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. <u>Equipment</u>

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. <u>Water Micro-Fog Inerting - Factory Mutual Research Corporation</u>

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 demonstrated that increasing the micro-fog temperature increases the effect on the 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. <u>Hydrogen Combustion Control Studies - Acurex Corporation</u>

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. <u>Hydrogen Distribution - Hanford Engineering Development Laboratory</u>

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 <u>Materials Engineering Laboratory</u>

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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- Second Quarterly Research Report (letter from L. M. Mills to A. Schwencer dated March 16, 1981)

- 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)

- Response to Additional NRC Questions on Hydrogen Control System (letters from L. M. Mills to E. Adensam dated December 1, 1981, and January 5, 1982)

Section III.B

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Section IV.A

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Section IV.B

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- Sixth Quarterly Research Report (letter from L. M. Mills to E. Adensam dated April 23, 1982)

- Summary of Testing to Determine Suitability of Tayco Igniter for Use in the Permanent Hydrogen Mitigation System at Sequoyah and Watts Bar Nuclear Plants (letter from L. M. Mills to E. Adensam dated June 14, 1982)

- Seventh Quarterly Research Report (letter from D. S. Kammer to E. Adensam dated July 28, 1982)

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

- Sequoyah Nuclear Plant Hydrogen Study, Volume II (letter from L. M. Mills to A. Schwencer dated September 2, 1980)

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