions concerning such practical aspects as the detonability limit and the detonation induction distance - the latter representing the salient feature of what became known as DDT, the deflagration to detonation transition. The major problem with this type of quest was that it was performed blindly and, as a consequence, could not produce satisfactory answers. As soon as correlation formulas were developed, experimental evidence was produced disproving their validity.

It is primarily due to the development of optical experimental techniques, especially pulsating, laser-powered, high-frequency (up to megahertz) schlieren cinematography, that the real nature of the phenomenon was discovered. The essence of truth turns out to be extremely simple. The process is by definition time dependent, and in the course of development, its history is dominated by the generation and subsequent effects of a highly turbulent flow. To make matters more interesting, the major culprits in creating such flow conditions are acoustic effects of small disturbances produced by the accelerating flame. These waves, or wavelets, coalesce to form shock fronts which interact in a variety of ways to give rise to an unrepeatable set of conditions that defy description by a unique set of global criteria.

The progress made as a consequence of the 25-year effort has been recorded in scientific journals, proceedings of combustion symposia, and in particular, the biennial international colloquia on dynamics of explosions and reactive systems. The tenth colloquium, after 20 years of activity, was held in Berkeley in August 1985. The development and structure of detonation waves evidently has been considered to have reached satisfactory solutions, so that major emphasis was placed this time upon the fluid mechanic aspects of combustion. Proceedings of this colloquium are to be published soon by the American Institute of Aeronautics and Astronautics.

In summary, answers to practically all the rational questions one may pose concerning the development and structure of gaseous detonations, with special emphasis placed upon hydrogen as the representative fuel, are available today. At the same time, they provide rational reasons that most of the practical questions concerning this subject are ill-posed and, hence, irrational--to great chagrin, no doubt, of the questioners.

RECOMMENDATIONS

1. All future efforts should be directed toward the study of alternative means for the prevention of hydrogen combustion hazard rather than the glow coil technique--the worst possible choice, primarily as a consequence of its passive nature. The few alternatives presented here should be regarded just as examples of what kind of measures can be devised. A properly mounted engineering effort is bound to produce much better and more effective means.
2. Due recognition should be given to the fact that in providing a seal of approval to the principle of deliberate burning, admission is made that it is not the process of hydrogen combustion that is hazardous, but just the onset of the detonation that it may cause; both events should be avoided by all means.
3. It should be realized that neither experiments on the development of detonation nor large-scale tests, let alone elaborate computer codes, can provide a satisfactory solution. Large-scale experimental demonstrations of the nonoccurrence of hazard at the sufficiently low level of probability one wishes to attain is simply unfeasible. One has no other recourse than to trust the theory.
4. Proper cognizance should be taken of the fact that in theory transition to detonation cannot be accomplished without an explosion-in-explosion--a blast wave by which it is triggered. The specific exothermic power required for this purpose cannot be lower than that driving a self-sustained detonation. Experimental data on the decay of such detonations therefore should be considered of much greater significance in establishing a limit of hazard than the tests of the nondevelopment of explosion. As a consequence, large-scale demonstration tests as well as their modeling analyses should be considered unsatisfactory and inadequate for the establishment of a limit of hazard at the desired extremely low level of probability. Concomitantly, the coverage of these topics in the report of the committee should be cut down to a minimum.
5. A critical assessment of the modeling techniques used and/or developed for the hydrogen combustion problem, as well as recommendations on their future use and/or development, should be considered to be outside the scope of the committee. Numerical analysis of transient flow systems should be recognized as a subject of great concern and significant cost to the government. Setting proper standards in this respect should be of much more general significance than our committee could provide. The Energy Engineering Board of the National Research Council should consider the formation of a special committee for this purpose. The cost to the office that would finance it, such as the Nuclear Regulatory Commission, should be significantly lower than the expense of supporting further work in this field. Members of this committee should be authorities in numerical fluid mechanics, rather than developers of codes, so that they could provide unbiased advice on strictly academic grounds without the handicap of vested interest in any particular methodology.

APPENDIX D

COMMENTS ON ISSUES RAISED IN MINORITY REPORT (APPENDIX C)

Norman C. Rasmussen, Chairman
Herbert J.C. Kouts, Vice Chairman
Eli K. Dabora
Gerard M. Faeth
Daniel J. Seery
Robert G. Zalosh

The statement of Professor Oppenheim (Appendix C) contains five recommendations, many of which were discussed by the committee and not included in the report, either because they were felt to be beyond the scope of our charge or a majority of the committee disagreed with them. We feel compelled to respond to them.

THE VALUE OF DELIBERATE IGNITION

In a large fraction of the hypothetical accidents analyzed, the hydrogen is released into the containment at an average rate of a few tenths of a kilogram per second. In many scenarios this release may be a series of bursts at 10 to 100 times higher rates as, for example, when relief valves open and close. Typically, such a release might continue for an hour or more. The points in the system from which the release might occur are almost all below the reactor floor. The goal of the igniter approach is to burn the hydrogen before a large amount of it can collect in the large volume above the reactor floor, thereby greatly reducing the probability that the hydrogen in this large volume might reach a detonable concentration. This approach is based on calculations that lead one to the conclusion that the containment cannot easily withstand a global detonation. To increase the likely level of success of this approach, a large number (>60) of igniters are used, with at least one in every compartment below the reactor floor and a number above the reactor floor as well. The remainder of the committee concluded that this is a reasonable approach and much preferred to doing nothing and waiting for a possible ignition by a random source later in the release after a significant amount of hydrogen has accumulated. In our judgment, the probability that a random source will eventually ignite a combustible mixture before it can be vented or recombined is essentially unity. Thus the committee concluded that given a hydrogen release, the sooner ignition occurs, the lower the risk of a containment-damaging detonation.

DELETERIOUS EFFECTS OF IGNITERS

It is known that once ignition occurs, the flame may start in a lean concentration and accelerate back toward a higher concentration region nearer the hydrogen source. Under certain conditions (see Chapter 5) this accelerating flame can cause the hydrogen to detonate. Thus, the igniter may be the cause of a detonation. Because of the large number of igniters, we conclude that it is highly likely that any potential detonation would be limited to a local region. In addition, in accidents where the hydrogen-generating process is terminated after a short time, the amount of hydrogen, if diluted in the containment, might be below the flammable limit. In this case the igniters might cause a fire in a reactor compartment that would not have occurred if the hydrogen were allowed to become dilute in the containment volume. Because of the limited amount of hydrogen generated, such an event is not of major concern. However, one cannot avoid the conclusion that in certain postulated accident scenarios the presence of igniters may aggravate the situation. Nevertheless, we conclude that the probability that the effects of igniters will be beneficial overwhelmingly outweighs the deleterious effects that can be postulated.

ALTERNATIVES TO IGNITERS

The committee did not consider methods for controlling hydrogen other than those currently in use. Professor Oppenheim suggests several possibilities that he feels would be better than deliberate ignition. On the surface, each seems to be a possible alternative method for reducing the likelihood of a detonation. It is possible to postulate ways in which each might fail to be effective. A careful analysis of benefits and liabilities of each of these systems compared to those of igniters would be worthwhile. Such an analysis seemed far beyond the committee charge, so it was not undertaken as part of this review.

LARGE-SCALE TESTING

We agree that it is not feasible to conduct enough large-scale tests to prove, to a high degree of certainty, the lowest concentration of hydrogen at which a detonation might occur. Theory must certainly be used, but of course, the theory must be consistent with experiment. We see no alternative but to use large codes to estimate the hydrogen concentration in the containment. A few large-scale experiments to verify that there are no major errors in extrapolation from small-scale tests seem appropriate.

PROPOSED COMMITTEE ON MODELING TECHNIQUES

Professor Oppenheim suggests that the assessment of modeling should be outside the committee scope and should be left to a committee more expert in this methodology. Because of numerous important applications of these models to a variety of problems, we believe that the formation of such a committee is a good idea.

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11. ABSTRACT *(200 words or less)*

Unresolved Safety Issue (USI) A-48 arose as a result of the large amount of hydrogen generated and burned within containment during the Three Mile Island accident. This issue covers hydrogen control measures for recoverable degraded core accidents for all boiling-water reactors (BWRs) and those pressurized-water reactors (PWRs) with ice-condenser containments. The Commission and the nuclear industry have sponsored extensive research in this area, which has led to significant revision of the Commission's hydrogen control regulations, given in Title 10, Code of Federal Regulations, Part 50 (10 CFR 50), Section 50.44. BWRs having Mark I and II containments are presently required to operate with inerted containment atmospheres which effectively prevent hydrogen combustion. BWRs with Mark III containments and PWRs with ice-condenser containments are now required to be equipped with hydrogen control systems to protect containment integrity and safety systems inside containment. Industry has chosen to use hydrogen igniter systems to burn hydrogen produced in a controlled fashion to prevent damage. An independent review by a Committee of the National Research Council concluded that, for most accident scenarios, current regulatory requirements make it highly unlikely that hydrogen detonation would be the cause of containment failure. On the basis of the extensive research effort conducted and current regulatory requirements, including their implementation, the staff concludes that no new regulatory guidance on hydrogen control for recoverable degraded-core accidents for these types of plants is necessary and that USI A-48 is resolved.

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