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MEMORANDUM FOR: Chairman Palladino
Commissioner Gilinsky
Commissioner Ahearne
Commissioner Roberts
Commissioner Asselstine

FROM: William J. Dircks
Executive Director for Operations

SUBJECT: Sequoyah SER Supplement On Hydrogen Mitigation System

Enclosed are copies of the **proposed** Supplement to the Sequoyah Safety Evaluation Report which updates the staff's evaluation of issues related to the hydrogen mitigation system for Units 1 and 2. Subject to the satisfactory resolution of two issues dealing with the TAYCO igniter surface temperature and the number of units in the upper compartment, we conclude that the license condition on hydrogen control is satisfactorily resolved.

The system, designated by TVA as their permanent hydrogen mitigation system, is being installed in Unit 1 and is to be installed in Unit 2 during the first refueling outage of that unit. Briefing slides are included for a forthcoming meeting on this subject matter.

Also, copies of the TVA Executive Summary Report are enclosed which sets forth the basis for TVA concluding that the system will perform its intended function in a manner that provides adequate safety margin.

(Signed) William J. Dircks

William J. Dircks
Executive Director for Operations

cc w/encl

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D:NRR	D:DE	D:DST	D:DSI	EDO
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No legal objection

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BRIEFING OUTLINE

I. CHRONOLOGY

II. REVIEW OF PERMANENT HYDROGEN MITIGATION SYSTEM

III. OPEN ISSUES

IV. CONFIRMATORY ITEMS

V. LICENSE CONDITIONS

CHRONOLOGY

SER ISSUED	MARCH 1979
LOW POWER LICENSE ISSUED	FEBRUARY 29, 1980
FULL POWER LICENSE ISSUED	SEPTEMBER 17, 1980
TVA EXECUTIVE SUMMARY REPORT ISSUED	SEPTEMBER 27, 1982
SSER #6 ISSUED	DECEMBER 1982

ORIGINAL LICENSE CONDITION

HYDROGEN CONTROL MEASURES (SECTION 22.2.II.B.7

(1) BY JANUARY 31, 1981, TVA SHALL BY TESTING AND ANALYSIS SHOW TO THE SATISFACTION OF THE NRC STAFF THAT AN INTERIM HYDROGEN CONTROL SYSTEM WILL PROVIDE WITH REASONABLE ASSURANCE PROTECTION AGAINST BREACH OF CONTAINMENT IN THE EVENT THAT A SUBSTANTIAL QUANTITY OF HYDROGEN IS GENERATED.

(2) FOR OPERATION OF THE FACILITY BEYOND JANUARY 31, 1982, THE COMMISSION MUST CONFIRM THAT AN ADEQUATE HYDROGEN CONTROL SYSTEM FOR THE PLANT IS INSTALLED AND WILL PERFORM ITS INTENDED FUNCTION IN A MANNER THAT PROVIDES ADEQUATE SAFETY MARGINS.

(3) DURING THE INTERIM PERIOD OF OPERATION, TVA SHALL CONTINUE A RESEARCH PROGRAM ON HYDROGEN CONTROL MEASURES AND THE EFFECTS OF HYDROGEN BURNS ON SAFETY FUNCTIONS AND SHALL SUBMIT TO THE NRC QUARTERLY REPORTS ON THAT RESEARCH PROGRAM.

CURRENT LICENSE CONDITION

HYDROGEN CONTROL MEASURES (SECTION 22.2.11.B.7)

(1) PRIOR TO STARTUP FOLLOWING THE FIRST REFUELING OUTAGE, THE COMMISSION MUST CONFIRM THAT AN ADEQUATE HYDROGEN CONTROL SYSTEM FOR THE PLANT IS INSTALLED AND WILL PERFORM ITS INTENDED FUNCTION IN A MANNER THAT PROVIDES ADEQUATE SAFETY MARGINS.

(2) DURING THE INTERIM PERIOD OF OPERATION, TVA SHALL CONTINUE A RESEARCH PROGRAM ON HYDROGEN CONTROL MEASURES AND THE EFFECTS OF HYDROGEN BURNS ON SAFETY FUNCTIONS AND SHALL SUBMIT TO THE NRC QUARTERLY REPORTS ON THAT RESEARCH PROGRAM.

(A) TVA SHALL AMEND ITS RESEARCH PROGRAM ON HYDROGEN CONTROL MEASURES TO INCLUDE, BUT NOT BE LIMITED TO, THE FOLLOWING ITEMS:

1) IMPROVED CALCULATIONAL METHODS FOR CONTAINMENT TEMPERATURE AND ICE CONDENSER RESPONSE TO HYDROGEN COMBUSTION.

2) RESEARCH TO ADDRESS THE POTENTIAL FOR LOCAL DETONATION.

3) CONFIRMATORY TESTS ON SELECTED EQUIPMENT EXPOSED TO HYDROGEN BURNS.

4) NEW CALCULATIONS TO PREDICT DIFFERENCES BETWEEN EXPECTED EQUIPMENT TEMPERATURE ENVIRONMENTS AND CONTAINMENT TEMPERATURES.

5) EVALUATE AND RESOLVE ANY ANOMALOUS RESULTS OCCURRING DURING THE COURSE OF ITS ONGOING TEST PROGRAM.

(B) A SCHEDULE FOR CONFIRMATORY TESTS SHALL BE PROVIDED BY TVA CONSISTENT WITH THE REQUIREMENT TO MEET SECTION (22)D.(2) OF THE LICENSE.

PERMANENT HYDROGEN MITIGATION
SYSTEM

PRINCIPAL REVIEW AREAS

- o PHMS DESIGN
- o HYDROGEN CONTROL RESEARCH
  - COMBUSTION
  - MIXING
  - DETONATIONS
- o DEGRADED CORE ACCIDENTS & HYDROGEN GENERATION
- o CONTAINMENT HYDROGEN ANALYSIS
- o SEQUOYAH STRUCTURAL CAPACITY
- o ESSENTIAL EQUIPMENT SURVIVABILITY

OPEN ISSUES

- PERFORMANCE OF TAYCO IGNITERS IN CONTAINMENT UPPER COMPARTMENT
- NUMBER AND LOCATION OF IGNITERS IN UPPER COMPARTMENT

CONFIRMATORY ITEMS

<u>ANALYTICAL</u>

- LOCAL DETONATIONS
- CLASIX/COMPARE CODE WORK

<u>EXPERIMENTAL</u>

- EQUIPMENT SURVIVABILITY
- COMBUSTION EFFECTS AT LARGE SCALE
- COMBUSTION PHENOMENA

PROPOSED LICENSE CONDITIONS
FOR UNIT 1

FOUR (4) ADDITIONAL IGNITER UNITS SHALL BE INSTALLED IN THE SEQUOYAH UNIT 1 CONTAINMENT UPPER CONTAINMENT COMPARTMENT IN LOCATIONS ACCEPTABLE TO THE NRC STAFF PRIOR TO STARTUP FOLLOWING THE SECOND REFUELING OUTAGE.

ADDITIONAL TESTS SHALL BE PERFORMED ON THE TAYCO IGNITER TO DEMONSTRATE THAT THE IGNITERS WILL MAINTAIN AN ADEQUATE SURFACE TEMPERATURE IN A SPRAY ENVIRONMENT SUCH AS THAT EXPECTED IN THE UPPER COMPARTMENT OF THE ICE CONDENSER CONTAINMENT. THESE TESTS SHALL BE COMPLETED BY SEPTEMBER 1983.

NUREG-0011
Supplement No. 6

Safety Evaluation Report
related to the operation of Sequoyah Nuclear Plant, Units 1 and 2

Docket Nos. 50-327 and 50-328

Tennessee Valley Authority

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

November 1982

ABSTRACT

Supplement No. 6 to the Safety Evaluation Report related to the operation of the Tennessee Valley Authority's Sequoyah Nuclear Plant, Units 1 and 2, located in Hamilton County, Tennessee, has been prepared by the Office of Nuclear Reactor Regulation of the U. S. Nuclear Regulatory Commission. The purpose of this supplement is to update the staff's evaluations of the issues related to the hydrogen mitigation system identified in the SER and previous supplements as needing resolution.

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1 INTRODUCTION

The purpose of this Supplement 6 to the Sequoyah Safety Evaluation Report (SER) is to update the staff's evaluation of the issues related to the hydrogen mitigation system that is being installed in Unit 1 and is to be installed in Unit 2 during the first refueling outage of that unit. Except where noted, the material herein supplements the information that has been reported previously. The following sections of this supplement are numbered to correspond to those in the SER and earlier supplements.

This supplement provides the basis for the staff's concluding that sufficient information is available to permit the installation and operation of a modified hydrogen mitigation system for Sequoyah Unit 1.

22 TMI-2 REQUIREMENTS

II.B.7 Analysis of Hydrogen Control

1 Background

The staff's licensing requirements relative to the provisions for hydrogen control beyond those prescribed in 10 CFR 50.44 have evolved from numerous deliberations among the Nuclear Regulatory Commission (Commission), the Advisory Committee on Reactor Safeguards (ACRS), the NRC staff, and applicants and licensees. In summary, the Commission's requirement for ice condenser containments is that a supplemental hydrogen control system be provided so that the consequences of the hydrogen release generated during the more probable degraded core accident sequences do not involve a breach of containment nor adversely affect the functioning of essential equipment.

In Supplements 4 and 5 to the Sequoyah SER (NUREG-0011), the staff concluded that the interim distributed ignition system (IDIS) installed at Sequoyah Units 1 and 2 is acceptable as an interim hydrogen control measure for degraded core accidents. However, the staff recommended that the detailed review of the distributed ignition system continue, so that a number of issues related to degraded core hydrogen control could be more thoroughly investigated before it endorsed a long-term commitment to deliberate ignition. These issues included items related to combustion phenomena as well as further consideration of a spectrum of degraded core accident sequences.

Based on these recommendations, the operating licenses of Sequoyah Units 1 and 2 were conditioned to require that the licensee, the Tennessee Valley Authority (TVA), continue research programs on hydrogen control measures and the effects of hydrogen-burn safety functions during the interim period of operation. The research program was to include: (1) improvement of calculational methods for containment temperature and ice condenser response to hydrogen combustion, (2) research to address the potential for local detonation, (3) confirmatory tests on selected equipment exposed to hydrogen burns, (4) new calculations to predict differences between expected equipment temperature environments and containment temperatures, and (5) evaluation and resolution of any anomalous results occurring during the course of the test program. The license condition required that TVA, by the end of the first refueling outage, provide the bases for a Commission determination that an adequate hydrogen control system for the plants is installed and will perform its intended function in a manner that provides adequate safety margins.

As part of its research activities, TVA in cooperation with Duke Power and American Electric Power (AEP) continued to investigate alternative measures of hydrogen control. As a result of continued studies, TVA has concluded that a deliberate ignition system, similar to the IDIS, provides adequate safety margins in controlling the consequences of degraded core accidents. The new system, designated the permanent hydrogen mitigation system (PHMS), is to be installed in Sequoyah Unit 1. The PHMS is identical in concept to the interim system but provides system design improvements. A detailed discussion of the PHMS is provided below.

The approach taken by TVA for establishing that the PHMS provides adequate safety margins relies on analytical modeling of the containment and equipment response to the degraded-core event. Because the models involve simplifying assumptions and input parameters describing such complex phenomena as containment mixing, flame speeds, and equipment heatup, the utility research program serves to verify key assumptions in the analyses.

2 System Description

The PHMS is a system of igniters and ancillary equipment TVA has installed within the containment of Sequoyah Units 1 and 2. The igniters are designed to ensure a controlled burning of hydrogen in the unlikely event that excessive quantities of hydrogen, well beyond the design bases required by 10 CFR 50.44, are generated as a result of a postulated degraded core accident. The PHMS is designed to promote the combustion of hydrogen in a manner such that containment integrity is maintained.

TVA has selected and tested a 120-V ac hermetically sealed thermal igniter manufactured by Tayco Engineering as the igniter to be installed in the PHMS. The heating element is formed into a cylindrical coil approximately 1.75-in. long and 0.75-in. in diameter. Power is supplied directly to the igniter at 120 V ac. The igniter is mounted in a National Electrical Manufacturers Association (NEMA) Type 4 enclosure with the heating element protruding. This enclosure is designed to remain watertight under various environmental conditions, including exposure to water jets. A spray shield is provided above the igniter to protect it from a direct spray.

The igniters in the PHMS are equally divided into two redundant groups, with 16 separate circuits per group, each with an independent circuit breaker and two igniters per circuit. Each group has independent and separate control, power, and igniter locations that ensure adequate coverage even in the event of a single failure. Manual actuation capability for each group is provided in the main control room (one switch per group), along with the status (on-off) of each group.

The igniters are powered from Class 1E power panels that have normal and alternate power supply from offsite sources. In the event of a loss of offsite power, the igniters would be powered from the emergency diesel generators. Group A igniters receive power from the train A diesels, and group B igniters from the train B diesels. In addition, the igniters will be seismically supported.

The permanent hydrogen mitigation system installed in Sequoyah Units 1 and 2 consists of 64 igniter assemblies distributed throughout the upper, lower, and ice condenser compartments. Following a degraded core accident, any hydrogen that is produced would be released into the lower compartment. To cover this region, 22 igniters (equally divided between trains) will be provided. Eight of these will be distributed on the reactor cavity wall exterior and crane wall interior at an intermediate elevation. Two igniters will be located at the lower edge of each of the five steam generator and pressurizer enclosures, two in the top of the pressurizer enclosure, and another pair above the reactor vessel in the cavity.

Any hydrogen not burned in the lower compartment would be carried up through the ice condenser and into its upper plenum. Because steam would be removed from the mixture as it passes through the ice bed, thus concentrating the hydrogen, mixtures that were nonflammable in the lower compartment would tend to become flammable in the ice condenser upper plenum. This phenomenon is supported by the CLASIX containment analysis code, discussed later in this SSER, which predicts that more sequential burns will occur in the upper plenum than in any other region. Controlled burning in the upper plenum is preferable because upper plenum burns involve smaller quantities of hydrogen and allow for the expansion of the hot gases into the upper compartment, thereby reducing the peak pressure.

TVA has chosen to take advantage of the beneficial characteristics of combustion in the upper plenum by distributing 16 igniters around it. The igniters are located on the containment shell side of the upper plenum at 16 equally spaced azimuthal locations. To handle any accumulation of hydrogen in the upper compartment, four igniters will be located in the upper compartment dome. Additional igniters are located at lower elevations in the upper compartment to take advantage of upward flame propagation at lower hydrogen concentrations; specifically, four igniters are located near the top inside of the crane wall, and one is located above each of the two air return fans. The air return fans provide recirculation flow from the upper compartment through the dead-ended volume and back into the lower compartment. To cover the deadended region, there will be a pair of igniters in each of the eight rooms through which the recirculation flow passes.

The staff has reviewed the number and locations of igniters provided in the PHMS and finds the system layout acceptable. The staff notes, however, that the PHMS would be improved by locating the upper plenum igniters alternately between the containment shell side and the crane wall side of the upper plenum in a staggered fashion, and locating additional igniters at lower elevations in the upper compartment. Installation of upper plenum igniters in a staggered arrangement will further reduce the likelihood of flammable mixtures bypassing the igniters, while additional upper compartment igniters would provide added assurance that any burning in the upper compartment will occur as discrete burns at low hydrogen concentrations characterized by upward flame propagation, rather than as a global burn. TVA is unable to relocate upper plenum igniters or add more upper compartment igniters during this refueling of the Sequoyah Unit 1. The staff may require TVA to relocate the upper plenum igniters in a staggered arrangement before restart following the next refueling for Sequoyah Unit 1 depending on the outcome of certain confirmatory testing as detailed in Section 10. The staff considers the present igniter locations to be acceptable for operation during the next cycle. However, installation of additional igniters in the upper compartment will provide greater margin of safety from events that could result in releases of hydrogen to the upper compartment. TVA has indicated a willingness to install four additional igniters in the upper compartment. The adequacy of the number and locations of the upper compartment igniters will be confirmed on the basis of certain large-scale confirmatory tests to be conducted at the Nevada Test Site in early 1983 as part of a joint Electric Power Research Institute (EPRI)/NRC hydrogen research program. These tests will include dynamic simulations of degraded core accidents at a scale comparable to the actual containment building, and will serve to identify scale effects on combustion phenomena. Upon completion of those tests, the staff will provide recommendations regarding the adequacy of the upper compartment igniter coverage and any required design enhancements.

With respect to operating procedures, the TVA emergency operating instructions direct the operator to actuate the PHMS following any reactor trip or safety injection initiation. These directions are included in the immediate actions of the diagnostic procedure used following reactor trip or safety injection, and actuation of the PHMS is verified in the procedure for responding to a loss-of-coolant accident (LOCA). Thus, the operator will have sufficient time to actuate the PHMS manually for any event in which it would be required. As recommended in SSER 5, the air handling units used for normal refrigeration in the ice condenser will be tripped for both units for accidents in which the PHMS is actuated. The procedures call for PHMS to remain actuated until the unit reaches safe cold shutdown and any threats as a result of hydrogen release are eliminated. The staff concludes that these procedural instructions are adequate for actuation and termination of the PHMS. In addition, the emergency operating instructions will be upgraded in response to TMI Action Plan Item I.C.1 and Commission Action on SECY-82-111. The upgraded instructions will address operation of hydrogen mitigation systems based on inadequate core cooling symptoms and containment pressure and hydrogen concentrations. The Tayco igniters have been subjected to endurance testing for a period of approximately 2 weeks.

To ensure that the PHMS will function as intended, TVA has proposed a preoperational and surveillance testing program similar to that performed for the IDIS. Preoperational testing, to be performed before restart after refueling, will verify that the current drawn by each group of igniters is within tolerance, and that the temperature of the igniter is at least 1700°F. During the preoperational tests the current in each circuit will be measured and the results used as the baseline for future surveillance tests. The igniter system will be subjected to periodic surveillance testing; this testing will consist of energizing the PHMS in the main control room and taking current readings of the circuits. If the current readings do not compare favorably with current measurements taken during preoperational testing, all igniters will be individually inspected to ensure their operability. The staff will also require that igniter temperatures be measured at specified intervals.

The operability of at least 31 of the 32 igniters per train will maintain an effective coverage throughout the containment, if there are no inoperable igniters on corresponding redundant circuits that provide coverage for the same region. The two trains of igniters should be operable during operational modes 1 and 2.

3 Combustion/Igniter Testing

In support of the IDIS, TVA, Duke Power, and AEP conducted two testing programs to obtain information pertinent to the performance characteristics of the glow plug igniters. Preliminary screening and qualification testing was performed at TVA's Singleton Laboratory. Combustion tests using the glow plugs were performed by Fenwal, Inc. to study igniter performance under various environmental conditions (Cross, 1980; Mills, 1981). Based on the results of these programs, the staff concluded in Sequoyah SSER 4 that the glow plug igniter would perform its intended function under various conditions.

During the past 2 years, to evaluate further the efficacy of ignition systems and to investigate possible enhancements to proposed deliberate ignition systems, the ice condenser utility owners and the Electric Power Research Institute (EPRI) have sponsored several test programs. This work is summarized in the TVA Executive Summary Report dated September 27, 1982. Basic combustion and igniter studies were conducted in a test program conducted at the Whiteshell Nuclear Research Establishment to evaluate the glow plug and Tayco igniters, along with testing to investigate the following items: lean mixture combustion, rich mixture deflagrations, fan- and obstacle-induced turbulence, and the effects of a compartmentalized geometry. To determine if a water spray/fog consisting of smaller water droplets than conventional containment spray systems would improve the overall performance of deliberate ignition systems, the utilities sponsored testing with the Factory Mutual Corporation and Acurex Corporation. Factory Mutual investigated, in a small-scale facility, the pressure suppression effects of a small droplet spray/fog. Acurex addressed the same phenomenon, as well as the effects of igniter location, in a larger scale vessel.

3.1 The Whiteshell Test Program

The experimental program carried out at Whiteshell consisted of small-scale igniter testing and large-scale combustion testing (Mills, 1982a, b, c; Kammer, 1982).

Small-scale tests were performed in a 17-liter vessel to investigate the effect of igniter surface temperature and type on the lower flammability limits of lean hydrogen-air-steam mixtures. The small-scale test program consisted of three phases. Data on the lower flammability limit were obtained in Phases 1 and 2 using a GMAC-7G glow plug operating at 14 and 12 V, respectively. In Phase 3 the tests were repeated using the Tayco igniter. Hydrogen concentrations were varied between 4 and 15%, and steam concentrations varied between 0 and [illegible] in all three phases.

Evaluation of the experimental data indicates that for quiescent mixtures, ignition occurs below hydrogen concentrations of 8.0% for steam concentrations of up to 30%. Consistent with other test data for steam concentrations above 30%, the flammability limit was shifted upward to higher hydrogen concentrations. The igniter consistently initiated combustion of mixtures with steam concentrations up to approximately 60%. Experimental results showed reliable ignition of turbulent mixtures with hydrogen concentrations of 5%, even for steam concentrations up to 40%.

The surface temperature of the igniter at the time of ignition was measured for each test. For dry mixtures, the Tayco igniter surface temperature at ignition was approximately 1200°F. Test data show that the igniter surface temperature at the time of ignition increases with steam concentration. This is consistent with the trend observed for GM glow plug igniters.

The large-scale tests were performed at Whiteshell using a 7.5-ft diameter sphere. The purpose of the tests was to investigate four different items: lean mixture combustion, rich mixture deflagrations, fan- and obstacle-induced turbulence, and compartmentalized geometry effects. Spark ignition was used in these tests.

In Phase 1 of the program, lean mixture tests were performed in the sphere to investigate the combustion phenomena under various conditions of steam and fan-induced turbulence. Hydrogen concentrations were varied from approximately 5 to 10 volume percent, and steam from 0 to 30%. Fans were activated in several of the tests.

Test results for quiescent mixtures with bottom ignition indicate that combustion was initiated at a 5 volume percent hydrogen concentration. Only about 20% of the hydrogen was burned at this concentration. For an 8% hydrogen concentration, virtually complete combustion was observed. These results are in general agreement with previously published data on the flammability of lean mixtures. Tests with steam present show that the addition of 15% steam does not have a significant effect on the completeness of burn.

Results obtained with fans activated confirm that turbulence enhances the rate and completeness of combustion. An increase in peak pressure to the corresponding adiabatic value was also observed. These findings corroborate the results of tests at Fenwal (Cross, 1980; Mills, 1981), Lawrence Livermore National Laboratory (LLNL) (NUREG/CR-2486), and Sandia National Laboratory (Roller and Falacy, 1982), but more importantly they indicate that turbulent plant conditions will promote burning at relatively lean concentrations.

During Phase 2 of the Whiteshell program, a series of rich mixture deflagration tests was performed to supplement existing knowledge of combustion of hydrogen-steam-air mixtures at high hydrogen concentrations and to confirm that detonations would not result. For these tests, hydrogen concentrations were varied from 10 to 42 volume percent, and steam from 0 to 40 volume percent. Fans were activated in several tests.

Complete combustion was achieved in nearly all tests, including those with a quiescent mixture of 10% hydrogen and 40% steam. For both dry mixtures and mixtures with steam present, the measured pressure was always less than the theoretical adiabatic pressure. This same result was observed in Sandia combustion tests conducted as part of the NRC research program. Furthermore, no detonations were observed even at stoichiometric and higher concentrations of hydrogen which are classically considered to be detonable. The absence of detonations is attributed to the fact that the energy release rate of the igniter is significantly less than that required to initiate a detonation.

In Phase 3 of the Whiteshell test program, the effects of turbulence induced by fans and gratings on the extent and rate of combustion were investigated. Hydrogen concentrations ranged from 6 to 27 volume percent in these tests. Results show that for rich mixtures, forced turbulence increases the rate of pressure rise but does not increase the peak pressure. With regard to the effect of gratings, the test results indicated that in lean mixtures without fans, the presence of gratings tended to increase the magnitude and rate of pressure rise. At high concentrations or with fans, the gratings reduced both the magnitude and rate of pressure rise by acting as heat sinks. In summary, the Phase 3 results indicate that no unanticipated pressure effects result from forced turbulence, even at high concentrations of hydrogen.

In the fourth and final phase of the Whiteshell program, compartmentalized geometry effects were investigated. Two connected compartments were simulated by attaching a 20-ft long, 1-ft-diameter pipe to the 7.5-ft-diameter sphere. The effects of igniter location and unequal concentrations in each vessel were investigated for hydrogen concentrations ranging from 6 to 25 volume percent. Two igniter locations were used, one at the end of the pipe and the other at the center of the sphere. For all tests, no detonations occurred, and the observed peak pressures were less than the calculated adiabatic values. With regard to tests with unequal concentrations, no significant effects of propagating flames between two connected vessels were observed.

3.2 The Factory Mutual/Acurex Test Program

To determine whether a water spray consisting of droplets smaller than conventional spray systems would improve the overall performance of a deliberate ignition system, a two-part experimental program was carried out under the sponsorship of EPRI. The Factory Mutual Corporation (FM) project was the first of the two-part program (Mills, 1982a). The purpose of the FM project was to evaluate the effects of water fog density, droplet diameter, and temperature on the lower flammability limit of hydrogen-air-steam mixtures. The FM work also served to identify a set of nominal conditions for the intermediate-scale hydrogen combustion studies dealing with the pressure-suppressant effects of fog. The intermediate scale studies were conducted by the Acurex Corporation (ibid) and were the second part of the two-part program.

The FM tests were conducted in a plexiglass tube approximately 3.5-ft long and 6-in. in diameter. A 2.8-Joule spark served as the ignition source. Several tests were also conducted with a GMAC-7G glow plug as the ignition source to verify the applicability of these tests to the installed distributed ignition systems. Five different spray nozzles were used to obtain different fog conditions (i.e., different characteristic droplet sizes and densities). Mean droplet sizes from approximately 10 to 150 microns were investigated at fog concentrations up to 0.1 volume percent. Tests were conducted at water temperatures of 20°C (69.8°F), 50°C (122°F), and 70°C (158°F), and hydrogen concentrations ranging from approximately 4 to 12 volume percent.

Results of the FM tests confirmed the analytical prediction that increased fog densities are required to achieve a given level of fog inerting when the characteristic droplet size is increased. Test results showed that at ambient temperature, visually dense water fogs had only a marginal effect on the hydrogen lower flammability limit. At higher fog temperatures, somewhat larger increases in the flammability limit were observed. TVA reported favorable agreement between the FM experimental data and theoretical models used to describe the effect of fog on hydrogen combustion.

As a follow-on to the small-scale FM tests, the effects of fogs and sprays on the characteristics of deflagration were investigated in larger scale tests conducted by Acurex. A 630-ft^3 vessel approximately 17 ft high and 7 ft in diameter was used for all tests. The tests were carried out in two phases.

All Phase 1 tests were dynamic tests with the glow plug preenergized. Tests were conducted with hydrogen injection, hydrogen/steam injection, and hydrogen/steam injection with water spray present. These tests investigated the effect of igniter location with igniter assemblies located near the top, at the center, or near the bottom of the test vessel. The results of the Phase 1 Acurex tests suggest that lowering the igniter location produces milder pressures during hydrogen combustion. This appears to be a result of increasing the fraction of the vessel volume exposed to upward propagating flames in lean hydrogen concentrations. For these dynamic tests, repeated burns were produced with pressure increases of 1 to 6 psi; for several tests without sprays, the pressure rises were higher, with a maximum increase of 28 psi. Because the Phase 1 tests were transient in nature, combustion parameters such as hydrogen concentration at ignition and completeness of burn were not conclusively determined.

During Phase 2 of the project, Acurex investigated the effects of a water fog on the pressure rise that accompanies a deflagration. Quiescent tests were conducted without water fog and with water fog at two different droplet sizes and concentrations. Dynamic tests were conducted with hydrogen injection and with hydrogen/steam injection. The igniter assembly was located near the bottom of the vessel for all tests.

For the transient tests conducted in Phase 2, the pressure increases from the repeated burns varied from 1 to 5 psi. The small pressure rises are attributed to ignition occurring at lower hydrogen concentrations. This conclusion is consistent with the Whiteshell findings that increased turbulence promotes ignition at lower hydrogen concentrations. Because the containment post-accident environment would resemble the transient test conditions, the pressure rises associated with hydrogen combustion in containment are expected to be relatively benign, as observed in the transient tests.

3.3 Tayco Igniter Testing

As discussed in previous supplements, the effectiveness and durability of the GM glow plug under endurance, cycling, and hydrogen combustion conditions has been demonstrated in testing conducted at Whiteshell and Singleton. To show that the Tayco model igniter is comparable to the GM glow plug, tests have been performed on the Tayco igniter at Whiteshell and Singleton.

Tests of the Tayco igniter conducted as Phase 3 of the small-scale igniter test program at Whiteshell show that the Tayco igniter was as effective at igniting lean mixtures as the GM glow plug. The results of the igniter surface temperature tests suggest that the Tayco igniter is capable of igniting mixtures at surface temperatures 125F° to 200F° less than the GM glow plug. This could be attributed to the helical geometry of the Tayco igniter, which may promote higher local gas temperatures within the coil.

Tests were conducted at Singleton to assess the durability of the Tayco igniters when they are subjected to endurance and cycling operations at minimum and maximum voltages and to hydrogen combustion. To summarize, four Tayco igniters were subjected to a series of five tests. These tests consisted of a 24-hour break-in at 120 V, continuous operation for 7 days at 120 and 135 V, and on/off cyclic operation at 120, 125, 130, and 135 V. Igniter surface temperature was monitored for the duration of the tests. The steady-state surface temperature remained above 1700°F through out the test series. The igniters were energized for a total of approximately 370 hours each. All Tayco igniters performed successfully during the tests except for one which failed after 340 hours of operation. Operation for 340 hours is considered acceptable because it is in excess of the expected period for which igniter performance will be required.

Tests were also conducted in which the igniter was exposed to hydrogen combustion in flowing mixtures with entrance conditions ranging from 4 to 12 volume percent. The Tayco igniter initiated combustion and survived the burn environment in all cases.

At the staff's request, additional tests were conducted at TVA's Singleton Laboratory to ensure that the Tayco igniter would operate as intended in a spray environment such as that in the upper compartment. Tests were conducted using a single hollow cone spray nozzle of the same type used in Sequoyah and in the Fenwal spray tests for the glow plug igniter. The nozzle was oriented vertically downward and was located 3 ft directly above the igniter. The igniter was oriented horizontally and was mounted under a horizontal spray shield of the same configuration as those on the igniter assemblies to be installed in Sequoyah.

Igniter performance was assessed on the basis of measured surface temperatures for four different environmental conditions: natural and fan-induced circulation, with and without spray. In tests without sprays, the igniter surface temperature remained above 1700°F at all times. When the spray nozzle was activated, the igniter temperature dropped to 1650°F and 1600°F with the fan off and on, respectively.

Although the 1600°F surface temperature is above the maximum surface temperature required for ignition as determined by Whiteshell, the staff considered the drop in surface temperature significant, and requested that TVA provide additional assurance that the Singleton test conditions were representative of those expected in the plant. Further TVA analysis of the Singleton test data showed that the spray density through the horizontal plane at the igniter elevation was approximately equivalent to that which would be provided by operation of one of the two spray trains in the Sequoyah plant. Moreover, because the majority of the spray flow with the hollow cone nozzle is concentrated at the periphery of the cone, the spray density directly below the test nozzle (i.e., at the location of the igniter assembly), would be even less than expected in Sequoyah with one spray train operating. Therefore, in the view of the staff, these Singleton spray tests did not adequately represent the containment spray environment.

In response to a staff request, TVA has performed a number of subsequent tests using a solid cone spray nozzle. In one test the nozzle was located between the igniter and the fan such that the edge of the spray cone just intersected the edge of the igniter spray shield. The height of the nozzle was adjusted to provide a spray density at the horizontal plane of the igniter equivalent to operation of both spray trains in Sequoyah. With the fan energized, an igniter surface temperature of approximately 1500°F was measured. The staff notes that while this test represents containment spray conditions better than the previous spray tests, vertical droplet velocities in the test were higher than expected in containment and would tend to underestimate spray transport across the igniter in the horizontal direction, even with the fan on. Some impingement of spray droplets on the igniter is expected in containment due to the presence of convective currents with velocities on the order of the droplet terminal velocity.

The staff has indicated to TVA that additional spray tests are needed to confirm satisfactory operation of the Tayco igniter in a spray environment. These tests must ensure that the Tayco igniter will reliably initiate combustion in a spray environment similar to that expected in containment. Satisfactory igniter operation can be confirmed by verifying experimentally that the igniter will sustain a surface temperature sufficient to initiate combustion in lean mixtures, or by demonstrating by test that combustion will occur. The minimum surface temperature for reliably initiating combustion is considered by the staff to be 1500°F. The staff will require that such tests be completed to its satisfaction before it grants final approval of the Tayco igniter.

3.4 Staff Conclusions Regarding Testing

The staff has reviewed the combustion testing programs conducted as part of the TVA research effort and concludes that the results support the use of a distributed ignition system for post-accident hydrogen control. Specifically, the results of tests conducted at Whiteshell show that thermal igniters will reliably initiate combustion for a wide range of hydrogen-steam-air mixtures. Tests conducted at higher hydrogen concentrations illustrate the difficulty in initiating detonations, even at stoichiometric and higher concentrations.

Also, the observed effects of steam, induced turbulence, connected geometries, and unequal concentrations on the nature of hydrogen combustion confirm the staff's previous understanding. Tests conducted at Factory Mutual and Acurex provide additional information on the pressure-suppression and inerting effects of sprays and fogs. Similarly, none of the results obtained in these studies would support a negative finding relative to the use of deliberate ignition system. With regard to the Tayco igniter, a number of tests remain to be completed to provide further confirmation that the igniter will operate as intended in a spray environment. However, igniter tests conducted to date provide a basis for concluding that the GM and Tayco igniters are equivalent.

4 Hydrogen Mixing and Distribution

Analyses discussed in SSER 3 have indicated that hydrogen released during a postulated degraded core accident could be expected to be reasonably well mixed by the time it leaves the lower compartment. Adequate mixing, in conjunction with ignition of lean mixtures, would effectively preclude the formation of detonable concentrations. However, previous containment mixing analyses were cursory in nature, and did not attempt to characterize quantitatively hydrogen mixing and distribution within the ice condenser containment. A series of large-scale tests were, therefore, conducted by the Hanford Engineering Development Laboratory (HEDL) as part of the EPRI research program to provide additional assurance that large hydrogen concentration gradients will not occur (Mills, 1982a).

The mixing tests were conducted at HEDL's Containment Systems Test Facility (CSTF). This facility has a vessel that is 67 ft tall, with a diameter of 25 ft. Because the upper compartment of the ice condenser containment will be well mixed by the sprays, the lower compartment region was chosen for modeling emphasis in the facility. The interior of the CSTF was modified to represent a divider deck, reactor cavity, refueling canal, the air return fans, and ice condenser lower inlet doors. For the purposes of these tests, geometric similarity was retained between the test compartment and the lower compartment of an ice condenser containment. Hydrogen and steam release rates used in tests were scaled to model the base case S_2D loss-of-coolant accident (LOCA)*. Helium was used to simulate hydrogen in most of the tests because of site safety considerations. Atmospheric temperatures, velocities, and gas concentrations were measured at several distributed points during the tests. The test matrix for the HEDL program was designed to characterize hydrogen distribution for two release scenarios: (1) a 2-in. pipe break with a horizontal orientation and (2) a 10-in. pressurizer-relief tank rupture disc opening with a vertically upward orientation. Two different release rates were investigated. The test program included tests with and without air return fans.

The results of the HEDL tests show that good mixing in the lower compartment can be expected if the air return fans remain operational throughout the accident. The air recirculation fans minimize both the peak helium concentration and the maximum helium concentration difference between points in the test compartment. In all cases with forced air recirculation, which included the two jet orientations and two different release rates, the maximum helium concentration difference between all points in the test compartment was less than 3 volume percent at all times and was generally on the order of 2%. These concentration differences had stopped increasing even before the release period was over and were less than 1 volume percent within 5 minutes after stopping the source gas.

The HEDL tests with no forced recirculation (air return fans inoperative) were inconclusive. During the helium-steam release for these tests, the maximum concentration difference between all measurement points in the test compartment was 2 volume percent. Following the helium-steam release, however, the test compartment developed a vacuum as the steam in the compartment condensed. This reverse migration coupled with the lack of a mixing mechanism from either the fans or the jet itself created a concentration difference of as much as 7

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*A single degraded core accident designated as S_2D in WASH-1400 (NUREG-75/014); it is a small-break LOCA accompanied by the failure of emergency core cooling injection.

volume percent helium. Although the later portion of the test may in no way be prototypical of the plant, as TVA contends, neither does it support a conclusion that adequate mixing will occur without forced circulation by the air return fans. In assessing mixing in the latter portion of the test, however, it should be noted that for tests both with and without forced recirculation, the test compartment volume is well mixed with less than 1 volume percent concentration difference between points within 20 minutes after stopping the hydrogen-steam or helium-steam source.

Based on review of the HEDL results, the staff concludes that the formation of significant hydrogen concentration gradients in containment is unlikely if the air return fans survive the accident environment. The operation of the deliberate ignition system near the lower hydrogen flammability limit in conjunction with the mixing by the air return fans ensures that hydrogen concentrations at or below the flammability limit will be maintained throughout containment for the duration of the accident. In this regard, the formation of detonable pockets of hydrogen is precluded.

5 Detonations

The TVA position regarding detonation is that detonation is not a credible phenomenon in the containment because: (1) there would be no rich concentrations throughout the containment because the distributed igniters would initiate combustion as the mixture reached the lower flammability limit and because effective mixing would occur; (2) there are no high-energy sources to initiate a detonation; and (3) there are no areas of the containment with sufficient geometrical confinement to allow for the flame acceleration necessary to yield a transition to detonation.

The staff agrees with the TVA position. Because of the well-mixed atmosphere in containment, as confirmed by the HEDL mixing tests, the potential for localized accumulation of significant concentrations of hydrogen is unlikely. Even given that a high concentration might be formed locally, detonation of the cloud is extremely remote because this would require that the cloud encounter an ignition source of sufficiently high energy to initiate a detonation before it passes through a region in which an igniter is located or before combustion is initiated. The staff concluded in SSER 5 that the energy level of the thermal igniter is not sufficient to initiate a detonation. This conclusion is supported by test data, including several of the tests recently conducted at Whiteshell and LLNL. Although these tests do not show conclusively that detonation or transition to detonation cannot occur, they do illustrate the difficulty involved in producing the phenomenon even using stoichiometric hydrogen-air mixtures such as those present in tests.

In the staff's view, the only scenario in which large concentrations of hydrogen might accumulate is one in which all igniters in a given region fail, along with the air return fan. TVA has provided redundant igniters on separate power trains in each region of the containment to preclude such an occurrence. The staff thus concludes that detonation of local pockets of hydrogen is extremely unlikely.

Another concern related to the detonation issue is that of flame acceleration. The phenomenon of flame acceleration as a possible mechanism for producing a detonation or large overpressures in containment was discussed in SSERs 4 and 5. The concern, expressed by Sandia National Laboratory, was that obstructions in the ice condenser region of the plant may serve to accelerate combustion to the point that a transition to detonation would occur. Utility consultants previously concluded and still contend that there are no areas in the containment that provide sufficient geometrical confinement to allow for the extreme flame acceleration necessary to result in a transition to detonation. For example, the vertical ice baskets in the ice condenser are not sufficiently confined radially and the circumferential upper plenum above the ice condenser is not sufficiently confined for transition to detonation to occur..

With regard to the ice condenser region of containment, the utility consultant's view was that, for an S_2D-type scenario, the upper plenum igniters would ignite the mixture as it first becomes flammable; then, as a richer mixture is vented to the upper plenum, the igniters will produce a horizontal standing flame. If the mixture is further enriched, the flame will propagate downward into the ice bed until it settles to an equilibrium point where sufficient steam has been condensed. TVA concluded that even if an inerted mixture with a high hydrogen concentration were introduced to the ice bed, which is highly unlikely because of operation of the lower compartment igniters and the air return fans, the flame front would simply propagate to an equilibrium elevation where sufficient steam was condensed to support combustion. The flame propagation will not allow the hydrogen-steam-air mixture to dry out to the point where detonable mixtures would develop. The staff previously considered these matters, as discussed in SSER 5, and concluded that a transition to detonation in the ice condenser region was not likely.

Results of recent research conducted at McGill University as part of the NRC Hydrogen Research Program support the TVA position that flame acceleration will not occur in an ice condenser containment. In laboratory-scale studies of flame propagation through obstacle fields, McGill researchers have investigated the rate of flame acceleration as a function of obstacle configuration and hydrogen concentration in dry air. In these tests, noticeable flame acceleration and transition to detonation were observed only at hydrogen concentrations in excess of 13 to 15 volume percent. This limit is lower than the often-quoted value of 18%, but is still well above the concentration expected in the containment building. The requisite concentration may shift upward if steam is added to the mixture. Furthermore, Sandia tests have confirmed that confinement of the gas mixture is a requisite condition for producing a transition to detonation. The composite evidence of these relatively recent tests has led Sandia to conclude that a transition to detonation in the upper plenum region is unlikely. The McGill findings are preliminary in nature, and additional tests are planned at both McGill and Sandia to address the effects of steam addition and scaling on the requisite concentration for flame acceleration. However, the staff believes that the preliminary findings by McGill will not be significantly altered by additional tests and that they provide an adequate basis for licensing decisions.

Although the potential for detonation and flame acceleration is extremely remote, TVA has calculated the response of the containment shell to a postulated local detonation of a 6-ft-diameter gas cloud and showed that a margin of safety of 3 exists before material yield would be reached. The results of this analysis were reported in SSER 4. At that time, further studies were thought to be necessary to bound the variation in pulse shapes to confirm the TVA findings. TVA was therefore required by license condition to address the potential for local detonation. TVA has considered the potential and has concluded, based on the results of its research program, that detonations and transitions to detonations are not credible in Sequoyah. TVA thus considers further studies of containment response to detonations unwarranted. The staff agrees with TVA that detonations are extremely unlikely in Sequoyah and therefore feels the TVA position is reasonable for the licensing decisions related to the PHMS.

Even though the staff's view is that sufficient information exists for closure of the detonation issue, the staff, with the support of Sandia, has initiated an independent calculation of containment response to postulated local detonations. Sandia, using the CSQ computer code in conjunction with a simple structural failure criterion, has calculated the effects of various postulated local detonations on the containment structure. Results of early calculations for the upper plenum of an ice condenser plant indicate that containment integrity can be threatened if the requisite conditions for detonations were attained. As previously stated, however, it is the view of the staff that the conditions that must prevail to produce detonations are extremely unlikely. Moreover, even with the presence of detonable mixtures, as assumed in the Sandia analysis, there has been no demonstration that a detonation would occur. Subsequent calculations performed by Sandia using a detailed structural model indicated the containment would survive upper plenum detonations.

The Sandia investigation, which is not yet complete, is viewed by the staff as a confirmatory item to provide further insight into the consequences of local detonations. The results of this effort are not expected to alter the staff's findings on the hydrogen control capability at Sequoyah for the aforementioned reason.

6 Degraded Core Accidents and Hydrogen Generation

As discussed in SSER 4, a small-break LOCA followed by a failure of emergency core cooling (ECC) injection (S_2D) was selected by TVA as the base case for evaluation of the hydrogen mitigation system. Hydrogen release rates are a time-varying function whose average is of the order of 20 lbs per minute. The staff considered these rates to be representative of releases that might be encountered in typical degraded core accidents less severe than total core melt or vessel failure, and considered them an acceptable upper limit basis for use in the interim evaluation; however, several concerns remained open. Among these were: (1) the possibility that other scenarios might present schedules of steam and hydrogen release not covered by the analysis chosen; (2) that steam inerting might occur at some time during the sequence allowing large concentrations of hydrogen to develop; (3) that the recovery period might produce an exceptional burst of steam or hydrogen; or (4) that hydrogen might be released after the loss of the ice heat sink. TVA was therefore asked to broaden the studies of steam and hydrogen releases.

In the follow-on CLASIX studies that were submitted by the applicant, steam and hydrogen releases were varied to correspond to higher release rates and releases after the ice had melted. It was shown that a representative selection of scenarios would be bounded by the calculated release rates, and thus it was claimed that a satisfactory group of alternative scenarios had been encompassed by the calculations. TVA states that the scenarios encompassed included an intermediate-break LOCA with a loss of ECC (S_1D), a small-break LOCA with a loss of containment heat removal (S_2G), a transient loss of main feedwater and loss of all ac power (T_BB_2), and a transient loss of main feedwater, loss of auxiliary feedwater, and loss of the ECC (T_BLD).

The staff has compared the release rates and sequences used in TVA's calculations to those developed in an independent study of degraded core accidents in ice condenser plants carried out at Brookhaven National Laboratory (Yang and Pratt, 1982). It is clear from this comparison that TVA's choices of hydrogen and steam release rates do indeed cover the above range of accident scenarios. The highest rate of hydrogen release calculated by Brookhaven was of the order of 1 lb per second. The Brookhaven calculations did not indicate that these rates would be exceeded during quenching or recovery from the degraded core conditions as well as in the initial core uncovery phase. On the other hand, TVA has calculated the effect of hydrogen release rates as 6 lb per second under representative steam conditions, with and without ice.

In addition, the staff has compared the release rates chosen by TVA to those suggested in a proposed rule ("Notice of Interim Requirements Related to Hydrogen Control" (46 FR 62281)). In this comparison, the release rates used by TVA were again found to be an adequate representation of the scenarios considered important in these degraded core situations.

The licensee's core reflood studies using MARCH, WFLASH, and LOCTA did not disclose any conditions that would be more adverse than the high release rates used in CLASIX.

The staff therefore finds TVA's treatment of scenarios to develop steam/hydrogen source terms in conformance to the requirements of existing hydrogen degraded core rules acceptable.

7 Sequoyah Containment Structural Capacity

In support of the initial licensing of the plant, the ultimate pressure-retaining capacity of the Sequoyah steel containment was calculated by five different investigators. These pressures ranged from a low of 27 psig to a high of 50 psig, as listed in column 2 of Table 22.1. The variation was the result of the difference in the material properties used in the analysis, the stress limit criteria, and the manner of incorporating the horizontal and vertical stiffeners. When the material properties and the stress limit criteria are normalized to actual mean material properties and Von-Mises criteria, respectively, to form a uniform basis for comparison, the ultimate capacity then varies from a low of 40 psig to a maximum of 60 psig as listed in column 3 of Table 22.1. To provide an adequate safety margin, the staff reduced its ultimate mean value of 60 psig by 3 standard deviations. The standard deviation computation incorporated the variations in the material properties, material sizes and thicknesses, stiffener spacing, and containment shell diameter. The standard deviation of the containment pressure was calculated to be 8 psig. Therefore the ultimate capacity of the containment adopted by the staff was 36 psig, which represents a lower bound value. An assessment of the containment penetrations was also made at the initial licensing stage and showed that the penetrations were not the controlling item for the containment ultimate pressure capacity, as reported in SSERs 3 and 4.

Table 22.1 Internal static pressure capacity for hydrogen burning, psig

Investigator	Column 1, Service Level C*	Column 2, Reported ultimate capacity**	Column 3, Normalized ultimate capacity†
TVA		38	40
Staff (Ames Laboratory)	30.0	36††	60
Franklin Research		30	51
Offshore Power		50	53
R&D Associates		27	40

*Based on ASME Code methods and Code allowables; 1/2-in. steel plate controls.

**Reported by individual investigators and summarized in NUREG/CR-1891.

†Capacity values normalized using actual mean material properties instead of Code values and Von-Mises yield criterion.

††Based on actual material properties and Von-Mises yield criterion; this value is the mean value minus 3 standard deviations.

The proposed rule, "Interim Requirements Related to Hydrogen Control," was published after these analyses. The proposed rule would require that the hydrogen control system perform its function without loss of containment structural integrity. For the PHMS installed at Sequoyah, the rule would require that the containment pressure throughout the accident transient remain at or below that which corresponds to Service Level C limits of the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers (ASME Code).

The staff's consultant, Ames Laboratory, computed the value of the internal pressure that would produce stresses in the steel shell corresponding to Service Level C Limits as specified in the ASME Code, Section VI, Division 1. This value is 30 psig and is shown in column 1 of Table 22.1. This value is based on the finite element analysis model used in computing the containment ultimate capacity reported earlier. The limiting section in the Ames Laboratory analyses is the 1/2-in. thick cylindrical plate between elevations 756 ft 3 in. and 810 ft 3 in. The staff agrees with the Ames estimated pressure retention capability for ASME Boiler and Pressure Vessel Code Service Level C limits is 30 psig with all of the inherent safety margins of the code implied.

TVA has also made an evaluation of the reinforced concrete floor that divides the upper and lower compartments. This evaluation showed the reinforced concrete floor differential pressure capacity to be equal to or greater than the containment shell capacity.

8 Containment Analysis

8.1 Containment Codes

Calculations of containment atmospheric pressure and temperature have been performed using the CLASIX computer code developed by Westinghouse Offshore Power Systems (Westinghouse OPS-36A31). Descriptions of the earlier version of CLASIX have been previously reported in SSERs 3, 4, and 5. As noted in SSER 5 and as part of the license condition, the staff asked TVA to provide improved calculational methods for containment pressure and temperature response to hydrogen combustion. Specifically, TVA was to refine CLASIX to permit the addition of structural heat sinks and the separate modeling of the upper plenum. In addition, TVA was to provide additional verification of the CLASIX code by comparison with results from other accepted codes and combustion tests. The present and latest version of CLASIX incorporates those changes requested by the staff.

The CLASIX code is a multivolume containment code that calculates the containment pressure and temperature response in the separate compartments. CLASIX has the capability to model features unique to an ice condenser plant--including the ice bed, recirculation fans, and ice condenser doors--while tracking the distribution of the atmosphere constituents--oxygen, nitrogen, hydrogen, and steam. The code also has the capability of modeling containment sprays. Unlike the earlier version, the present version of CLASIX includes heat sinks and models the upper plenum as a separate model. Mass and energy released to the containment atmosphere in the form of steam, hydrogen, and nitrogen is input to CLASIX. The burning of hydrogen is calculated in the code with provisions to vary the conditions at which the burn initiates and propagates to other compartments.

CLASIX input for each compartment consists of the net free volume, temperature, contents by constituent, burn control parameters, and passive heat sink data. The burn control parameters include the hydrogen concentration and oxygen concentration required for ignition, the hydrogen concentration for propagation, the hydrogen fraction burned, and the minimum oxygen concentration required to support combustion and the burn time. The flow area, flow loss coefficient, and propagation delay time for each intercompartment flow path is also required. Additional input data are supplied to describe the ice condenser, fans, and sprays.

The major difference between the present and earlier version of CLASIX is in the heat sink model. The analytical model of the structural heat sinks represents all heat sinks as multilayered slabs. Heat transfer to the exposed surfaces by both convection and radiation is modeled. Radiation is assumed to occur only between the water vapor in the containment atmosphere and the surface of the heat sinks. A conventional finite difference formulation is used to model internal heat transfer.

The staff, with the support of Los Alamos National Laboratory (LANL), has completed a preliminary assessment of the CLASIX code. This assessment involved an evaluation of the validity and adequacy of the assumptions and models employed and review of the TVA-supplied comparisons between CLASIX results and those for other containment codes and combustion experiments.

A number of technical concerns were identified during the code review. With regard to the CLASIX radiation model, the staff requested that TVA clarify the expression used to compute the net radiant heat exchange. Specifically, the staff questioned the inclusion of gas and wall emissivities as multipliers on the temperature terms. TVA has reviewed the development of the radiation model and has concluded that use of the emissivities is inappropriate. However, TVA notes that use of the emissivities results in an underestimate of radiant heat flux to the walls and, thus, leads to conservative containment temperature and pressure predictions. Based on an independent review and on the TVA clarification provided, the staff and LANL concur in the TVA finding that CLASIX underpredicts the radiation heat transfer.

LANL, as part of its review, also identified a number of questions regarding the fluid flow equations used in the code. LANL's concerns centered on the use of (1) steady-flow equations to describe the transient phenomena and (2) constant loss coefficients for subsonic flows. The rationale provided by TVA for the CLASIX flow equations is that the Mach number for all CLASIX cases analyzed to date has been less than the commonly accepted criteria for assuming incompressible flow. On this basis, the staff and LANL agree that the CLASIX approach is valid.

To increase the level of confidence in the CLASIX code, TVA has validated CLASIX by comparing calculated results with the calculated results of the Westinghouse COCOCLASS9 code (Westinghouse, 1981), the Westinghouse Transient Mass Distribution (TMD) code (WCAP-8077,-8078), and the measured results of selected Fenwal and LLNL tests.

COCOCLASS9 is based on the NRC-accepted code COCO (WCAP-8326, 8327), and has been used in support of licensing activities for dry containments. The COCOCLASS9 analytical model has the capability to simulate heat transfer to passive heat sinks and containment sprays as well as high enthalpy water mass and energy addition. However, the COCOCLASS9 model provides only a single volume representation of containment, and does not allow spray evaporation as CLASIX does. Also COCOCLASS9 does not have the capability to model the addition of hydrogen during a burn. This limitation precludes comparison of a transient burn case.

Comparative runs were made with CLASIX and COCOCLASS9 assuming no heat sinks, heat sinks, and heat sinks with radiation. The comparison indicates that despite the previously cited discrepancy in the CLASIX radiation model, the two codes produced almost identical results for all cases considered. TVA attributes the excellent agreement to the use of a similar heat transfer model in COCOCLASS9.

The TMD program was developed for analyses of the ice condenser containment response during the initial few seconds following the onset of a design-basis LOCA. TMD contains a multicompartment analytical model but does not include models for containment sprays, air return fans, heat sinks, or hydrogen addition. Therefore, the comparison of CLASIX and TMD results is limited to multicompartment pressure and temperature responses to high enthalpy water mass and energy addition. This comparison provides verification of CLASIX pressure and temperature response calculations, flow path calculations, and certain aspects of the ice condenser model.

Four CLASIX-TMD comparison runs were made covering the anticipated range of the blowdown energy from saturation to superheat conditions. A containment similar to the Sequoyah ice condenser plant was modeled in all cases. Direct comparisons were made between the calculated temperature and pressure responses. Comparisons indicate that the two programs are in excellent agreement with the CLASIX-calculated values for both temperature and pressure being generally more conservative. CLASIX is expected to be conservative relative to TMD because of differences in the treatment of breakflow as the flow enters containment.

For the final part of the verification, CLASIX was used to model hydrogen combustion experiments conducted at Fenwal and LLNL. These comparisons provide limited verification for such features in CLASIX as the hydrogen burn model, the models for hydrogen and high enthalpy water mass and energy addition, and to some extent the passive heat sink and containment spray models. The approach taken to establish CLASIX input data for the experimental simulation was to utilize to the fullest extent possible all reported test measurements for the selected experiments. This included the CLASIX initial conditions as well as burn parameters such as the fraction of hydrogen burned and the burn time.

A total of 17 tests were selected for CLASIX verification. These included six dry tests and nine steam tests reported by Fenwal and LLNL. Hydrogen concentrations for both the dry and steam tests ranged from 8 to 15 volume percent. Steam concentrations for the latter tests ranged from 5 to 10 volume percent. In addition, one transient test and one test with spray were analyzed. Comparison of CLASIX-calculated results with those measured in the tests indicated that CLASIX predictions for peak pressure are consistently higher than those measured in the tests. Temperature comparisons were not attempted because of the slow response time of the thermocouples used in the tests. Only in a few cases were the CLASIX-calculated pressures higher than those measured. This was attributed to inaccuracies or inconsistencies in the estimated burn fractions.

In addition to its limited assessment of the CLASIX code and the TVA-supplied comparative runs, the staff directed its contractor, LANL, to develop the capability to model containment response to degraded core accidents independently. The ultimate purpose of the LANL effort was to perform confirmatory calculations for Sequoyah and other ice condenser plants; however, comparison of the models and results for the LANL-developed code with those for CLASIX provides an additional basis for evaluating the adequacy of the CLASIX code.

A modified version of the NRC COMPARE code was developed by LANL to model containment response to degraded core accidents. COMPARE was previously developed to perform confirmatory subcompartment analyses, and included capabilities required to analyze ice condenser containments, heat transfer to passive heat sinks, and the thermodynamics of atmospheres composed of steam, water, and ideal gases. To apply the COMPARE code to the analysis of hydrogen burning in containments, several capabilities were added, specifically a new ice condenser door model, a fan cooler model, a sump recirculation heat exchanger model, and a hydrogen burn model. A complete and total evaluation of the hydrogen burn version of COMPARE was not performed during the LANL effort. However, the applicability of the COMPARE code for the performance of subcompartment analyses has been evaluated rather extensively. Verification of the models added to the subcompartment version of COMPARE was performed by LANL. These evaluations show that the models provided results that are consistent with the original objective of the model.

A verification of the hydrogen burn analysis capabilities of the hydrogen burn version of COMPARE is also provided by the comparisons of calculated results with those obtained using the CLASIX code. These comparisons, discussed below, indicate that similar calculated values of pressure and temperature are obtained even though the codes were developed independently and utilize different models.

Based on its assessment of models used in the CLASIX code, a review of comparative runs provided by TVA, and the reasonable agreement found between CLASIX and the hydrogen burn version of COMPARE, the staff concludes that use of the CLASIX code to predict ice condenser response to a degraded core accident is acceptable, if appropriate input values are used. Approval of the CLASIX code for application to this particular class of accidents does not, however, constitute NRC endorsement of CLASIX for applications involving other classes of accidents, or variations of CLASIX to model other containment types. The staff will continue to assess the adequacy of the CLASSIX code as part of its ongoing confirmatory effort.

8.2 Containment Pressure and Temperature Calculations

The approach taken by TVA to establish the acceptability of the hydrogen control system was to select an accident sequence based on its significance and characteristics from the standpoint of hydrogen threat, and to then parametrically vary key aspects of the containment analysis. As in previously reported analyses, a small-break LOCA with failure of safety injection, the S_2D event was chosen as the base case.

TVA has performed calculations of the containment pressure and temperature response to the base case scenario using the latest version of CLASIX and the releases calculated from the MARCH code. For the base case calculation, TVA assumed a lower flammability limit of 8 volume percent hydrogen, a burn fraction of 85%, and a flame speed of 6 fps. Test data from Fenwal and Whiteshell, as well as the literature on combustion, indicate that ignition in the turbulent post-accident environment will occur around 5 volume percent hydrogen, with a burn completeness of 30 to 40%. Test data and the literature also show that at an 8% hydrogen concentration flame speeds are between 1 and 3 fps rather than 6 fps. The assumptions of ignition at the higher concentrations with a faster flame speed result in a greater amount of energy being released over a shorter period of time, and thus are conservative. Another conservatism in the CLASIX analysis is the assumption that ignition will occur simultaneously at all igniter sites in a compartment. This assumption will act to further increase the calculated pressures and temperatures.

The results of the CLASIX base case analysis indicate that the hydrogen will be ignited in a series of 7 burns in the lower compartment and 30 burns in the upper plenum. The burns occur over a 2500-second interval, with the 7 lower compartment burns intermixed, some concurrently, with 15 upper plenum burns over the first half of the interval. The peak calculated containment pressures and temperatures are 18.7 psig and 1245°F for the lower compartment, 18.1 psig and 257°F for the dead-ended region, 13.1 psig and 1220°F for the upper plenum, and 10.4 psig and 163°F for the upper compartment. The pressure in containment before the first burn was approximately 5 psig.

As a result of the action of engineered safety features such as the ice condenser, air return fans, and upper compartment spray, the pressure and temperature spikes were rapidly attenuated between burns. After the last hydrogen burn, which occurs at approximatley 7100 seconds into the accident, roughly 780,000 lbs of ice are calculated to remain in the ice condenser section (representing at least 110 x 10^6 BTUs in remaining heat removal capacity).

In summary, the results of the TVA base case analysis show an increase in containment pressure as a result of hydrogen burns on the order of 13 psi, with the containment remaining well below the lower bound ultimate capacity of 36 psig. The analysis predicts the burning will occur in the lower compartment and upper plenum, thereby gaining the advantage of heat removal by the ice bed and venting to the large upper compartment volume. It should also be noted that each burning cycle involved the combustion of only 30 lbs of hydrogen, or roughly 2 x 10^6 BTUs of energy addition. By burning at a given concentration in the lower compartment (and upper plenum), there is also the advantage of burning less total hydrogen at a time because the combined volumes account for less than one-third of the total containment volume.

To assess the efficacy of the PHMS more realistically, a best estimate calculation was performed by TVA assuming a lower flammability limit of 6 volume percent, a burn fraction of 60%, and a flame speed of 3 fps. The best estimate case results in a peak containment pressure of 10.6 psig, which is below the 12 psig containment design pressure.

TVA has also performed sensitivity studies to determine the effects of CLASIX burn parameters, safeguards performance, and reduced igniter performance on the containment response. To bound reported data regarding hydrogen combustion, a number of cases were analyzed in which burn parameters such as hydrogen concentration for ignition, burn completeness, and flame speed were varied either throughout containment or in selected compartments. Ignition criteria analyzed ranged from ignition at 4% hydrogen with 40% burn completeness, to complete combustion at 10% hydrogen. Flame speeds were varied from 1 to 12 fps. Additional cases were run to assess the effects of partial operation of the containment air return fans and sprays, heat removal by ice, and hydrogen release rates. In some of these cases several parameters were varied simultaneously such as a case with partial fan and spray operations, and modified ignition criteria (see Table 22.2). Finally, there were investigations of the effects of such postulated phenomena as fogging reducing the burn completeness in the upper plenum and steam inerting the lower compartment.

As discussed in SSER 5, the staff requested that TVA quantitatively assess the formation of fog and its effect on the performance of the igniter system. With regard to the effect of fogs and sprays on combustion, analytical studies of the requisite fog density and droplet size for inerting have been conducted by Westinghouse, Sandia, and others. Based on considerations of the heat of combustion and fog/spray droplet vaporization, these studies show that to fog inert an otherwise flammable mixture, two conditions must exist simultaneously:

Table 22.2 Containment sensitivity studies*

	Calculated peak pressure (psig)		Calculated peak temperature (°F)	
	LC	UC	LC	UC
Base case	18.7 (14.2)	10.4 (14.4)	1245 (1262)	163 (236)
Ignition criteria				
All ignition at 6% H_2, 60% burned	12.8	8.9	805	148
All ignition at 10% H_2, 100% burned	8.0 (8.6)	9.7 (8.9)	214 (237)	171 (175)
Flame speed				
1 fps flame	10.1	9.6	884	150
12 fps flame	23.5 (12.4)	10.8 (13.2)	1306 (1243)	182 (205)
Safeguards				
1 fan, 1 spray operational, UC and DE ignition at 6% H_2, 60% burned	17.6	18.0	1159	606
No ice, UC ignition at 6% H_2, 60% burned	22.8 (18.3)	26.9 (25.3)	1132 (1236)	548 (575)
Hydrogen release				
3 x base case H_2 release rate	19.1	15.3	1578	498
Same as above with 6 lbs/sec spike, no ice	24.9	25.3	1310	542
Reduced igniter performance				
UP ignition at 8% H_2, 40% burn	17.6	10.5	1284	157
No LC ignition	7.8	9.2	214	153
LANL mechanistic burn model				
Conservative (see text)	(26.1)	(24.2)	(1585)	(513)
Best estimate (see text)	(18.5)	(20.0)	(1382)	(360)

*LC = Lower compartment; UC = upper compartment; DE = dead-ended region; UP = upper plenum

All cases assume base case parameters except as noted; ( ) = results predicted by LANL using hydrogen burn version of COMPARE.

the fog density must be sufficiently high and the droplet diameter sufficiently small. The requisite fog density increases approximately as the square of the droplet diameter. Both of these parameters vary as a function of the hydrogen concentration of the mixture. In general, fog droplets on the order of 10 microns or less in diameter are capable of vaporizing completely in the flame front and quenching the flame. However, if the majority of the droplets in the population are larger than 10 microns, the fog is not expected to significantly influence the flame structure and may in fact exhibit beneficial effects such as the suppression of combustion pressure and any detonation waves.

To determine the significance of fog with regard to the PHMS installed in Sequoyah, TVA conducted a study to identify the major fog formation and removal mechanisms within an ice condenser containment. Analysis revealed that the upper and lower compartments maintained lower fog concentrations than the upper plenum. When the hydrogen concentration reached the lower flammability limit in the lower and upper compartments, the calculated fog concentrations were well below the calculated inerting limit. For the upper plenum, the fog is predicted to increase the flammability limit slightly. When the hydrogen concentration reaches 8.0 to 8.5 volume percent hydrogen in the upper plenum, the calculated fog concentration is two times smaller than the required concentration for inerting.

The staff has reviewed the TVA analysis and the results of the fog/spray tests conducted in support of the deliberate ignition system. Based on the information provided as a result of these investigations, the staff concludes that the presence of fogs and sprays in a post-accident atmosphere may affect the operation of the PHMS by increasing slightly the concentration at which ignition is initiated, but will not preclude satisfactory operation of the PHMS, because ignition is still expected to occur with acceptable consequences. The staff notes that even though there is still reasonable assurance that reliable ignition will be achieved with the PHMS, reduced igniter performance has been assumed by TVA in CLASIX containment analysis, and the results have been found acceptable.

After the issuance of SSER 4, TVA performed sensitivity studies of the hydrogen release rates and has computed the hydrogen release rates for a number of other accident sequences using the MARCH code. Two different sensitivity cases were considered. In the first, a hydrogen release rate three times that of the base case was assumed for the period up to and including the maximum release rate (spike). To provide equivalent hydrogen mass additions, the duration of blowdown following the spike was correspondingly decreased. For conservatism, the steam releases were not changed, because additional steam would act as a burn heat sink. In the second case, the hydrogen release rate was similarly assumed to be three times the base case; however, a maximum release rate of approximately six times the base case value was assumed.

The CLASIX code was used to analyze the containment response for the two cases: first assuming ice to be present, and assuming all the ice melted. The highest peak pressure predicted by CLASIX for all the sensitivity runs was 27 psig. This pressure is well below the lower bound pressure capacity for the Sequoyah containment.

The results of selected CLASIX sensitivity analyses are summarized in Table 22.2, along with the results predicted by LANL using the hydrogen burn version of the COMPARE code. Comparison of the CLASIX and COMPARE results indicates excellent agreement between the two codes. The peak containment pressures calculated by COMPARE are consistently lower than comparable CLASIX values, illustrating the conservatisms in CLASIX. The peak temperatures calculated by COMPARE are generally equivalent to those calculated by CLASIX but in some cases are slightly higher.

In conclusion, the results of the CLASIX sensitivity analyses demonstrate that (1) the effect of ignition criteria on containment pressure is dominated by the corresponding changes in burn location and sequence, but within the parameter ranges considered it does not result in peak pressures significantly greater than for the base case; (2) flame speed has a considerable effect on containment pressure but does not pose a threat to containment integrity even for conservative flame speeds; (3) partial versus full operation of the air return fans makes little difference in the calculated results; (4) ice condenser heat removal is effective in reducing containment pressure; (5) the rate of hydrogen release has little effect on the peak containment pressure; and (6) even with reduced igniter efficiency or lower compartment inerting, the PHMS will continue to perform its intended function. It should be noted that the cases with no ice are not mechanistic, i.e., they are not representative of the S_2D scenario. However, these cases importantly demonstrate that, even without ice, the containment pressure with the assumed igniter operation remains below the containment pressure capacity. This serves to indicate some insensitivity to whatever accident scenario is chosen.

8.3 Confirmatory Analysis and Conclusion

At the request of the staff, LANL has performed confirmatory analyses for the base case and several other cases using the hydrogen burn version of COMPARE. Code input equivalent to that for the CLASIX code was used in the confirmatory analyses with one exception. In the LANL analyses, the ice condenser section was represented by four separate nodes each accounting for one-fourth of the ice condenser volume; this is a finer model representation of the ice bed than used in CLASIX. The hydrogen burn parameters for the ice condenser and lower plenum nodes were specified to preclude the initiation of independent burns but to permit burning by propagation if the hydrogen concentration exceeded 8 volume percent.

Agreement between COMPARE and CLASIX was quite good, with COMPARE predicting peak pressures throughout containment of 14 psig. The mass of ice left in the ice condenser after the last burn is estimated at 289,000 lbs. This value is less than predicted by CLASIX because more burning in the ice bed region is predicted by COMPARE, but is not a safety concern because the remaining ice represents adequate heat removal capacity.

The TVA sensitivity studies indicate that containment integrity will be maintained for the base case and all sensitivity variations considered; however, upper compartment burns occurred in only two of the TVA cases. The subject of burning in the upper compartment was previously identified as a staff concern. Staff interest in this area lies in the fact that ignition in the large, relatively open upper compartment conceivably represents the largest energy release rate by combustion and thus the greatest threat to containment. Although the TVA upper compartment burns did not result in excessive pressures, the staff asked LANL to investigate this phenomenon further.

In response to the NRC request, LANL performed a number of additional sensitivity analyses using the modified COMPARE code. The approach taken by LANL was to identify the combination of burn parameters required to produce a maximum containment pressure, and then to assign parameter values based on a mechanistic burn model that is substantiated by test. Independent burn initiation in the upper comapartment was identifed as necessary to produce maximum pressures.

The model used by LANL to establish parameter values for the COMPARE containment analyses is based on estimates of turbulence levels and fluctuations and their relationship to eddy diffusivity and burn velocity. The controlling rate mechanism for the transport of the hydrogen from its source to an igniter can, in general, be estimated by using turbulence theory. The rate of burning for the lean mixtures under consideration is also controlled by the turbulence level. The level of turbulence is estimated by summing all of the dissipation sources (sprays, fans, jets, natural convection, etc.) and by using a formulation that relates the turbulent kinetic energy, mixing length, and eddy diffusivity to the rate of dissipation of kinetic energy. The turbulence model was used to estimate the mean concentration at the initiation of burning and the flame speed for the ice condenser containment burn analyses in which the first burn occurred in the upper compartment.

Two COMPARE calculations were performed to assess the significance of upper compartment burning. Burn parameters for these runs were specified so that burning could only initiate in the upper compartment, but could propagate into any compartment in which the hydrogen concentrations is greater than 4.1 volume percent. The first COMPARE run conservatively assumed ignition at 5% hydrogen with 40% burn completion, and a flame speed of 30 fps. The second run assumed the best estimates for these parameters based on the mechanistic burn model, i.e., ignition at 4.2% hydrogen with 10% burn completion, and a flame speed of 16 fps. Results of these calculations, summarized in Table 22 2, show that for both cases peak pressures will remain below the estimated failure pressure.

The staff concludes that the CLASIX containment analysis performed by TVA and confirmed in part by LANL provides an adequate basis for concluding that hydrogen combustion associated with the operation of the PHMS will not pose a threat to the integrity of the Sequoyah containment. While concluding that the use of CLASIX to predict ice condenser response to a degraded core accident is acceptable, the staff will continue the effort as part of its ongoing code assessment work.

9 Survivability of Essential Equipment

By letters dated June 2, 1981, December 1, 1981, and November 29, 1982, TVA submitted an evaluation of survivability of the essential equipment exposed to the thermal environment postulated in the containment during hydrogen burns initiated by the PHMS. Although this system was designed to prevent high hydrogen concentration buildup by deliberate ignition of relatively low concentrations of hydrogen in hydrogen-air-steam mixtures, the resulting release of thermal energy may still be sufficient to increase the temperature of the equipment located in the containment significantly. Because some of this equipment is needed to ensure maintenance of a a safe shutdown condition and containment integrity, TVA was required to demonstrate that the essential equipment located inside the containment will survive the hydrogen burn environment resulting from operation of the PHMS. TVA determined analytically and experimentally the thermal response of selected pieces of essential equipment exposed to a hydrogen burn environment. Comparing the resulting temperatures with the qualification temperatures for this equipment, TVA provided information to demontrate the survivability of the equipment.

9.1 Essential Equipment

The selection of equipment that must survive a hydrogen burn was based on its function during and after an accident. In general, all the equipment in the following four categories of systems located in the containment was considered to be essential for safety of the plant:

(1) systems mitigating the consequences of the accident

(2) systems needed for maintaining integrity of the containment pressure boundary

(3) systems needed for maintaining the core in a safe condition

(4) systems needed for monitoring the course of the accident

TVA's selection of safety-related equipment was based on the shutdown and safety function diagrams (letter from R. T. Cross, TVA, to R. L. Tedesco, December 15, 1980). The list of safety-related equipment is in Table 22.3.

Table 22.3 Essential equipment

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1. Mitigating Systems
    - 1.1 Hydrogen igniters
    - 1.2 Air return fan
    - 1.3 Associated power and control cables
    - 1.4. Hydrogen recombiner
2. Systems Maintaining Containment Pressure Boundary
    - 2.1 Air locks and equipment hatches
    - 2.2 Containment isolation valves including hydrogen sample valves
    - 2.3 Electrical penetrations
    - 2.4 Gaskets and seals for flanges
    - 2.5 Electrical boxes
3. Systems Maintaining Core Safety
    - 3.1 Reactor vessel vent valves (PORV)
4. Monitoring Systems
    - 4.1 Steam generator, pressurizer and sump water level transmitters
    - 4.2 Core exit thermocouples
    - 4.3 Reactor coolant system pressure transmitter
    - 4.4 Hot leg RTD
    - 4.5 Cold leg RTD
    - 4.6 Reactor vessel level system
    - 4.7 Associated cables (in conduits and exposed)
    - 4.8 Junction boxes
    - 4.9 Operators on solenoid valves
    - 4.10 Hydrogen analyzer

TVA restricted the survivability evaluation to the equipment which is most sensitive to temperature change. This reduced considerably the number of thermal response analyses and/or experiments that had to be performed. The following equipment items were selected for an evaluaton of their thermal response to the hydrogen burn environment:

(1) igniter assembly
(2) Barton transmitter
(3) igniter power cable in conduit
(4) thermocouple cable
(5) resistance temperature detector (RTD) cable

The staff has compared TVA's list of equipment selected for survivability evaluation with the lists of essential equipment prepared independently by the staff, and finds that the TVA list contains the equipment essential for safe operation of the plant under accident condition. The staff has also reviewed the criteria used by TVA in selecting the equipment for analytical and experimental investigations. Determination of the survivability of these pieces of equipment will be sufficient for establishing survivability of all the equipment listed in Table 22.3, provided these pieces of equipment have been included in the TVA equipment qualification (EQ) program. For pieces of equipment that are not in the EQ program, TVA has provided separate bases for the survivability finding.

9.2 Thermal Environment Response Analysis

The thermal environment for evaluating equipment survivability was determined by the CLASIX computer code. It corresponded to energy release from burning hydrogen which was generated during the accident resulting from a small-break LOCA with a loss of emergency core coolant injection (S_2D sequence), but with both trains of sprays and air return fans operating. The hydrogen was assumed to be ignited by the PHMS when it reached 8 volume percent concentration, with each burn being 85% complete. It was further assumed that the flame propagated throughout the containment with a velocity of 1 fps and its temperature remained constant at the adiabatic flame temperature of 1400°F. The CLASIX code predicted 6 burns in the lower compartment and 26 burns in the upper plenum of the ice condenser for this scenario. No burns were predicted in the upper compartment. The average time between the burns in the lower compartment is about 200 seconds, and the highest temperature reached by the gas is 884°F. In the upper plenum, the average time between burns is about 90 seconds and the highest temperature reached by the gas is 1114°F. In addition, for the analysis to demonstrate thermal stability of the ice condenser foam insulation, the licensee has referenced the Duke Power Company's analysis (Parker, 1981) in which it was assumed that hydrogen was burning continuously for 45 minutes at the midpoint of the ice condenser baskets; the resulting flame was conservatively assumed to be 1-in. thick with a temperature of 1600°F.

The thermal responses of the igniter assembly, Barton transmitter, and igniter power cable in conduit were analytically predicted for the thermal environment described in the previous section. The igniter assembly was analyzed using the upper plenum temperature profile that is considered to be the most severe thermal environment for igniters. It should be noted that the TVA analysis was done for the igniter assembly used for the IDIS. TVA has now decided to use a different igniter assembly for the PHMS, one that does not employ a transformer. Because the transformer was the most sensitive component of the previous igniter assembly, the staff concludes the same analysis could be applied to the new igniter assembly. The Barton transmitter was analyzed using the lower compartment temperature profile, and the igniter power cable in conduit was analyzed for both the upper plenum and the lower compartment temperature profiles. The staff has reviewed and concurs with this choice of thermal profiles for analysis, because these profiles conservatively represent the thermal environments to which the given equipment would be exposed during an accident.

The analytical models used in predicting thermal responses of equipment considered thermal energy transfer from the moving flame by radiation and from the hot gases by natural convection only.

Standard heat transfer equations were used to calculate this heat transfer. The heat transfer inside the equipment was determined by TVA using the HEATING

5 computer code (ORNL). This code was applied to solve heat transfer equations for two-dimensional models of different components. Therefore, these components had to be represented by relatively simple geometries. TVA prepared such simplified models which, despite their simplicity, included significant heat transfer characteristics.

The models used in the analysis were verified by comparing calculated results with the results derived from other accepted computer programs or obtained experimentally. The validity of the pressure transmitter model was determined by comparing its response to the results of the temperature transient analysis performed for equipment qualification using the COCO computer program (WCAP-8936). This program was previously verified by the staff. The agreement between temperature responses predicted by these two programs is satisfactory. TVA verified the model for thermal response of thermocouple cable by comparing it to the results of the test performed by Fenwal (Fenwal, 1980). Analytical results predicted the melting of the teflon insulation that was observed in the experiments. The staff has reviewed the methodology used by TVA and finds that in general the models conservatively overestimate heat transfer from the flame because it is assumed to move in the containment with an artificially slow velocity and at an adiabatic temperature, despite its loss of energy to different heat sinks. On the other hand, the transfer of heat by radiation from the hot gases was neglected by the licensee. The staff's consultant, Sandia, performed independent verification of TVA's analyses (McCulloch, 1982) and concluded that although they do not reflect true mechanisms of energy transfer for the hydrogen burn environments used, they yield conservative results.

Thermal responses for the thermocoupole and RTD cables were determined experimentally at TVA's Singleton Laboratory. The cables were exposed to the simulated hydrogen burn environment in a Lindberg Tube furnace, and the temperatures reached by cable insulation were measured. The cables were exposed to 1400°F for five 30-second cycles. Between the cycles (170-second period), the temperature was reduced to 200°F. The staff concluded that this environment conservatively represents the condition existing in the lower compartment during hydrogen burn.

Thermal response of the igniter cable used in the IDIS was determined experimentally at Singleton Laboratory. The cable was placed in a conduit with both ends sealed. The cable in the conduit was placed in a Blue M oven and was exposed to about 700°F for about 45 minutes. The staff concluded the environment conservatively represents the condition existing in the lower compartment or in the upper plenum of the ice condenser. The IDIS cable was not part of the NUREG-0588 qualification program, although the cable used for PHMS is qualified to meet NUREG-0588 requirements. Also, the materials used in the construction of the IDIS cable are more sensitive to heat than the materials used in the PHMS cable.

The acceptance criterion used for evaluating survivability of essential equipment is based on the qualification temperature of the equipment and the duration for which the temperature is maintained. The equipment located in the containment will survive the hydrogen burn if the temperature reached by its most sensitive component will not exceed the temperature reached by this component during qualification tests. Because the actual temperature reached by the tested equipment during these tests was not measured and qualification temperature was the temperature of thermal environment to which the test equipment was exposed, there is no direct way to determine the actual qualification temperature reached by the limiting components. However, TVA claims that environmental qualification tests are typically conducted for extended periods of time and the equilibrium surface temperature should achieve thermal equilibrium with the test chamber during the tests. Because of several conservative assumptions in the thermal response analysis, the staff is of the opinion that use of the qualification temperature by TVA as a criterion for evaluating the survivability of limiting components is acceptable. To confirm equipment survivability at elevated temperatures, TVA has performed tests in Singleton Laboratory in which the igniter power cable in conduit was exposed to 700°F for 45 minutes. Although some degradation of the insulation was observed, the cable qualified in the subsequent high voltage test.

The analytically calculated thermal responses during hdyrogen burn are compared with the qualification temperatures in Table 22.4. In all cases, the qualification temperatures are not exceeded. It is the opinion of the staff that this equipment will survive a hydrogen burn.

The survivability of thermocouple and RTD cables was determined experimentally by actually verifying their behavior in a simulated hydrogen burn environment. The temperatures reached by the cable insulation are listed in Table 22.4. Only slight degradation of cable insulation was observed. Both cables successfully passed high voltage tests.

All equipment except the core exit thermocouple, reactor vessel level thermocouple, and vessel vent valves has been included in the TVA EQ program. The core exit thermocouples are located inside the vessel head and are not exposed to the hydrogen burn environment. The reactor vessel level thermocouple and vent valves will be included in the EQ program when they are added to the plant.

Table 22.4 Comparison of analytically calculated thermal responses during hydrogen burn and qualification temperatures

Component	Maximum temp, °F (calculated)	Design/test temp, °F
Igniter (used in IDIS)		
Interior box air	227	428 (transformer)
Cable	171	
Transformer core	157	
Barton transmitter		
Interior air	231	310
Case surface	245	
Cable in conduit (used in IDIS)		
Copper	251	tested to 700
Insulation	260	
Conduit surface	332	
Thermocouple cable insulation		1126
RTD cable insulation		1013

In a submittal dated November 29, 1982, TVA stated that all the equipment listed in Table 22.3--except for thermocouple and RTD cable--reaches the equilibrium temperature during the qualification testing. Based on this statement and the experimental verification of RTD and thermocouple cables, the staff concludes that all the equipment listed in Table 22.3 will survive the hydrogen burn environment.

It should be noted, however, that the tests conducted by the licensee were performed in a relatively small oven. In NUREG-CR/2730, the staff's contractor (Sandia) has stated that on the basis of some preliminary test results, scaling (volume of containment building vs. volume of the test chamber) may be a significant factor in analyzing the survivability of the equipment. During fiscal year 1983, Sandia will be performing some additional confirmatory tests to address this concern. But, based on the conservative assumptions and available margins in the work done to date, the staff finds that the essential equipment will survive the hydrogen burn environment. The results from Sandia's upcoming tests will be relied on to confirm the findings made above.

Secondary fires in the Sequoyah plant may originate either when combustible materials located in the containment reach their ignition temperature or when the insulation on the ice condenser cooling ducts is heated to the point at which polyurethane foam starts to decompose and emit combustible gases. After reviewing different possible sources of combustible materials, TVA identified organic cable insulation as the only significant source. In most cases, however, cables are completely enclosed in conduits or cable trays, and are not directly exposed to the hydrogen burn. Those cables that have exposed insulation have been tested to ensure their flame resistance. In evaluating the thermal stability of insulation at ice condenser cooling ducts, TVA referenced the analysis performed by Duke Power Company for the McGuire plant (Parker, 1981). Because the ice condenser designs are similar in both plants, the analysis performed for McGuire is applicable to Sequoyah. This analysis indicates that the polyurethane foam will not reach temperatures at which pyrolysis could generate combustible gases. The staff has reviewed this analysis and concurs with TVA's conclusion.

9.3 Pressure Effects

For the pressure profile inside the containment during the hydrogen burn, the conservative pressure profile was obtained from the CLASIX analysis with a 12 fps flame speed. This analysis is identified in TVA's submittal of December 1, 1981.

With the PHMS, the highest predicted pressure in the containment does not exceed the pressures used during the qualification testing of equipment. However, a pressure differential could be developed between the lower and upper compartments of the containment that could strain the blades of the air return fans. TVA has indicated that the fans are protected by backdraft dampers; hence this pressure differential would not affect their performance. In addition, TVA performed a structural analysis that indicates that the fans could take static loads in excess of those produced by the predicted pressure differential.

9.4 Staff Conclusions Regarding Equipment Survivability

After reviewing TVA's analysis and/or experimental investigation of equipment survivability, the staff concludes that TVA has provided sufficient evidence that all the equipment required to ensure safe shutdown conditions and containment integrity will survive the environment created by burn of the hydrogen generated during a postulated accident. This conclusion is based on the following:

(1) The list of equipment provided in the submittal included all the essential equipment.

(2) The equipment selected for the analytical and experimental investigations adequately characterizes the essential equipment on the list.

(3) The analytical methods used by the applicant adequately calculate thermal response of equipment, based on the postulated thermal environment.

(4) The comparison of analytically determined thermal responses to the corresponding qualification temperatures for some sample components has indicated that these temperatures will not be exceeded during a hydrogen burn.

(5) Experimental determination of survivability of the thermocouples, RTD cables, and igniter cable in conduit in the test chambers conservatively predicts their behavior in a hydrogen burn environment.

(6) It was satisfactorily demonstrated that burning hydrogen will not initiate secondary fires in the containment by igniting combustible materials by generating combustible gases from the decomposition of polyurethane foam insulation.

10 Overall Conclusions

The operating licenses for Sequoyah Units 1 and 2 contain a condition requiring that, "prior to startup following the first refueling outage, the Commission must confirm that an adequate hydrogen control system for the plant is installed and will perform its intended function in a manner that provides adequate safety margins." The licenses include another condition dealing with the TVA research program which provides, among other things, that "...TVA shall...evaluate and resolve any anomalous results occurring during the course of its ongoing test program."

The staff has concluded its review of the matter of hydrogen control for postulated degraded core accidents at the Sequoyah plant. The staff finds that (1) four additional igniters must be installed in the upper compartment in locations satisfactory to the staff prior to restart after the second refueling of Unit 1, and (2) certain additional testing of the Tayco igniter in a simulated spray environment is required by September 1983. Subject to the satisfactory resolution of the above contingencies, the staff finds that

- The peak pressures as a result of igniter-induced burns will be less than the containment pressure capacity. The results of many accident analyses suggest that the peak containment atmosphere pressure will be close to the design pressure of 12 psig. Even considering a broad range of accident scenarios and combustion assumptions that is more conservative, it is expected that the containment pressure will remain below 30 psig. With adequate margins, the containment pressure capacity is 36 psig.

- The essential equipment has been identified and the peak temperatures during a hydrogen burn for the most sensitive piece of equipment have been shown to be less than its qualification temperature.

The contingencies identified in the above findings deal with design features of the PHMS. Specifically, they concern the capability of the Tayco igniter to maintain (1) a surface temperature sufficient to initiate combustion in a spray environment and (2) the density of the igniters in the upper containment to ensure favorable consequences of the hydrogen burns in the upper compartment. Recent tests conducted by TVA indicate that the igniters will function as intended. However, the temperature margin provided by the igniters appears to be small under spray condition. The staff will require that TVA complete certain additional tests to verify that the Tayco igniter will maintain an adequate surface temperature in a spray environment such as that expected in the upper compartment of the ice condenser containment. This work can be performed at the Nevada Test Site in early 1983, as part of the EPRI/NRC hydrogen research program. The staff will require the installation of four additional igniters in the upper compartment at locations satisfactory to the staff, and TVA has indicated its willingness to comply with this requirement.

As part of its PHMS evaluation, the staff also identified a number of technical concerns that it intends to investigate further as confirmatory items. The confirmatory items are

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

The subject of local detonations in confined regions of the containment is currently under investigation at Sandia under a staff technical assistance contract. This work is considered confirmatory in nature because: (1) mixing of the containment atmosphere, in conjunction with igniter operation at low hydrogen concentrations, will preclude the formation of detonable mixtures, and (2) recent analyses performed by Sandia using the CSQ code and a refined structural analysis indicate that the Sequoyah containment can withstand the postulated detonation of a 20 volume percent hydrogen mixture in the upper plenum of the ice condenser. The Sandia investigation should be completed by mid-1983.

The staff will continue to assess the adequacy of the CLASIX code as part of its technical assistance program with the Los Alamos National Laboratory. This containment code work is considered to be confirmatory in light of the staff's findings regarding the adequacy of the CLASIX models and the reasonable agreement obtained between CLASIX and the hydrogen burn version of COMPARE. The code work will be an ongoing effort.

The staff will also continue to investigate equipment survivability for a spectrum of degraded core accidents. This investigation will be carried out as part of the NRC Hydrogen Burn Survival Program already in place at Sandia. The results of the hydrogen release rate sensitivity analyses and the substantial margins between predicted and qualification temperatures for the more temperature-sensitive pieces of equipment provide the bases for classifying this item as confirmatory.

The staff will monitor the results of other ongoing NRC and EPRI hydrogen research programs to: (1) confirm the adequacy of the number and location of igniters in the upper compartment of containment; and (2) confirm the lack of significant flame acceleration at large scale. Research programs to address these concerns will be performed at the Nevada Test Site and the Sandia FLAME facility, respectively. These programs are considered confirmatory because similar test programs have been completed at smaller scale with acceptable results.

Accordingly, subject to satisfactory resolution of the open item dealing with the Tayco igniter surface temperature, the staff finds the license conditions dealing with hydrogen control during postulated degraded core accidents to be satisfactorily resolved.

APPENDIX A

CONTINUATION OF CHRONOLOGY OF NRC STAFF RADIOLOGICAL SAFETY REVIEW OF SEQUOYAH STATION

APPENDIX A

CONTINUATION OF CHRONOLOGY OF NRC STAFF RADIOLOGICAL SAFETY REVIEW OF SEQUOYAH STATION

May 5, 1981	Letter from licensee concerning program for training for mitigating core damage.
May 15, 1981	Letter from licensee concerning survivability of hydrogen recombiners and containment temperature profile.
May 18, 1981	Letter from licensee concerning EPRI hydrogen research program.
June 1, 1981	Letter to licensee concerning conceptual design for mitigating effects of potential core-melt accident.
June 2, 1981	Letter from licensee forwarding nonproprietary version of "Resolution of Equipment Survivability Issues for Sequoyah Nuclear Plant."
June 16, 1981	Letter from licensee forwarding "Research Program on Hydrogen Combustion and Control, Quarterly Progress Report 3."
July 1, 1981	Letter from licensee forwarding "Selection of Permanent Hydrogen Mitigation System for Sequoyah Nuclear Plant."
July 8, 1981	Letter to licensee requesting additional information on hydrogen control.
July 17, 1981	Letter to licensee forwarding agenda for July 23 hydrogen control/combustion meeting to review R&D programs.
July 14, 1981	Letter from licensee concerning research project regarding conceptual design for mitigation of effects of potential core-melt accidents.
August 17, 1981	Letter from licensee advising that TVA is replacing interim distribution system with permanent hydrogen mitigation system.
August 27, 1981	Letter to licensee requesting information regarding equipment temperature response to hydrogen burns.
September 22, 1981	Letter from licensee forwarding "Research Program on Hydrogen Combustion and Control, Quarterly Progress Report 4."

October 1, 1981	Letter from licensee forwarding additional hydrogen control information.
October 29, 1981	Letter to applicant forwarding "Evaluation of Quarterly Progress Report 3, Research Program on Hydrogen Combustion and Control."
November 30, 1981	Letter from licensee forwarding comments on R. Strehlow's August 17 report on hydrogen control and combustion.
December 1, 1981	Letter from licensee responding to request for information regarding hydrogen control and equipment temperature response to hydrogen burns.
January 22, 1981	Letter from licensee forwarding "Research Program on Hydrogen Combustion and Control, Quarterly Progress Report 5."
January 29, 1982	Letter to licensee extending date by which NRC must confirm that adequate hydrogen control system is installed and functioning.
February 12, 1982	Letter to licensee concerning delay in submitting R&D program on hydrogen control and combustion.
February 12, 1982	Letter to licensee requesting additional information regarding hydrogen control.
February 25, 1982	Letter from licensee responding to request for information on hydrogen control and combustion.
April 6, 1982	Letter from licensee responding to request for information on hydrogen control.
April 13, 1982	Letter to licensee requesting summary report regarding adequacy of hydrogen control measures within 60 days of completion of ice condenser owners' group hydrogen control R&D program.
April 23, 1982	Letter from licensee forwarding "Combustion Studies at High Hydrogen Concentrations, Effect of Obstacles on Combustion."
May 17, 1982	Letter to licensee forwarding R. Strehlow's report regarding hydrogen control system.
June 14, 1982	Letter from licensee forwarding "Summary of Testing to Determine Suitability of Tayco Igniter for Use in Permanent Hydrogen Mitigation System."
July 12, 1982	Letter to licensee forwarding agenda for August 4, 1982 meeting concerning R&D program for hydrogen control and combustion in ice condenser plants.

July 28, 1982	Letter from licensee forwarding quarterly progress report on R&D program for hydrogen combustion and control.
September 17, 1982	Letter to licensee requesting additional information regarding hydrogen control.
September 27, 1982	Letter from licensee forwarding "Executive Summary Report on Adequacy of Permanent Hydrogen Mitigation System for Sequoyah Nuclear Plant."
October 1, 1982	Letter to licensee requesting additional information on equipment temperature response to hydrogen burns.
November 1, 1982	Letter from licensee responding to request for information on hydrogen control.

APPENDIX B
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400 Chestnut Street Tower II

September 27, 1982

Director of Nuclear Reactor Regulation
Attention: Ms. E. Adensam, Chief
Licensing Branch No. 4
Division of Licensing
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Ms. Adensam:

In the Matter of) Docket Nos. 50-327
Tennessee Valley Authority) 50-328

Enclosed is our response to R. L. Tedesco's April 13, 1982 letter to H. G. Parris regarding the request for a summary report on the adequacy of the hydrogen control measures required by operating license conditions 2.C.(22).D (unit 1) and 2.C.(16).h for the Sequoyah Nuclear Plant. This response also represents the final quarterly report required by the above operating license conditions.

As stated in the enclosed report, we have concluded that the permanent hydrogen mitigation system, described in the enclosed report, is an adequate hydrogen control system that will perform its intended function in a manner that provides adequate safety margins.

If you have any questions concerning this matter, please get in touch with J. E. Wills at FTS 858-2633.

Very truly yours,

TENNESSEE VALLEY AUTHORITY

L. M. Mills

L. M. Mills, Manager
Nuclear Licensing

Sworn to and subscribed before me
this 27th day of Sept. 1982

Bryant M. Lowery
Notary Public
My Commission Expires 4/8/86

RHS:JEW:LHB
Enclosure

cc: U.S. Nuclear Regulatory Commission (Enclosure)
Region II
Attn: Mr. James P. O'Reilly, Regional Administrator
101 Marietta Street, Suite 3100
Atlanta, Georgia 30303

cc: See page 2

ENCLOSURE

EXECUTIVE SUMMARY REPORT
ON THE ADEQUACY OF THE
PERMANENT HYDROGEN MITIGATION SYSTEM
FOR THE
SEQUOYAH NUCLEAR PLANT

SEPTEMBER 1982

TENNESSEE VALLEY AUTHORITY

I. Introduction

This report is an executive summary whose purpose is to provide an overview of the Tennessee Valley Authority's (TVA) position that the Permanent Hydrogen Mitigation System (PHMS) is an adequate hydrogen control system for the Sequoyah Nuclear Plant and would perform its intended function in a manner that provides adequate safety margins. Highlights of the PHMS design and supporting analyses and research are presented. A more comprehensive technical summary is provided as an attachment to this report.

II. Permanent Hydrogen Mitigation System (PHMS) Description

TVA has selected the concept of controlled ignition using thermal igniters for the PHMS at the Sequoyah Nuclear Plant. Briefly, the concept is to reliably ignite lean hydrogen-air mixtures throughout the containment to achieve periodic or continuous burning. This moderated energy addition rate would allow the containment heat sinks to absorb the heat of combustion more effectively and reduce the overall containment pressurization. This selection was made after a number of alternatives were thoroughly evaluated.

In early 1980, the TVA Board of Directors requested the TVA staff to investigate potential mitigation systems for degraded core accidents at Sequoyah. An intensive study was undertaken of concepts to prevent or minimize the effects of hydrogen combustion as well as concepts to increase containment capacity for overpressure events. After evaluating each of these strategies, the TVA staff recommended the implementation of a controlled ignition system. This concept was the basis for the Interim Distributed Ignition System (IDIS) installed at Sequoyah in the summer of 1980. Beyond this commitment to the IDIS, TVA, together with Duke Power and American Electric Power (AEP), continued to investigate alternative methods of hydrogen control. After completing these evaluations and comparing the alternatives, TVA selected controlled ignition for the PHMS.

A durable thermal igniter capable of maintaining an adequate surface temperature was specified for the PHMS. An igniter developed by Tayco Engineering to operate at a standard plant voltage of 120V ac was selected and has been shown to be capable of maintaining an adequate surface temperature for extended periods, initiating combustion, and continuing to operate in various combustion environments. To assure adequate coverage, a total of 64 igniters will be distributed throughout the major regions of containment in which hydrogen could be released or to which it could flow in significant quantities (see figure in attachment). There will be at least two igniters, controlled and powered redundantly, located in each of these regions.

The PHMS components inside containment will maintain their functional capability under the effects of postaccident conditions including combustion. In addition, the PHMS components will be seismically supported.

The igniters in the PHMS are equally divided into two redundant groups to ensure adequate coverage even in the event of a single failure. Manual control and status indication of each group will be provided in the main control room. The system would be energized manually following the start of any accident which indicates inadequate core cooling without waiting for any hydrogen buildup. Separate trains of power will be provided for each group of igniters and will be backed by automatic loading onto the diesel generators upon loss of offsite power.

In addition, appropriate surveillance testing requirements and technical specifications have been provided.

We conclude that the PHMS design, as described here, is adequate and that the system would perform its intended function in a manner that provides adequate safety margins.

III. Supporting Analyses

Numerous analyses have been performed by TVA and its subcontractors during the past two years to study the effects of mitigating hydrogen by controlled ignition on ice condenser containment structures and equipment during selected degraded core accidents.

Calculations of containment atmospheric pressure and temperature have been performed using the CLASIX computer code developed by Westinghouse Offshore Power Systems. The CLASIX code results have been compared favorably to results from other containment codes. The code also has been shown to conservatively predict the response from several experiments. For input to the CLASIX code, values for combustion parameters were obtained from the literature and values for hydrogen and steam release rates were calculated with the NRC-funded MARCH code. Enough sensitivity studies were performed on containment parameters, combustion parameters, and release rates to reasonably bound the expected response. The calculated peak containment pressure for the base case set of parameters was 19 psig while the highest pressure calculated in the sensitivity studies was less than 28 psig.

The response of the containment shell and internal structures to these static pressure loads has been evaluated. The minimum calculated structural capacity at yield of 45 psig bounds these calculated internal pressures with considerable margin.

Our analyses and research have indicated that dynamic loads from a detonation do not have to be considered because detonation is not a credible phenomenon in the containment. Briefly, this is because: (a) there are no high-energy sources to initiate a detonation, (b) there would be no rich concentrations throughout the containment because the distributed igniters would initiate combustion as the mixture reached the lower flammability limit and because effective mixing would occur, and (c) there are no areas of the containment with sufficient geometrical confinement to allow for the flame acceleration necessary to yield a transition to detonation. However, at the NRC's request, TVA has calculated the response of the containment shell to an impulse pressure from a hypothetical local detonation. The results showed that a margin of safety of three existed before material yield would be reached.

The survivability of key equipment has been evaluated for the calculated atmospheric pressure and temperature profiles augmented by radiative flame effects. The equipment temperature response was calculated using the NRC-funded HEATING5 code and the results were compared with the original qualification temperatures. This comparison showed that the key equipment would survive under postaccident conditions including combustion.

In summary, these analyses have demonstrated that the containment structures and key equipment would survive the effects of selected degraded core accidents when mitigated by the PHMS and continue to remain intact and operational. We conclude that the PHMS, as supported by the analyses described here, is adequate and would perform its intended function in a manner that provides adequate safety margins.

IV. Supporting Research

Extensive research has been sponsored by TVA, Duke, AEP, and Electric Power Research Institute (EPRI) during the past two years to study hydrogen combustion, distribution, and mitigation. The research programs were designed to be confirmatory in nature. They were necessarily limited in scope and depth due to time constraints imposed by the Sequoyah operating license conditions and the availability of test facilities. The programs focused on the engineering applications of hydrogen combustion technology in support of a mitigation system.

TVA, Duke, and AEP sponsored combustion experiments at Fenwal Incorporated to investigate the ignition characteristics and reliability of the General Motors (GM) igniter used in the Interim Distributed Ignition System. TVA, Duke, AEP, and the EPRI sponsored an integrated research program at Whiteshell Nuclear Research Establishment, Factory Mutual Research Corporation, Acurex Corporation, and Hanford Engineering Development Laboratory. In one phase of the Whiteshell tests, the lean ignition limits and minimum surface temperatures were determined for both the GM and Tayco igniter. In other tests at Whiteshell, the extent of reaction of lean mixtures, the behavior of deflagrations in rich mixtures, the effects of fan- and obstacle-induced turbulence, and the behavior in an extended vessel geometry were each investigated. At Factory Mutual, the pressure suppression effects of a water micro-fog were studied in small scale. In the intermediate-scale tests at Acurex, the effects of igniter location within the test vessel and the presence of a water micro-fog were both investigated. Simulation of postaccident conditions in an ice condenser lower compartment was performed at Hanford to study the potential for hydrogen pocketing or nonuniform distribution. TVA also conducted experiments at its Singleton Laboratory on the survivability of electrical cables and the durability of igniters under cycling, endurance, and combustion conditions.

The original research programs have been successfully concluded and the data have been submitted to the NRC. The tests showed no unexpected results and confirmed the judgments made in the design and analysis supporting the PHMS. Both types of igniters were shown to be reliable and effective under a wide range of conditions. In general, the combustion parameter results agreed with values from the literature. In particular, the transient tests exhibited sequential combustion accompanied by relatively mild pressure rises which are characteristic of the behavior calculated with the CLASIX code. No detonations were ever observed even at high concentrations of hydrogen or in an extended vessel geometry. The micro-fog was ineffective as a heat sink for pressure suppression during combustion. The Hanford simulation showed good mixing with no pocketing of hydrogen.

We conclude that the PHMS, as supported by the research here, is adequate and would perform its intended function in a manner that provides adequate safety margins.

V. Conclusions

TVA has designed a Permanent Hydrogen Mitigation System employing controlled ignition to mitigate the effects of hydrogen during potential degraded core accidents at the Sequoyah Nuclear Plant. The system is redundant, capable of functioning in a postaccident environment, seismically supported, capable of actuation from the main control room, and has an ample number of igniters distributed throughout the containment. The containment structures and key equipment have been shown by analysis or testing to survive the pressure and temperature loads from selected degraded core accidents and to continue to function. An extensive research program has confirmed our analytical assumptions, demonstrated equipment survivability and shown that controlled ignition can indeed mitigate the effects of hydrogen releases in closed vessels. We conclude that the PHMS is an adequate hydrogen control system that would perform its intended function in a manner that provides adequate safety margins.

ATTACHMENT TO ENCLOSURE

TECHNICAL SUMMARY REPORT
ON THE ADEQUACY OF THE
PERMANENT HYDROGEN MITIGATION SYSTEM
FOR THE
SEQUOYAH NUCLEAR PLANT

SEPTEMBER 1982

TENNESSEE VALLEY AUTHORITY

TABLE OF CONTENTS

I. Introduction

This report is a technical summary whose purpose is to substantiate the Tennessee Valley Authority's (TVA) position that the Permanent Hydrogen Mitigation System (PHMS) is an adequate hydrogen control system for the Sequoyah Nuclear Plant and would perform its intended function in a manner that provides adequate safety margins. The report draws from and references the many technical reports that have been submitted by TVA to the NRC over the past two years. First, the criteria and final design for the PHMS is described. Next, a discussion is provided of the numerous analyses performed to determine the effects on key structures and equipment of mitigating degraded core accidents with the PHMS. Last, the research program conducted to confirm our understanding of hydrogen combustion control is reviewed. Throughout this report, resolution of the various technical issues that have been raised (containment capability, equipment survivablity, local detonation, etc.) is provided and application of the test data and analyses is made in support of the adequacy of the PHMS.

II. Permanent Hydrogen Mitigation System (PHMS) Description

TVA has selected the concept of controlled ignition using thermal igniters for the PHMS at the Sequoyah Nuclear Plant. Briefly, the concept is to reliably ignite lean hydrogen-air mixtures throughout the containment to achieve periodic or continuous burning. This moderated energy addition rate would allow the containment heat sinks to absorb the heat of combustion more effectively and reduce the overall containment pressurization. This selection was made after a number of alternative concepts were thoroughly evaluated and compared. In early 1980, the TVA Board of Directors requested the TVA staff to investigate potential mitigation systems for degraded core accidents at Sequoyah. An intensive study was undertaken of concepts to prevent or minimize the effects of hydrogen combustion such as preinerting with nitrogen, postinerting with Halon, or controlled ignition. Also investigated were concepts to increase containment capacity for overpressure events such as augmented atmospheric cooling or various forms of containment venting. Each of these mitigation strategies was evaluated based on their effectiveness, technical feasibility, additional risk, reliability, and cost. The report recommended the implementation of a controlled ignition system. This concept was the basis for the Interim Distribution Ignition System (IDIS), installed at Sequoyah in the summer of 1980.

Beyond this commitment to the IDIS, TVA, together with Duke Power and American Electric Power (AEP), continued to investigate alternative methods of hydrogen control. The potential electromagnetic interference effects of spark igniters were examined. A conceptual design study for a postaccident Halon 1301 injection system was commissioned. The corrosive effects on stainless steel of Halon decomposition products were later demonstrated by TVA at its Singleton Materials Engineering Laboratory. Bench-scale tests on controlled combustion with catalytic combustors were performed and the effects of catalyst poisoning by fission products were investigated. TVA also evaluated controlled ignition enhanced with spray fogging, oxygen removal with a gas turbine, and postaccident inerting with carbon dioxide. After completing all these evaluations and comparing the alternatives, TVA selected controlled ignition for the PHMS. Brief descriptions are provided below of the PHMS and its design criteria, operating procedure, surveillance testing, and technical specifications.

To assure that hydrogen would be ignited at any containment location as soon as the concentration exceeded the lower flammability limit, a durable thermal igniter capable of maintaining an adequate surface temperature was specified. An igniter developed by Tayco Engineering was selected for use in the PHMS since it operates at a more standard plant voltage of 120V ac than the lower voltage required by the General Motors (GM) glow plug used in the IDIS at Sequoyah. The Tayco model igniter has been shown by experiment to be capable of maintaining surface temperatures in excess of the required minimum for extended periods, initiating combustion, and continuing to operate in various combustion environments. Information on such proof testing is included in sections IV.B and IV.F of this summary report.

To assure adequate spatial coverage, a total of 64 igniters will be distributed throughout the major regions of containment in which hydrogen could be released or to which it could flow in significant quantities (see figure). There will be at least two igniters, controlled and powered redundantly, located in each of these regions. Following a degraded core accident, any hydrogen which is produced would be released into the lower compartment inside the crane wall. To cover this region, 22 igniters (equally divided between trains) will be provided. Eight of these will be distributed on the reactor cavity wall exterior and crane wall interior at an intermediate elevation to allow the partial burning that accompanies upward flame propagation. Two igniters will be located at the lower edge of each of the five steam generator and pressurizer enclosures, two in the top of the pressurizer enclosure, and another pair above the reactor vessel in the cavity. These 22 lower compartment igniters would prevent flammable mixtures from entering the ice condenser. Any hydrogen not burned in the lower compartment would be carried up through the ice condenser and into its upper plenum. Since steam would be removed from the mixture as it passed through the ice bed, thus concentrating the hydrogen, mixtures that were nonflammable in the lower compartment would tend to become flammable in the ice condenser upper plenum. This phenomenon is supported by the CLASIX containment analysis code (discussed in section III.A of this summary report) which predicts more sequential burns to occur in the upper plenum than in any other region. Controlled burning in the upper plenum is preferable since the amount of hydrogen consumed in each lean-limit burn is so low due to the relatively small volume of the region that the energy addition rate to the containment is moderated. We also conclude, based on the expert opinion of Dr. Bernard Lewis and Bela Karlovitz, that there is no realistic potential for a transition to detonation in the upper plenum because the available ignition strength is weak, the entering mixtures will be just-flammable, and the plenum does not have sufficient geometrical confinement above or below the region of combustion. Therefore, we have chosen to take advantage of the beneficial combustion characteristics of the upper plenum by distributing 16 igniters equally around it. Four igniters will be located around the upper compartment dome, four more around the top inside of the crane wall, and one above each of the two air return fans. The air return fans provide recirculation flow from the upper compartment through the 'dead-ended' volume and back into the main part of the lower compartment. To cover this region, there will be a pair of igniters in each of the rooms (a total of 16 igniters) through which the recirculation flow passes.

The PHMS components inside containment will maintain their functional capability under postaccident conditions. These components will survive the effects of multiple hydrogen burns and will be protected from spray impingement and flooding. In addition, the PHMS components will be seismically supported.

The igniters in the PHMS are equally divided into two redundant groups, each with independent and separate controls, power, and locations, to ensure adequate coverage even in the event of a single failure. Manual control of each group of igniters will be provided in the main control room and the status (on-off) of each group will be indicated there. The system would be energized manually following any accident upon the occurrence of any condition which indicates inadequate core cooling without waiting for a potential hydrogen buildup. Separate trains of Class 1E 480V ac auxiliary power will be provided for each group of igniters and will be backed by automatic loading onto the diesel generators upon loss of offsite power. Each individual circuit will power two igniters and have a design voltage of 120V ac.

Surveillance testing proposed for the PHMS will consist of energizing the system from the main control room and taking voltage and current readings from each circuit at the distribution panels located in the auxiliary building. These readings can then be compared to ones taken during preoperational testing of the system to indicate whether or not both igniters on each circuit are operational without requiring containment entry. The operability of at least 31 of the 32 igniters per train would conservatively guarantee an effective coverage throughout the containment. Appropriate technical specifications on test intervals and restoration to operable status have previously been proposed.

We conclude that the PHMS design, as described here, with igniter type and locations, redundancy, capability of functioning in a postaccident environment, seismic support, main control room actuation, and remote surveillance is adequate and the system would perform its intended function in a manner that provides adequate safety margins.

III. Supporting Analyses

Numerous analyses have been performed by TVA and its contractors during the past two years to study the effects of mitigating hydrogen by controlled ignition on ice condenser containment structures and equipment during selected degraded core accidents. Calculations of containment atmospheric pressure and temperature during these accidents have been performed using the CLASIX code. The response of the containment shell and internal structures to the peak calculated pressures has been evaluated. The response of the containment shell to an impulse pressure from a hypothetical local detonation has been calculated. The survivability of key equipment has been evaluated for the calculated atmospheric pressure and temperature profiles augmented by radiative flame effects. The analyses have demonstrated that the containment structures and key equipment would survive the effects of selected degraded core accidents when mitigated by the PHMS and continue to remain intact and operational. We conclude that the PHMS, as supported by the analyses described below, is adequate and would perform its intended function in a manner that provides adequate safety margins.

A. Structures

Containment atmospheric pressure loadings on the shell and internal structures during degraded core accidents including hydrogen combustion have been calculated using the CLASIX containment analysis code written by Offshore Power Systems (OPS), a division of Westinghouse. The expertise developed over the years in writing and verifying NRC-accepted design basis containment analysis codes was used as a basis for this effort. The ice condenser containment was modeled in CLASIX using such standard assumptions as homogeneous volume nodes. Extensions to this traditional methodology were included in the code to account for the effects of degraded core accidents such as hydrogen combustion. Hydrogen combustion was represented by a simple model that added the heat released during burning to the surroundings when flammability criteria were met in that region. The CLASIX code has been compared by OPS to TMD, an NRC-accepted subcompartment ice condenser analysis code, and to COCOCLASS9, a degraded core accident containment analysis code based on the NRC-accepted COCO code. The comparisons showed good agreement. The CLASIX code was also used to model hydrogen combustion experiments conducted at Fenwal Incorporated and Lawrence Livermore National Laboratory. The code conservatively overpredicted the pressure and temperature response measured during the tests. We conclude that the CLASIX code is adequate to use for conservative prediction of the ice condenser containment response to degraded core accidents including hydrogen combustion.

The CLASIX input required to model the Sequoyah containment response to such an event consisted largely of physical parameters such as volumes, areas, and material properties that have been used previously in design basis licensing analyses. Several of these parameters, including containment spray flow rate, initial ice mass, and air return fan flow rate, were varied in sensitivity studies. In addition, several hydrogen combustion parameters were specifiable in the input to allow for a wide range of sensitivity studies. These include the lower flammability limit (LFL), the fraction of burn completeness, and the burn duration. The burn duration actually represents the pressure rise time based on flame propagation at a constant speed after simultaneous ignition at all igniters located in that volume. In our latest studies, the conservative assumptions used in the base case calculation were an LFL of 8 volume percent, a burn fraction of 85 percent, and a flame propagation speed of 6 ft/sec. The parameters assumed in the best estimate calculation were an LFL of 6 volume percent, a burn fraction of 60 percent, and a propagation speed of 3 ft/sec. In the various sensitivity studies, the LFL was varied between 4 and 10 volume percent, the burn completeness fraction between 40 and 100 percent, and the burn duration based on flame speeds between 1 and 12 ft/sec. These value ranges are supported by numerous references in the literature for turbulent combustion in lean-limit mixtures. Results from the recent Electric Power Research Institute (EPRI) -utility lean-limit hydrogen combustion experiments validated the use of these value ranges. Information and conclusions from this combustion research is included in sections IV.B, IV.C, and IV.D of this summary report. In further comparisons to actual data, as stated above, the CLASIX code was able to conservatively overpredict experimental pressures measured at two different facilities. The parameter sensitivity studies were performed to bound reported data and to account for such postulated phenomena as steam inerting the lower compartment or fogging reducing the burn completeness in the upper plenum. We conclude that the combustion parameter input, including sensitivity variations, is adequate to be used in the CLASIX code for conservative prediction of containment response.

Another set of CLASIX input parameters required to model a degraded core event included the hydrogen and steam release rates into the containment. Allowances were made in the CLASIX code for these input parameters to be varied over a wide range since they would be dependent on the accident sequence being studied. A small-break LOCA with failure of safety injection (S_2D) was chosen as the base case for analysis because it is similar to the TMI-2 class of accidents. The S_2D event is also an appropriate selection because it is believed to be the most probable accident sequence that would result in core damage at Sequoyah. Recovery of core cooling was assumed to occur prior to core slump and the cladding reaction was terminated at a conservative level of 75 percent. In addition, a review of other probable scenarios shows the S_2D transient results in more than twice as much hydrogen generation prior to core slump as was found in the other scenarios. Beyond the S_2D base case, sensitivity studies were performed to evaluate the effects of increasing the hydrogen release rate throughout the event by as much as a factor of three and increasing the rate in a 'spike' fashion over a segment of the event. In addition, the hydrogen release rates from analyses (using the MARCH computer code) of a number of other accident sequences were reviewed and found to be bounded by either the S_2D base case or the sensitivity studies. The S_2D base case release rate used in the TVA analysis also bounded the release rates presented in NUREG/CR-2540, 'A

Method for the Analysis of Hydrogen and Steam Releases to Containment During Degraded Core Cooling Accidents.' Since the PHMS is intended to mitigate degraded core events which are terminated prior to core slump, the release rates during the core recovery phase were calculated and also found to be less than already covered by the studies. We conclude that the hydrogen and steam release rate input, including sensitivity variations, is adequate to use in the CLASIX code for conservative prediction of containment response.

The CLASIX code calculations for the base case set of input parameters described above resulted in a peak containment pressure of 19 psig. The best estimate case resulted in a peak pressure of less than 12 psig, the containment design pressure. The highest peak pressure that resulted from any of the numerous sensitivity studies was less than 28 psig. As described below, the Sequoyah containment yield strength has been calculated to be at least 45 psig.

Structural analyses have been performed to determine the static pressure capability of the containment and internal structures. The pressure rise resulting from a hydrogen deflagration is slow enough to be treated as a static pressure load in the analysis. The associated temperature effects were found to be negligible. An elastic-plastic analysis was performed by TVA using a finite element model of the limiting section (1/2' cylindrical plate between elevations 756' 3' and 810' 3') of the steel containment shell. All other containment boundary components were evaluated and it was determined that this shell section was limiting in terms of containment yield strength. Using the actual minimum yield strength of the plate material, the yield pressure of this shell section was found to be at least 45 psig. Other independent structural evaluations have been made that confirmed this minimum capacity. An evaluation was also made of the concrete divider deck (the main internal structure between the upper and lower compartment) that revealed its differential pressure capacity to be equal to or greater than the containment shell capacity. We conclude that the capability of the containment shell and internal structures is adequate to withstand the static pressure loads during hydrogen combustion in the degraded core accidents studied.

In addition to these analyses of static pressure capability, TVA has performed an analysis of the dynamic response of the containment to an impulse load from a hypothetical local detonation. Development of the impulse load and the structural analysis was requested by the NRC, although our analyses and research have indicated that local detonation is not a credible phenomenon in the containment. To briefly review, several factors affect the potential for a detonation including ignition strength, hydrogen concentration, and geometrical confinement. Addressing these factors individually, the thermal igniters used for controlled ignition are considered by experts, including Dr. Roger Strehlow (an NRC consultant), to be 'soft' or 'weak' sources of ignition and as such are not likely initiators of detonation. Second, rich concentrations of hydrogen will not be present throughout large regions of the containment because the PHMS igniters will initiate combustion near the LFL. This has been demonstrated on numerous occasions (see sections IV.A, IV.B, IV.C, and IV.D) including tests in the presence of steam or spray. In addition, isolated rich concentrations away from the source due to extreme hydrogen gradients or pocketing will not occur. This has been confirmed by results from the mixing tests in the simulated ice condenser containment at Hanford Engineering Development Laboratory (see section IV.E). Third, we have identified no areas of the containment with sufficient geometrical confinement to allow for the extreme flame acceleration necessary to yield a transition to detonation. For example, the vertical ice baskets in the ice condenser are not sufficiently confined radially and the circumferential upper plenum above the ice condenser is not sufficiently confined above or below for a transition to detonation to occur (see section II). Even if rich mixtures were postulated to exist in a confined geometry, it is improbable that a detonation would result. Illustrating this fact are two of the tests conducted at Whiteshell Nuclear Research Establishment that failed to produce a detonation when igniting a stoichiometric (about 29.5 volume percent hydrogen) mixture in an enclosed sphere or even when igniting a 25 volume percent mixture in a pipe attached to the sphere in a configuration more conducive to a transition to detonation. For more information see section IV.B of this summary report. We conclude that detonation is not a credible phenomenon in the ice condenser containment. However, as stated above, TVA has developed an impulse load from a hypothetical local detonation and analyzed the dynamic containment response. The hypothetical load was based on the detonation of a six-foot diameter spherical cloud with wave speeds (to calculate the pressure rise time) and peak overpressures obtained from the literature. The impulse was assumed to act at the center of the same critical containment shell section used for the static analysis. The results showed that a margin of safety of three existed before material yield would be reached. We conclude that the containment shell could survive even such a hypothetical local detonation.

Based on the above analyses, we conclude that the containment structures would survive the effects of selected degraded core accidents when mitigated by the PHMS and continue to remain intact.

B. Equipment

Containment atmospheric pressure and temperature loadings on key equipment in the containment have been calculated using the CLASIX code discussed above in section III.A. The parameters assumed previously for the base case were used again except that the burn duration was based on a low flame speed of one ft/sec chosen at the NRC's request to enhance the heat contribution from the flame. To account for these flame effects, the CLASIX temperature transient in each of the regions containing key equipment selected for analysis was augmented by a radiative heat flux term. The radiative heat flux was imposed during each burn and was based on a conservative adiabatic flame temperature of 1400°F. This combined temperature load was imposed on the equipment in an analysis using the standard HEATING5 thermal code which was developed with NRC funding. The equipment was initially assumed to be in equilibrium at the highest preburn atmospheric temperature resulting from the postulated degraded core accident. The thermal analysis was extended until well after all the temperature peaks associated with burns had passed.

Key equipment inside containment essential for safe shutdown of the plant was identified. That subset of equipment either considered to be potentially sensitive to temperature or located in regions of numerous burns such as the ice condenser upper plenum was then selected. This subset would bound the remaining key equipment items for the evaluation of temperature survivability. The pressure capability of the key equipment was judged to be controlled by the limiting containment shell section pressure capability described above in section III.A. The subset of key equipment included the exposed incore thermocouple cable and hot and cold leg RTD cable, the Interim Distributed Ignition System (IDIS) igniter assembly, the igniter assembly power cable in conduit, and a transmitter assembly representative of the types installed in the plants. The decision was made to test the exposed cables rather than attempting to analyze them due to the potential for changing surface properties (see section IV.F). Thermal analyses were performed on the remaining key components.

The igniter assembly analysis was performed on a Sequoyah IDIS assembly which should conservatively bound the PHMS assembly response. It showed that the core of the transformer inside the igniter assembly would reach 157°F while the transformer windings were designed to operate at up to 428°F. Analysis also showed that the conduit for the igniter assembly power cable would reach 332°F (and the interior even less) while tests conducted at TVA's Singleton Laboratory showed the cable in conduit would function without degradation up to 600°F. The transmitter analysis resulted in a casing surface temperature of 245°F (and the interior even less) while the transmitter has been qualified to operate at 320°F. This thermal analysis methodology was compared to an NRC-accepted Westinghouse equipment thermal qualification model and showed good agreement. In addition, the methodology was applied to sample Fenwal test data and found to conservatively overpredict thermal response.

In addition to the key subset described above, the effects of temperature and pressure were evaluated for other key equipment such as the air return fans. No burns were predicted by CLASIX to occur in the upper compartment for the base case parameter assumptions. However, even for those sensitivity studies which resulted in upper compartment burns, the atmosphere only very briefly exceeded the elevated temperatures at which the fans were designed to operate in an emergency. In addition, the massive fan motor and casing (weighing approximately 1300 lbs.) have a significant amount of thermal inertia. The backdraft dampers above the fans avoid pressure loads on the fans during lower compartment pressurization. Again, no upper compartment burns are predicted for the base case. However, the fan blades have been structurally analyzed to take a static load (in addition to the normal operating stresses) greater than even the maximum peak differential pressure predicted in the sensitivity studies discussed in section III.A.

In addition to analyzing the survivability of the key equipment described above, special areas such as the foam insulation around the ice condenser were evaluated for temperature effects. A thermal analysis using the HEATING code mentioned above was performed by Duke Power to evaluate whether heat from combustion in the ice condenser could decompose the foam to form flammable products. The analysis showed that even the heat flux from a constant band of flame applied locally for 45 minutes to the ice condenser walls would not be sufficient to elevate the foam behind it to its pyrolysis temperature.

Based on the above analyses and tests, we conclude that the containment key equipment would survive the effects of selected degraded core accidents when mitigated by the PHMS and continue to remain operational.

IV. Supporting Research

Extensive research has been sponsored by TVA, Duke, AEP, and EPRI during the past two years to study hydrogen combustion, mitigation, and distribution. The research programs were designed to be confirmatory in nature. They were necessarily limited in scope and depth due to time constraints imposed by the Sequoyah operating license conditions and the availability of test facilities. The programs focused on the engineering applications of hydrogen combustion technology in support of a mitigation system. TVA, Duke, and AEP sponsored combustion experiments at Fenwal Incorporated. TVA, Duke, AEP, and EPRI sponsored research at Whiteshell Nuclear Research Establishment in combustion and igniter development, at Factory Mutual Research Corporation in combustion and mitigation, at Acurex Corporation in combustion and mitigation, and at Hanford Engineering Development Laboratory in distribution. TVA conducted experiments at its Singleton Laboratory in equipment survivability and igniter development. The original research programs have been successfully concluded and the data have been submitted to the NRC. To summarize, the tests showed no unexpected results and confirmed the judgments made in the design and analysis supporting the PHMS. We conclude that the PHMS, as supported by the research described here, is adequate and would perform its intended function in a manner that provides adequate safety margins.

A. Igniter Performance Testing - Fenwal, Incorporated

A two-phase experimental program was undertaken at Fenwal to investigate the ignition characteristics and reliability of the General Motors (GM) igniter. The test vessel was a 134 ft^3 steel sphere that was heated and insulated. Phase 1 consisted of a series of premixed combustion tests with hydrogen concentrations at 8, 10, and 12 volume percent. The effects of fan-induced turbulence and steam addition were investigated in several tests. The performance of the GM igniter in igniting hydrogen mixtures was demonstrated to be reliable. In addition, comparison of such test results as pressure rises and ignition limits with previously published information showed good agreement.

The Phase 2 follow-on tests consisted of further premixed tests with hydrogen concentrations between 5-10 volume percent, tests where hydrogen was continuously injected into the test vessel, and a series of tests using water sprays. The most important result of the Phase 2 program was the ability of the igniter to reliably ignite lean hydrogen mixtures under adverse conditions, including the presence of steam and water sprays, and to continue to operate. The minimal pressure rises experienced during the continuous injection tests indicated the igniter's capability to initiate local combustion of hydrogen-air mixtures just as they became flammable. The series of sequential burns that occurred during the continuous injection tests were characteristic of the behavior predicted with the CLASIX code (section III.A). No detonations were ever observed even when pure hydrogen was being admitted to the vessel during the transient tests.

B. Hydrogen Combustion Phenomena - Whiteshell Nuclear Research Establishment

The experimental program at Whiteshell consisted of a small-scale igniter testing segment and a multifaceted large scale segment aimed at enhancing our understanding of basic combustion phenomena. The results of this program are summarized below.

Small-scale tests were performed in a 17-liter vessel to provide further evidence of the capability of both GM and Tayco thermal igniters to reliably ignite lean hydrogen mixtures. Numerous tests were conducted to determine the lower ignition limits and corresponding igniter surface temperatures in various premixed hydrogen-air-steam mixtures. Hydrogen concentrations were varied between 4-15 volume percent and steam concentrations varied between 0-60 volume percent. The measurement of igniter surface temperature required for ignition showed that the igniter at its normal operating temperature has considerable margin even for high steam concentrations.

The larger-scale tests were performed in the Whiteshell Containment Test Facility using a 223 ft^3 heated and insulated metal sphere and, for some tests, a 20-foot long by 1-foot diameter attached pipe. These tests were grouped into four principal areas:

(a) Extent of reaction of lean mixtures
(b) Laminar spherical deflagration
(c) Effects of fan- and obstacle-induced turbulence
(d) Extended geometry (sphere and attached pipe)

The lean mixture tests were performed in the sphere to investigate the extent of reaction under various conditions of steam and fan-induced turbulence. Hydrogen concentrations were varied between 5-11 volume percent and steam between 0-30 volume percent. Fans were activated in several of the tests. Results were in agreement with previously-published data on the flammability of lean mixtures. Results also showed that the addition of relatively large (over 30 volume percent) amounts of steam reduced the pressure rise following burns due to the added heat capacity. This indicates that pressure rise data from dry tests may be overconservative for application to plant environments with high steam concentrations. Results also showed that turbulence increased the rate and magnitude of pressure rise for a given concentration by increasing the burn completeness, thus corroborating the Fenwal results. This indicates that burning at relatively lean concentrations would be promoted by the turbulent plant conditions.

The laminar spherical deflagration tests were performed in the sphere to compare the actual pressure rises with the corresponding theoretical adiabatic pressure rises and to confirm that no detonations would result even at high concentrations of hydrogen. Hydrogen concentrations were varied between 10-42 volume percent and steam between 0-40 volume percent. Fans were activated in several tests. Results again showed that the addition of large amounts of steam reduced the pressure rise following burns. The actual pressure was always less than the theoretical pressure and the margin increased as the hydrogen concentration was increased. No detonations were observed even at stoichiometric and higher concentrations of hydrogen which are classically considered to be detonable.

The turbulence tests were performed in the sphere to investigate the effects of turbulence induced by fans and gratings on the extent and rate of combustion. In these tests, hydrogen concentrations varied between 6-27 volume percent. One test was run with 10 volume percent steam. Results showed that for rich mixtures, forced turbulence did not increase the overall pressure rise but did increase the rise rate slightly. In lean mixtures without fans, the presence of gratings tended to increase the magnitude and rate of pressure rise. At high concentrations or with fans, the gratings reduced both the magnitude and rate of pressure rise by acting as heat sinks. These results indicate that no unanticipated pressure effects result from forced turbulence even at high concentrations of hydrogen.

The extended geometry tests were performed by attaching the pipe to the side of the sphere. The effects of varying igniter location, fans, and unequal concentrations in each vessel were investigated. The hydrogen concentration varied between 6-25 volume percent. All of these tests were run without adding steam. Results of varying the igniter locations between the end of the pipe and the center of the sphere confirmed that lean mixtures propagate a flame more readily in the upward than horizontal direction and in the presence of turbulence. Although the burst disc initially separating the mixtures in the pipe and sphere induced local turbulence which enhanced the rate and extent of reaction, no significant effects of propagating flames between unequal concentrations were observed. Even in a long, narrow pipe, at high concentrations of hydrogen with no steam present, no detonation occurred.

The Whiteshell tests investigated a number of parameters related to the potential hydrogen combustion phenomena inside the containment. Based on their results, we conclude that the GM and Tayco igniters would reliably ignite lean mixtures of hydrogen in a postaccident environment. We also conclude that the observed effects of steam, induced turbulence, connected geometries, and unequal concentrations on the nature of hydrogen combustion have confirmed our previous understanding. None of the results would preclude the application of distributed ignition for postaccident hydrogen control. In particular, the tests are important for what they did not show, the occurrence of a detonation even in the presence of extremely severe conditions.

C. Water Micro-Fog Inerting - Factory Mutual Research Corporation

The Factory Mutual project was the first of a two-part experimental program to investigate the pressure suppressant effects of a water micro-fog. The purpose of the Factory Mutual project was to experimentally identify in small scale a set of nominal micro-fog conditions for investigation in the Acurex intermediate scale hydrogen combustion studies (Section IV.D). Since the interest was in the pressure suppressant effects of a water micro-fog, the Factory Mutual project was necessary in order to avoid inadvertently inerting the Acurex test vessel. Therefore, the approach taken by Factory Mutual to achieve the project objective was to experimentally determine the water micro-fog requirements for inerting hydrogen-air mixtures and then simply recommend to Acurex a set of micro-fog conditions that did not meet those requirements. Emphasis was placed on visually dense fogs with number mean droplet sizes between 1-100 microns.

Tests were conducted in a plexiglas tube approximately 3.5 feet long with a 6 inch inner diameter. A 2.8 Joule spark served as the ignition source. Several tests were also conducted with a GM glow plug as the ignition source to verify the applicability of these tests to installed distributed ignition systems. Thermocouples were used to determine the presence of combustion. Five different spray nozzles were used in order to obtain different fog conditions, i.e., a characteristic droplet size and density. Varying the pressure drop across each spray nozzle also allowed different fog conditions to be obtained. Additionally, the micro-fog temperature and hydrogen concentration were varied.

Test results showed that at ambient conditions, visually dense water micro-fogs only marginally increase the hydrogen lower flammability limit. Additionally, as the characteristic droplet size is increased, the fog density required to maintain the same level of inerting is significantly increased. It was also demonstr[illegible]t increasing the micro-fog temperature increases the effe[illegible]e hydrogen lower flammability limit. Finally, the Factory Mutual tests showed that a glow plug and a strong spark source performed with no noticeable difference in combustion results.

D. Hydrogen Combustion Control Studies - Acurex Corporation

The Acurex project consisted of two phases. Phase 1 investigated the effect of igniter location within an enclosed compartment, while Phase 2 was the second of the two-part water micro-fog program (see Section IV.C). Quiescent tests have been conducted by other organizations where the ignition source location was varied. However, conditions inside the containment during a degraded core accident cannot be considered quiescent. Thus, the purpose of the Phase 1 test program was to qualitatively address the importance of igniter location during transient conditions. The purpose of the Phase 2 test program was to experimentally investigate the pressure suppressant effects of the two water micro-fog conditions recommended by Factory Mutual in both transient and quiescent tests.

Tests were conducted in a 17-foot high vessel with a 7-foot inner diameter. The total free volume was approximately 630 ft^3. Thermocouples were used to detect flame front location and vessel atmosphere temperature. Strain gauge and piezoelectric pressure transducers were used to measure the vessel atmospheric pressure. Transient tests were conducted in Phases 1 and 2 with a continuous injection of either hydrogen or a hydrogen-steam mixture. The hydrogen and hydrogen-steam flow rates used in the tests were calculated by applying the volume ratio of the test vessel and the combined lower and 'dead-ended' plant compartments to the average release rates calculated with the MARCH Code for an S_2D accident sequence. An igniter assembly supplied by Duke Power was preenergized for all transient tests. In the Phase 1 tests, the igniter was located either near the top, at the center, or near the bottom of the test vessel. Some Phase 1 tests were conducted with water sprays present. Phase 2 tests were conducted both with and without two separate micro-fog conditions and with various hydrogen concentrations. The Phase 2 transient tests were conducted with the bottom igniter location.

Results of the Phase 1 tests indicated that igniter location has some effect on combustion characteristics. This effect was shown to depend on: (1) whether the test was quiescent or transient, (2) the location of the igniter relative to the hydrogen source, and (3) the amount of turbulence present. The tests showed that, during transient injection periods, the pressure rise was less when the igniter was located near the region where the entering hydrogen mixed and first became flammable. The location of this region within containment would be determined by the geometry of each plant compartment, the hydrogen entry location and velocity, and the presence of turbulence within the compartment. Since these tests have demonstrated the desirability of near-limit combustion, we conclude that igniters should be located in the ice condenser upper plenum to allow near-limit combustion to occur as the hydrogen exits from the ice condenser. The Phase 1 tests also indicated that the potential for a larger pressure rise existed when the hydrogen source jet continued to bypass the igniter until the bulk of the vessel had reached a flammable concentration. This would tend to support locating igniters in the upper portion of the lower compartment to preclude the source jet from potentially bypassing nearby igniters. It is important to note that multiple igniters were located throughout the containment regions at various elevations to ensure near-limit combustion (see Section II). In addition, it is noteworthy that the Hanford tests (described in Section IV.E) demonstrated that the lower compartment region would be well-mixed, which, according to the Acurex tests, tends to reduce the significance of igniter location relative to the inlet mixing region. The Phase 1 tests also confirmed previous findings on the pressure mitigative effects of steam and water sprays due to turbulence-induced mixing.

Results of the Phase 2 tests showed that a water micro-fog had no pressure mitigative effect during hydrogen combustion in quiescent mixtures. This indicated that the dominant effect of the fog droplets was not as a heat sink. The pressure mitigative effect of micro-fogs in the transient tests seemed to be due to induced turbulence similar to the effect of sprays in some of the Phase 1 tests. This induced turbulence promoted mixing which enhanced the potential for near-limit combustion of the entering hydrogen.

Since an ice condenser containment would be sufficiently turbulent to ensure good mixing during a degraded core accident (see Section IV.E for a discussion of the Hanford tests), we conclude that inducing additional turbulence with micro-fogging would be unnecessary.

In addition to the above conclusions based on the test objectives, an evaluation of the tests revealed additional information from which conclusions were drawn. The GM igniter assemblies, identical to those in Duke Power's McGuire Nuclear Station and very similar to those used in the TVA IDIS, survived over five cumulative hours of exposure to combustion test environments. The assembly and power cable continued to operate without failure. The second additional conclusion dealt with estimated flame speeds. Although the test was not specifically instrumented to obtain flame speeds, it was possible to calculate 'average' flame speeds from the pressure rise data of several transient and quiescent tests. The calculated flame speeds in the transient tests varied from 1-2 ft/sec with steam present and either top or bottom ignition to 4 ft/sec with no steam present and bottom ignition. Flame speeds from the quiescent tests varied from 3-8 ft/sec as the hydrogen concentration was increased from 5 to 11 volume percent. Thus, we conclude that these data support the flame speed ranges used in the CLASIX analyses (see Section III.A). Another important result of the transient test series was that the nature of combustion was always deflagrative instead of detonative even when a hydrogen-rich mixture was entering the vessel. Perhaps the most significant observation was the extreme contrast in pressure rise between quiescent and transient combustion tests. The pressure rises during all of the transient tests in both Phase 1 and 2 was dramatically less than during the quiescent tests (with the exception of one very lean mixture quiescent test). From this contrast, we conclude that caution must be used in the direct application of data from quiescent tests to the investigation of transient conditions. A final conclusion is that since the expected containment postaccident environment would more closely resemble the transient test conditions, it follows that the pressure rises from sequential combustion should be relatively benign.

E. Hydrogen Distribution - Hanford Engineering Development Laboratory

Tests were conducted at Hanford to investigate the potential for nonuniformities or gradients in the distribution of hydrogen during a degraded core accident in an ice condenser containment. The purpose was twofold: (1) to investigate whether the potential existed for pocketing of rich mixtures that could lead to a local detonation and (2) to determine whether the well-mixed nodalization assumptions in the containment analysis were valid. The effects of temperature, forced circulation, and jets were studied. The emphasis was placed on representing a small break LOCA in the ice condenser containment since that was the base case used for design and analysis of the ignition system.

The Hanford Containment Systems Test Facility was selected because its relatively large volume (30,000 ft^3) reduced scaling effects and because its interior could be customized to represent the structures of an ice condenser containment. Helium was used as a simulant for hydrogen in most of the tests due to site safety regulations.

Since the upper compartment of the ice condenser containment is well mixed by the sprays, the lower compartment region was chosen for modeling emphasis in the facility. A divider deck, reactor cavity, refueling canal, the air return fans and ice condenser lower inlet doors were all represented. The hydrogen (helium)/steam release was scaled from small break LOCA calculations using the MARCH computer code. Two release scenarios were modeled: (1) a 2' pipe break with a horizontal orientation and (2) a 10' pressurizer relief tank rupture disc opening with a vertically upward orientation. Atmospheric temperatures, velocities, and gas concentrations were measured at several distributed sample points during the tests.

The test results showed that mixing was very good, even without forced circulation by the air return fans. The maximum hydrogen concentration difference at any time during the release between any two sample points in the lower compartment was 2-3 volume percent. In addition, these concentration differences had stopped increasing even before the release period was over. We conclude that there is no potential for pocketing of rich mixtures and that the well-mixed assumptions in the containment analysis were justified.

F. Cable Survivability and Igniter Durability - TVA Singleton Materials Engineering Laboratory

Tests were conducted at Singleton to demonstrate the survivability of electrical cable and the durability of both GM and Tayco igniters. Samples of the exposed incore thermocouple and hot and cold leg RTD cables and the igniter assembly power cable in conduit were subjected to temperatures conservatively higher than calculated containment atmospheric temperature profiles during hydrogen burns. In a separate test series, the GM and Tayco igniters were subjected to durability testing consisting of thermal cycling, endurance, and combustion.

Since surface temperature effects could be important to the survivability of exposed thermocouple and RTD cable in the containment, tests were conducted at Singleton in lieu of analysis. A transient temperature profile that conservatively bounded the calculated transient atmospheric profile of the lower compartment (where the thermocouple and RTD cables are located) was imposed on the exposed cables in an oven. An indication of the conservatism of the test was the fact that the measurement thermocouple placed inside an outer cable jacket showed temperatures during the test even higher than the peak calculated atmospheric temperature in containment. In another test, a constant temperature profile that conservatively bounded the integrated heat flux from the calculated transient atmospheric profile of the upper plenum (where the igniter power cable would be exposed to the most burns) was imposed on the cable in conduit in an oven. The fact that the cable reached and maintained internal temperatures during the test well above the calculated cable temperature is evidence of the conservatism of this test. Following each of the tests, all the cable insulation successfully passed visual inspection and a resistance check for breakdown under high voltage. We conclude that both the exposed cable and cable in conduit would survive a degraded-core accident that included hydrogen combustion.

Durability tests were performed at Singleton on both the GM and Tayco igniters. The thermal cycling tests consisted of repeated activations in air at several constant voltages. The endurance tests consisted of activation at several constant voltages for extended periods of up to one week. The combustion tests consisted of activations in both a premixed closed vessel and in a flowing mixture in an open combustion tube. Each of the igniter types continued to operate satisfactorily during all of these tests and successfully passed posttest visual inspections. We conclude that either the GM or Tayco igniter is sufficiently durable to provide controlled ignition in a degraded core accident.

V. Conclusions

TVA has designed a Permanent Hydrogen Mitigation System employing controlled ignition to mitigate the effects of hydrogen during potential degraded core accidents at the Sequoyah Nuclear Plant. The system is redundant, capable of functioning in a postaccident environment, seismically supported, capable of actuation from the main control room, and has an ample number of igniters distributed throughout the containment. The containment structures and key equipment have been shown by analysis or testing to survive the pressure and temperature loads from selected degraded core accidents and to continue to function. An extensive research program has confirmed our analytical assumptions, demonstrated equipment survivability and shown that controlled ignition can indeed mitigate the effects of hydrogen releases in closed vessels. We conclude that the PHMS is an adequate hydrogen control system that would perform its intended function in a manner that provides adequate safety margins.

VI. References

Section II

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- Third Quarterly Research Report (letter from L. M. Mills to E. Adensam dated June 16, 1981)
- Selection of the Permanent Hydrogen Mitigation System for the Sequoyah Nuclear Plant (letter from M. R. Wisenburg to E. Adensam dated July 1, 1981)
- Fourth Quarterly Research Report (letter from L. M. Mills to E. Adensam dated September 22, 1981)
- Response to Additional NRC Questions on Hydrogen Control System (letter from L. M. Mills to E. Adensam dated December 1, 1981)

Section III.A

- Sequoyah Nuclear Plant Hydrogen Study, Volume II, Revision in Response to NRC Questions (letter from J. L. Cross to R. L. Tedesco dated December 11, 1980)
- Additional Information Requested by NRC (letter from J. L. Cross to R. L. Tedesco dated December 17, 1980)
- Resolution of Equipment Survivability Issues for the Sequoyah Nuclear Plant (letters from L. M. Mills to E. Adensam dated June 2, 1981, and June 3, 1981)
- CLASIX Topical Report (letter from L. M. Mills to E. Adensam dated December 1, 1981)
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Section III.B

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- Resolution of Equipment Survivability Issues for the Sequoyah Nuclear Plant (letters from L. M. Mills to E. Adensam dated June 2, 1981, and June 3, 1981)

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Section IV.B

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Section IV.C

- Fifth Quarterly Research Report (letter from L. M. Mills to E. Adensam dated January 22, 1982)

Section IV.D

- Fifth Quarterly Research Report (letter from L. M. Mills to E. Adensam dated January 22, 1982)

Section IV.E

- Fifth Quarterly Research Report (letter from L. M. Mills to E. Adensam dated January 22, 1982)

Section IV.F

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- Resolution of Equipment Survivability Issues for the Sequoyah Nuclear Plant (letters from L. M. Mills to E. Adensam dated June 2, 1981, and June 3, 1981)

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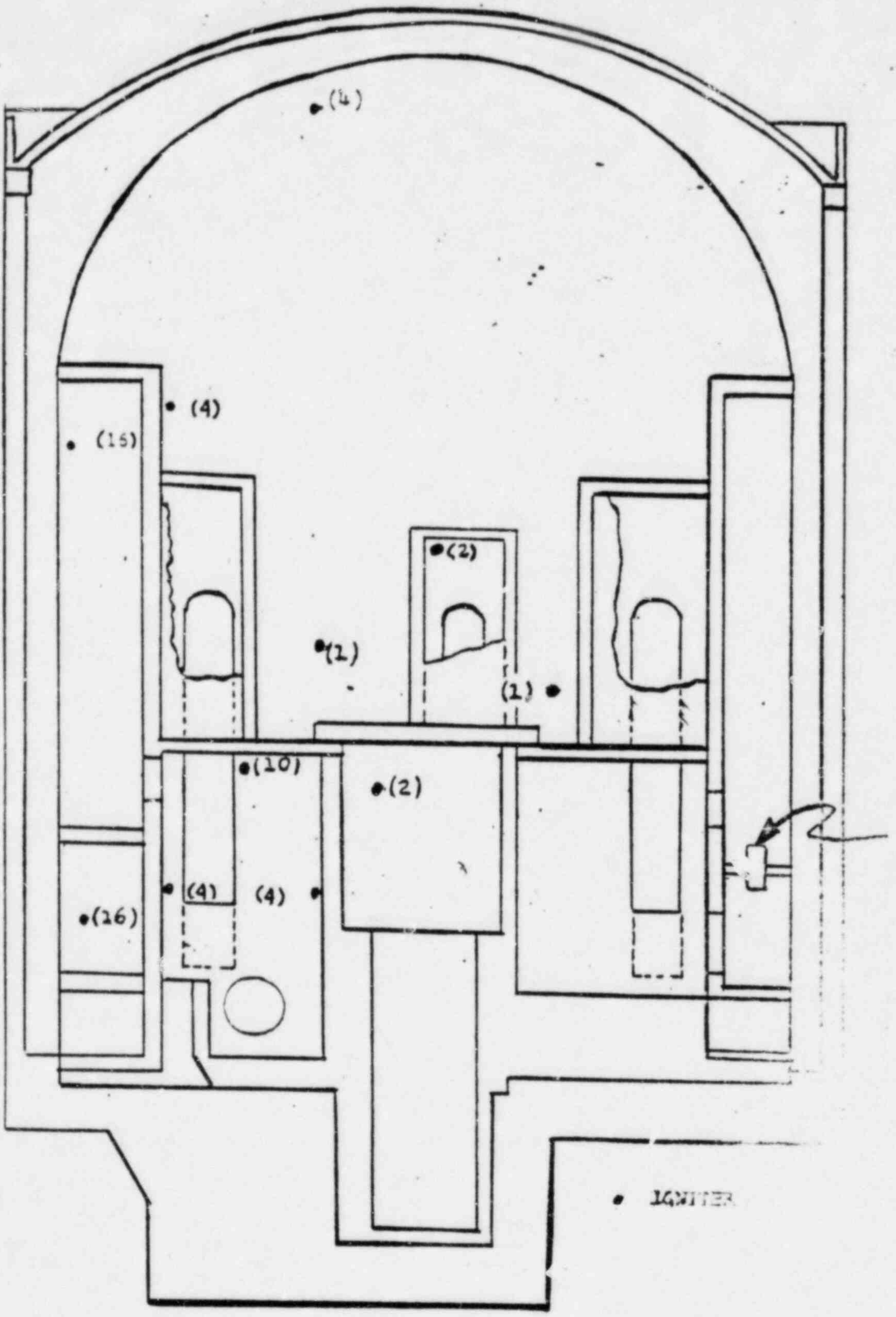

ICE CONDENSER CONTAINMENT ELEVATION VIEW
SHOWING RELATIVE PHMS IGNITER LOCATIONS