MARK III CONTAINMENT
HYDROGEN CONTROL OWNERS GROUP

J. R. Langley, Project Manager

c/o Gulf States Utilities • North Access Road at Highway 61 • St. Francisville, LA 70775

504-635-6094
Ext. 2832

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HGN-111-NP

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

Attention: Document Control Desk

Reference: 1) Letter from J.R. Langley to R. Bernero, "Report of CLASIX-3 Generic Analyses and Validation of CLASIX-3 Against 1/4 Scale Test Facility Data," HGN-092, dated June 10, 1986

2) Letter from J.R. Langley to USNRC, "CLASIX-3 Summary Report," HGN-111, dated December 15, 1987

Subject: CLASIX-3 Summary Report

The Hydrogen Control Owners Group (HCOG) has utilized the CLASIX-3 computer code to analyze the Mark III containment and drywell response to hydrogen generation events. The CLASIX-3 code has been used to analyze containment response to combustion below the diffusion flame threshold and to analyze the drywell response to combustion at all postulated hydrogen release rates. In order to clarify the manner in which the CLASIX-3 code is being used to address combustion in the containment in the Hydrogen Control Program, a summary report has been developed which delineates both the manner in which the CLASIX-3 code results will be used in this program and the basis upon which the code's results are deemed acceptable. Attachment 2 provides this Summary report.

In Reference 1, the HCOG demonstrated that the CLASIX-3 analyses yield conservative predictions of the thermal environments which would be produced in the containment during events with sustained hydrogen production below the diffusion flame threshold. The summary report provided in Attachment 2 identifies the hydrogen release regimes that have been evaluated with the CLASIX-3 code. Attachment 2 also provides a discussion of the conservatisms inherent in the CLASIX-3 code and the HCOG base case, as well as the acceptability of using CLASIX-3 predictions as a bounding representation of the combustion phenomena that occur at low hydrogen release rates.

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In response to related questions and comments from the NRC staff in the October 7, 1987 meeting, Attachment 3 provides a report which addresses combustion phenomena at low hydrogen release rates. This report discusses the nature of combustion at low flows, provides examples of its effect in the containment, and addresses the potential severity of the thermal environment that may be associated with this combustion.

The attached document is the non-proprietary version of Reference 2 and is submitted in accordance with 10 CFR 2.790. The proprietary information contained in Reference 2 has been omitted from this document.

This submittal was compiled by HCOG from the best information available for submittal to the Nuclear Regulatory Commission. The submittal is believed to be complete and accurate, but it is not submitted on any specific plant docket. The information contained in this letter and its attachments should not be used for evaluation of any specific plant unless the information has been endorsed by the appropriate member utility. HCOG members may individually reference this letter in whole or in part as being applicable to their specific plants.

Very truly yours,

J. R. Langley
J. R. Langley
Project Manager

JRL/jlw

Attachment

cc: see attached list

cc: Mr. Lawrence C. Shao
Director, Division of Engineering
and System Technology
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D.C. 20555

Mr. Ashok Thadani
Assistant Director for Systems
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D. C. 20555

Mr. . . Kudrick
Plant Systems Branch
Division of BWR Licensing
Office of Nuclear Reactor Regulation
Washington, D.C. 20555

Mr. Lester L. Kintner
Hydrogen Control Project Manager
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D.C. 20555

Attachment 1
to HGN-111-NP

CLASIX-3 SUMMARY REPORT

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1.0 INTRODUCTION

The Hydrogen Control Rule, as defined in 10 CFR 50.44, requires that Mark III facilities ensure via a program of testing and analysis that the installed hydrogen Control systems are "capable of handling without loss of containment integrity an amount of hydrogen equivalent to that generated from a metal-water reaction involving 75% of the fuel cladding surrounding the active fuel region. "In response to this Rule, the Hydrogen Control Owners Group (HCOG) was formed to conduct the required testing and analysis in support of the resolution of issues related to hydrogen control in Mark III containments during degraded core events. The initial focus of the Owners Group was to evaluate the potential overpressurization threat to the containment structure that was postulated to result from hydrogen combustion. An evaluation of the expected combustion phenomena was conducted to determine the most threatening combustion mechanism which could result from hydrogen release into a Mark III containment. Deflagrations were subsequent by identified as the combustion mechanism which would produce the highest and most rapid pressure rise in the Mark III containment and, thus, would represent the greatest pressure challenge to the containment structural integrity. The HCOG then investigated different analytical tools capable of modeling deflagrations in the Mark III containment and selected the CLASIX code to analyze containment response.

The CLASIX code had been used for the analysis of hydrogen combustion in ice condenser pressure suppression containments. It was determined that the CLASIX code could be modified to model many elements common to the Mark III containments (e.g., upper pool dump, containment spray system, suppression pool). Therefore, the HCOG completed several modifications to the CLASIX code to develop an analytical model of the Mark III geometry. The modified code was renamed CLASIX-3.

As early focus of HCOG's program was to ensure that hydrogen combustion initiated by the hydrogen ignition system would not threaten containment structural integrity, the HCOG completed extensive calculations which demonstrated that each Mark III plant containment structure had adequate capability to withstand the peak pressures calculated by CLASIX-3 for the postulated hydrogen deflagrations. Subsequently, it was recognized that the hydrogen flow rates considered in the early containment response analysis would produce steady diffusion flames anchored at the suppression pool surface as opposed to the discrete deflagrations postulated in the previous analysis. The consideration of diffusive combustion at the postulated hydrogen flowrates required that HCOG shift the focus of the program to address the ability of equipment to survive the potentially severe thermal environments that could result from diffusion flames on the suppression pool surface.

To support a testing and analysis program to define thermal environments which could be used in equipment survivability analyses, the HCOG delineated two accident scenarios which provided representative hydrogen release histories for evaluating degraded core events that involve significant hydrogen generation. As discussed in previous correspondence with the NRC (Reference 1), mechanistic analyses were conducted using these accident scenarios to define the hydrogen generation profiles which would result. The HCOG was unable to define a scenario in which both a mass of hydrogen equivalent to that which would be produced in a 75% metal-water reaction would be generated and a recoverable core geometry would be maintained. Therefore, the hydrogen release histories utilized in the HCOG's Hydrogen Control Program were comprised of two components. The first component was entitled the "reflood" portion of the history and represented the calculated hydrogen release that was predicted to be generated during the mechanistically defined portion of the accident scenario. The reflood portion of the release history represents the hydrogen that is produced when a depressurized reactor with a * uncovered core is recovered by injecting water into the reactor pressure vessel. This component typically represented hydrogen generated in a * percent metal-water reaction. The HCOG's 1/4 Scale Testing Program has confirmed that diffusion flames on the suppression pool surface will occur for this portion of the release history. The reflood portion of the release history is, therefore, outside the scope of this report since the environment that results from diffusive combustion on the pool surface will be defined via the 1/4 Scale Test Program.

The second component of the hydrogen release history is referred to as the "tail" and represents a non-mechanistical by defined constant hydrogen generation rate. The tail portion is modeled by a 0.1 lbm/sec release rate that is extended until the total hydrogen generation is equivalent to that which would result from the interaction of water with 75 percent of the zircaloy cladding in the active fuel region. As a result of data from the 1/20th Scale Test Program, the 0.1 lbm/sec tail portion of the release history was considered to be well below the hydrogen generation rate that would support diffusive combustion on the suppression pool surface. That is, this flow rate was believed to represent a flowrate at which deflagrations would be possible. However, data from the 1/4 Scale Test Program indicates that diffusive pool burning occurs at this flowrate and that the threshold for extinction of diffusive combustion on the pool surface is lower than * , depending on background hydrogen concentration.

Subsequent testing in the 1/4 Scale Test Facility indicated that the threshold for diffusive combustion could be defined at flows of * and * lbm/sec, depending on the local gas concentrations. The test program indicated, however, that the combustion which occurred below this threshold was

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Even though deflagrations did not occur during 1/4 scale testing, the HCOG decided to utilize CLASIX-3 for the analysis of hydrogen combustion which would occur at hydrogen production rates below the diffusion flame threshold. This decision was based on the expectation that CLASIX-3 would

*Deleted due to proprietary information.

bound the combustion below the diffusion flame threshold by modeling a combustion mechanism which produces more severe thermal environment at low hydrogen flowrates. The HCOG does not contend that CLASIX-3 models the localized combustion phenomena, but that in modeling deflagrations it is modeling a combustion mechanism that predicts a more severe global environment than has been measured locally in the 1/4 Scale Test Facility for localized combustion.

The report outlines the basis for considering CLASIX-3 to be acceptable for predicting bounding temperatures that could occur in a Mark III containment at the low hydrogen flowrates in the tail. The discussion focuses or conservatisms used in modeling the deflagration combustion phenomena, conservatisms in code input (as verified by sensitivity studies), and conservatisms in application of the code results.

2.0 BACKGROUND

As noted in Section 1.0, the CLASIX code was selected by the Hydrogen Control Owners Group (HCOG) after an extensive search for a computer code which could model the Mark III configuration and also deflagrations. The version of the code utilized in early combustion analyses by the HCOG contained modifications made by the HCOG to the original CLASIX code in order to accurately model the Mark III configuration. These modifications included the addition of a suppression pool model, and models for upper containment pool interaction, and a Mark III specific containment spray carryover model for flows from the containment to the wetwell. The modified version of the code was renamed CLASIX-3. The first submittal to the NRC of analyses using the CLASIX-3 code has made in 1982 via Reference 2. The CLASIX-3 code was subsequently revised to incorporate NUREG0588 heat transfer correlations and a natural circulation model. A large number of analyses were completed by the HCOG as documented in References 3, 4 and 5. Reference 3 also validated the CLASIX-3 results against data obtained from the 1/4 Scale Test Facility.

In evaluating the adequacy of the CLASIX-3 code, the NRC requested the HCOG to discuss the conservatisms incorporated into both its approach for calculating thermal environments using CLASIX-3 and in utilizing these thermal environments in assessing equipment survivability. This report presents a discussion of the CLASIX-3 conservatisms, the conservative nature of the CLASIX-3 code in bounding the localized combustion phenomena, and the conservatisms in the HCOG's application of the resulting thermal environment predictions.

3.0 CLASIX-3 CONSERVATISMS

In discussing the conservative nature of the CLASIX-3 code's prediction of combustion at low hydrogen flowrates, three issues will be examined. The first involves the conservatisms inherent in the base case input model that is used for CLASIX-3 analyses. As presented in Section 3.1, several different input parameters have been assigned values that provide for a conservative prediction of the thermal environment produced by deflagrations. The second issue deals with the conservative nature of the deflagration combustion phenomenon modeled by CLASIX-3 versus the combustion mechanism detected in a scaled test program. As discussed in Section 3.2, the frequency and severity of deflagrations as modeled by CLASIX-3 definitively bounds the localized combustion phenomena recorded in the 1/4 Scale Test Program. The third issue concerns the conservative manner in which the CLASIX-3 results have been utilized in the HCOG's generic equipment survivability analyses. As summarized in Section 3.3, the use of the wetwell environment predicted in the no spray base case presents a significant conservatism in subsequent equipment response analyses.

3.1 CLASIX-3 Model Conservatisms

The CLASIX-3 code model has subdivided the Mark III containment into four compartments: drywell, wetwell, intermediate volume and containment volume as shown in Figure 1. Flow between compartments is modeled as shown in Figure 2. Also included in the CLASIX-3 model are the suppression pool, containment spray system, upper pool dump and combustible gas Control system. A major conservatism relative to the definition of the Mark III geometries in the base case code input model is discussed in Subsection 3.1.1 below. In addition, several of the other primary conservatisms which have been incorporated into the input deck are addressed in subsections 3.1.2 through 3.1.6 below.

3.1.1 Model Geometry

The Perry Nuclear Power Plant was used as the base plant for the CLASIX-3 model. Perry has the second largest core of all the HCOG member utility plants, and the smallest containment volume to core size ratio. In addition, the Perry wetwell volume, where the majority of the predicted combustion occurs, is representative of the other three HCOG plants (i.e., all three are within ten percent of the Perry wetwell volume). Therefore, from an energy addition perspective, the CLASIX-3 base case temperatures will be representative predictions for both the Perry facility and the other HCOG facilities.

3.1.2 Release History

The tail release rate is represented by a constant flow rate of 0.1 lbm/sec. As characterized in past HCOG correspondence (Reference 6), this release rate was calculated using a non-mechanistic model since the HCOG was unable to develop accident scenarios that would mechanistically model an event that results in hydrogen production equivalent to a 75 percent metal-water reaction (MWR). The non-mechanistic model which has been used to predict hydrogen production is based upon an energy balance in a severely damaged core which no longer retains an intact geometry. The core is assumed to have deformed into a debris bed which is postulated to form following in injection of ECCS into a severely overheated core. Although injection of ECCS into the vessel should rapidly quench the core and terminate hydrogen production, the HCOG has considered the improbable case which results in continued oxidation equivalent to 75% MWR. The energy balance of this core configuration which was subsequently completed by the HCOG calculated a peak release rate of 0.1 lbm/sec. For conservatism, the HCOG used this peak rate for the entire tail.

In reality, however, constant hydrogen generation at 0.1 lbm/sec during a prolonged degraded core accident is highly improbable. In lieu of the constant hydrogen release rate assumed by the HCOG, a more realistic tail release history would probably be characterized by hydrogen production at a rate initially less than 0.1 lbm/sec which decreases with time. A release of this nature would be expected to represent a less severe thermal environment for equipment. This is due to the fact that while localized combustion would be expected to occur initially, as the rate of hydrogen production decreased, the frequency of combustion activity would also decrease. This behavior is bounded by the multiple burns predicted by the CLASIX-3 code.

In applying this release rate in the Hydrogen Control Program, the HCOG initially used the CLASIX-3 code since early (1/20th scale) test data indicated that deflagrations would occur at this flow rate. Subsequent testing in the 1/4 Scale Test Facility, however, indicated that *

. No deflagrations were recorded in the 1/4 Scale Test Program. In addition, the test data indicate that the temperatures that result during the tail are non-threatening to equipment survivability (i.e., less than *).

In spite of the results of the 1/4 Scale Program which indicated the presence of * ,
the HCOG chose to use the CLASIX-3 code to conservatively predict the thermal environment that would result from combustion at low hydrogen flow rates. Relative to the accident sequences utilized in the HCOG program, the CLASIX-3 analyses are used to model only the tail portion of the release history.

Therefore, it can be concluded that the use of a constant hydrogen generation rate of 0.1 lbm/sec for the tail portion of the hydrogen generation events as analyzed by HCOG (i.e., as analyzed with the CLASIX-3 code), represents a bounding profile.

*Deleted due to proprietary information.

3.1.3 Burn Parameters

One of the dominant input parameters for the CLASIX-3 code is the flame speed or burn duration assumed for each of the deflagrations modeled by the code. As discussed in Reference 3, the HCOG modified the flame speed used in CLASIX-3 during the analysis program to provide additional conservatism in the code's predictions. The flame speed used in early CLASIX-3 analyses was * feet per second, while the current value is * feet per second. The reduced flame speed is considered a more realistic value. The use of a lower flame speed in CLASIX-3 and survivability calculations will result in an increase in the burn duration. This represents a more severe thermal environment from the standpoint of equipment response, since an extended burn duration will offset the lag time inherent in equipment response, and ultimately produce higher equipment temperatures. While the use of the higher flame speed produces higher peak temperatures, the equipment response will be lessened due to the shorter period of time at these elevated temperatures. Therefore, the use of a lower, more realistic, flame speed can be seen to provide a greater challenge to equipment in the associated survivability analyses.

3.1.4 Heat Transfer Correlations

The initial analyses conducted by the HCOG with the CLASIX-3 code (Reference 2) used heat transfer correlations utilized by the original CLASIX code. Based on discussions with the NRC, the HCOG modified the code to allow NUREG 0588 heat transfer coefficients to be used, if desired. The HCOG has utilized the NUREG 0588 heat transfer correlations in its CLASIX-3 analyses.

As documented in Case XIV of Reference 4, the use of NUREG 0588 correlations * predicted wetwell (and drywell) peak temperatures compared to those analyses where the original CLASIX correlations are used. Since, as will be discussed below, the HCOG has used the wetwell environment in its generic survivability analyses of containment equipment, it is evident that use of NUREG 0588 analysis results in thermal environments which are *

3.1.5 Spray Operation

As reflected in the generic survivability analyses (Reference 7) conducted by the HCOG, the CLASIX-3 analyses used assumed no spray operations. While this approach is different from the position documented in Reference 8 by the HCOG, it has been taken to ensure that the code's prediction of the resulting thermal environment will be conservative. This position is supported by the no-spray versus spray sensitivity study presented in Reference 4. This sensitivity study indicated that peak temperatures increased * * when sprays were absent.

*Deleted due to proprietary information.

3.2 Combustion Phenomena

A more fundamental conservatism which is exhibited in the use of CLASIX-3 analyses to model combustion at low hydrogen flow rates is the combustion mechanism modeled by the code. As indicated earlier, the CLASIX-3 code models combustion as deflagrations. A deflagration is defined as the combustion of a volume of hydrogen/air/steam mixture in which a well-defined flame front propagates away from an ignition source through the combustible gas volume. Deflagrations, as modeled by CLASIX-3, involve the entire gas volume in a specified region of the model (e.g., wetwell volume, intermediate volume or drywell volume). Deflagrations, as modeled by CLASIX-3,

*

*, a different combustion mode was detected in the 1/4 Scale Test Program. Thermocouple traces from the 1/4 Scale Test Facility reflect * throughout the facility at low hydrogen flow rates (i.e., at and below *). This combustion mechanism has been termed localized combustion and, as indicated in Section 1.0, is characterized *. While Attachment 3 provides a more comprehensive discussion of localized combustion as it was recorded in the 1/4 Scale Test Facility, a brief comparison of CLASIX-3 deflagration environments to 1/4 scale localized combustion environments is presented below.

Due to the occurrence of diffusive combustion on the pool surface at hydrogen flowrates near the 0.1 lbm/sec tail release rate, and the presence of localized combustion at various locations *, the HCOG utilized test data recorded during two scoping tests (i.e., Tests S.14 and S.15) to define the diffusion flame extinguishment limit more precisely. The release history used during these tests involved a Case B reflood profile followed by a hydrogen release rate in the tail 1 that was systematical by adjusted to remain below the threshold for diffusion flames, except for a period of * hydrogen release intended to reduce the global oxygen concentration in the test facility. This hydrogen release history is illustrated in Figure 3.

As anticipated, as sustained diffusive combustion on the suppression pool surface was prevented by the reduced hydrogen release rate,

*

Figure 4 is a trace from an

*

represents one of the more sustained measurements of the effects of localized combustion in the 1/4 Scale Test Facility. *

*Deleted due to proprietary information.

*

The hydrogen flow for the first time period (* *) averaged * . Hydrogen flow in the second time period (*) averaged * . [During the period from * seconds to * seconds, the hydrogen release rate was increased to * to reduce the global oxygen concentration. * .]

To assess the severity of this environment from an equipment survivability perspective, the thermal load created by the measured localized combustion environments was calculated. Thermal load is defined as * . The thermal load has been used by the HCOG to select limiting test configurations for subsequent survivability analyses, and is considered an acceptable method for assessing the relative severity of the two combustion modes being examined here. Table 1 lists the thermal load data calculated for the two periods of localized combustion identified in Figure 4 during Test S.15. The average temperature for these time periods is also recorded.

A CLASIX-3 code run has also been conducted using the Test S.15 hydrogen release history reflected in Figure 3. This analysis produced multiple wetwell burns with peak temperatures of approximately * as evidenced in * compared to peak temperatures of approximately * during periods of * Test S.15. The CLASIX-3 response was subsequently analyzed to calculate the thermal load that would result from these burns. * lists the CLASIX-3 thermal load and average temperature values for the periods over which localized combustion was recorded in the 1/4 Scale Test Facility. As indicated in Table 1, the combustion mode modeled by the CLASIX-3 code, i.e., deflagrations, produces * as measured in the 1/4 Scale Test Facility.

It should be noted that the comparison of the wetwell CLASIX-3 environment to an environment recorded in a region of the 1/4 Scale Test Facility's intermediate volume is an acceptable methodology since the CLASIX-3 wetwell environment has been used for the generic equipment survivability analysis which includes equipment located in the intermediate volume.

3.3 Application of CLASIX-3 Results

CLASIX-3 code results have been utilized by HCOG as boundary conditions for the HEATING-6 computer code in the generic survivability analysis program (Reference 8). HEATING-6 is used to determine the thermal response of equipment which is required to survive environments produced by hydrogen combustion. The CLASIX-3 code does not predict local temperatures, but rather calculates a global temperature for each of the four compartments. Since a unique temperature at each equipment's specific location cannot be obtained from the code, the HCOG utilized the global wetwell temperature as the thermal environment for all containment

*Deleted due to proprietary information.

equipment analyzed (including equipment that is actually located outside of the wetwell). This approach is very conservative. The wetwell presents the most severe thermal environment since all *

. The wetwell case chosen for the generic equipment survivability analyses is a no spray case. This means that even though sprays would be available to remove heat from the hot wetwell gases in a postulated accident, credit was not given for them in the CLASIX-3 base case analyses. These effects all combine to produce a containment thermal environment that is extremely conservative for all Mark III plants.

*Deleted due to proprietary information.

4.0 CONCLUSION

The CLASIX-3 code yields conservative predictions of combustion in containment during low hydrogen flow periods by modeling this combustion as serial deflagrations. In addition, the HCOG has utilized some conservative assumptions in establishing the input parameters for the CLASIX-3 code. These conservatisms ensure the code yields bounding results for the types of combustion which would occur in the containment as a result of degraded core accident. In addition, the HCOG has included additional conservatisms in the application of the CLASIX-3 code results which defined thermal environments used for generic containment equipment survivability analyses. Therefore, the use of the CLASIX-3 code to analyze the containment response to degraded core accidents is appropriate.

5.0 REFERENCES

1. Letter from J. D. Richardson to H. R. Denton, "Report on Hydrogen Control Accident Scenarios, Hydrogen Generation Rates and Equipment Requirements", HGN-006, dated September 9, 1982.

2. Letter from J. D. Richardson to H. R. Denton, "Hydrogen Control Owners Group (HCOG) BWR-6 Mark III Containment Sensitivity Study for Hydrogen Generation Event", HGN-001, dated January 15, 1982.

3. Letter from J. R. Langley to R. Bernero, "Report of CLASIX-3 Generic Analyses and Validation of CLASIX-3 Against 1/4 Scale Test Facility Data", HGN-092, dated June 10, 1986.

4. Letter from J. R. Langley to R. Bernero, "CLASIX-3 Generic Sensitivity Analysis", HGN-109, dated December 9, 1986.

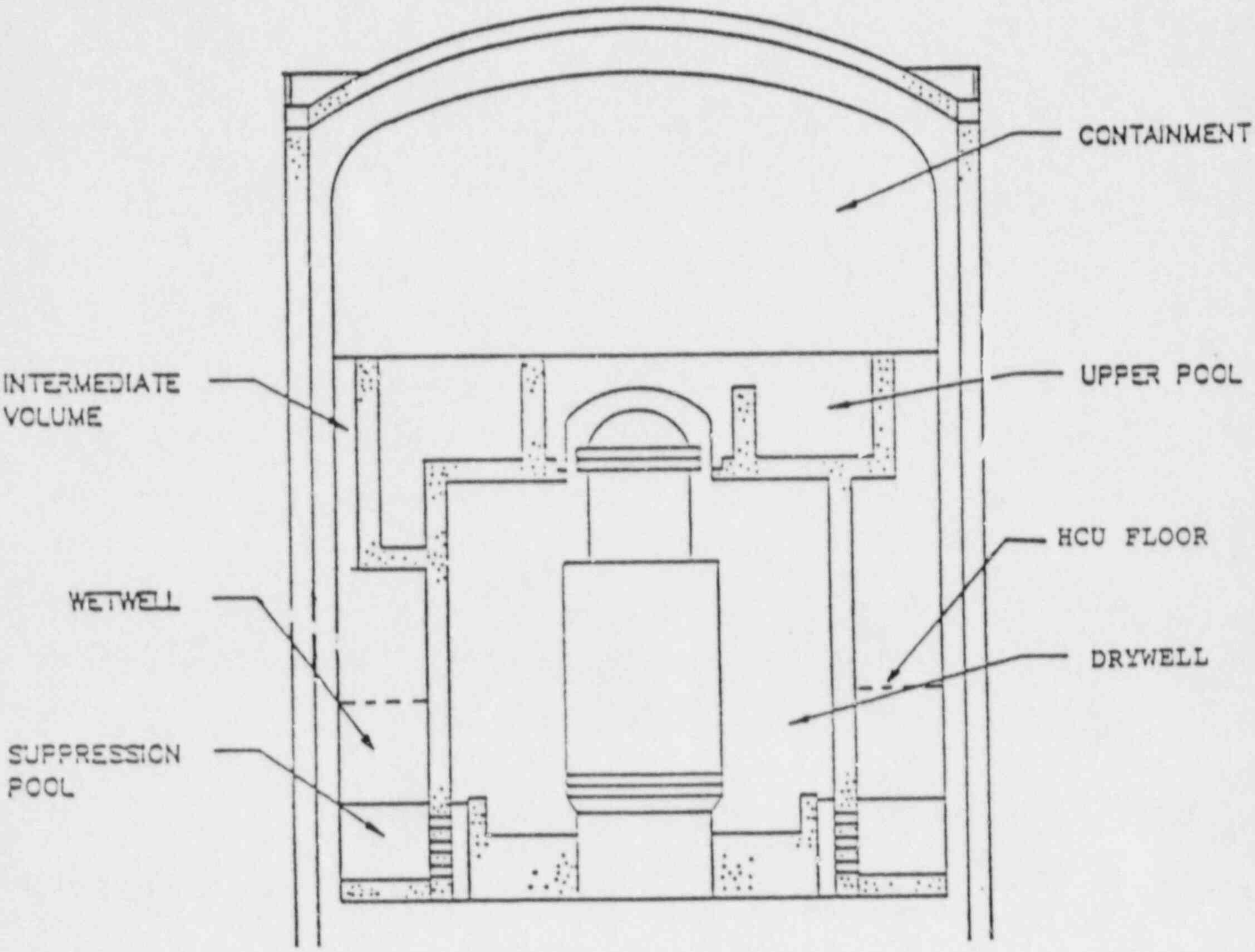
5. Letter from J. R. Langley to R. Bernero, "CLASIX-3 Delayed ADS Generic Sensitivity Study", HGN-120, dated June 25, 1987.

6. Letter from S. H. Hobbs to R. Bernero, "Model for Hydrogen Production Equivalent to 75% MWR", HGN-034, dated May 17, 1985.

7. Letter from J. R. Langley to NRC, "Generic Equipment Survivability Analysis", HGN-118, dated August 7, 1987.

8. Letter from S. H. Hobbs to R. Bernero, "Availability of Containment Spray System", HGN-051, dated July 26, 1985.

Table 1 has been excluded due to the
proprietary nature of its contents.



MARK III CONTAINMENT

FIGURE 1

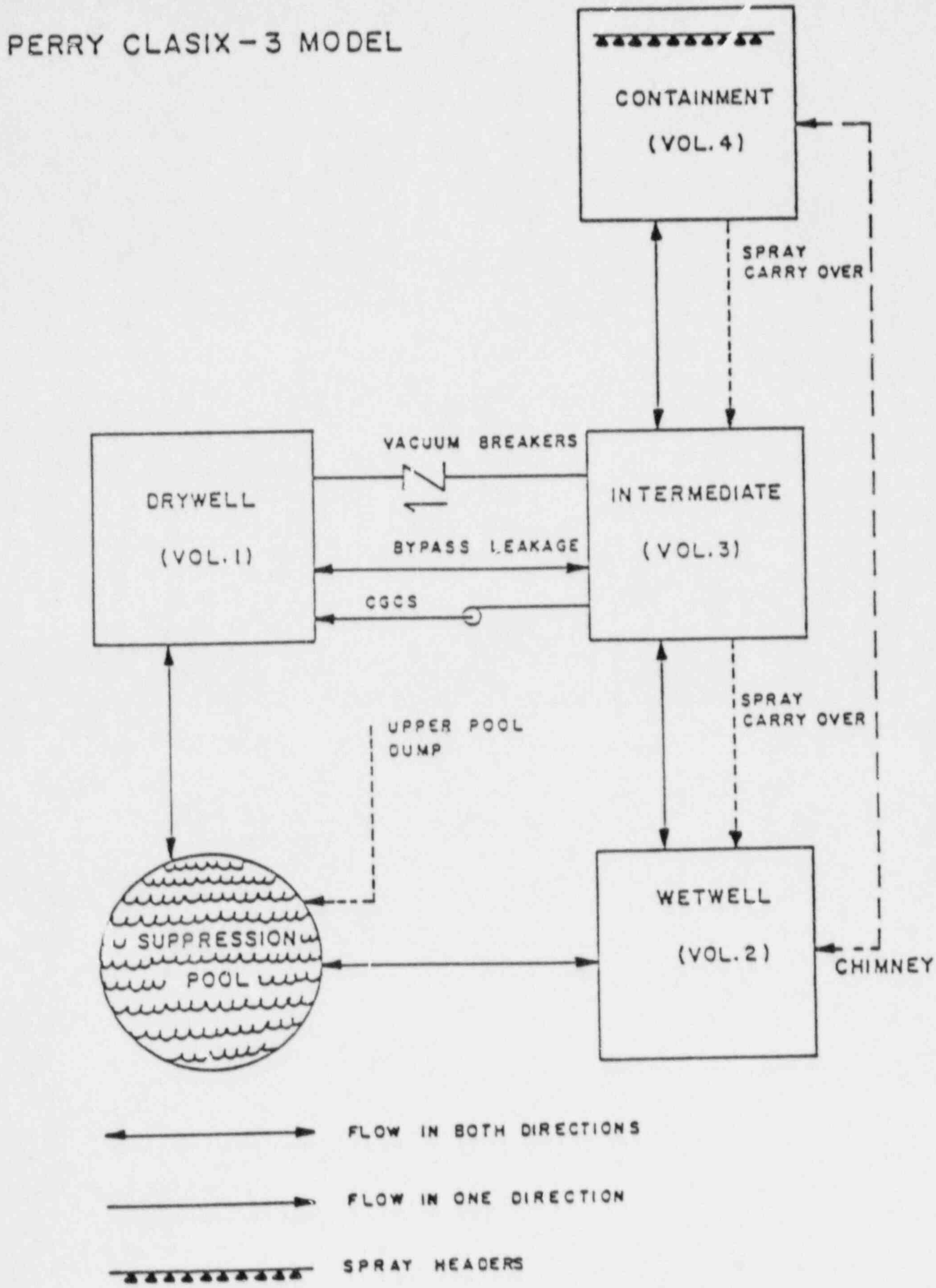

PERRY CLASIX-3 MODEL
CONTAINMENT
(VOL. 4)
SPRAY
CARRY OVER
VACUUM BREAKERS
DRYWELL
(VOL. 1)
INTERMEDIATE
(VOL. 3)
BYPASS LEAKAGE
CGCS
SPRAY
CARRY OVER
UPPER POOL
DUMP
SUPPRESSION
POOL
WETWELL
(VOL. 2)
CHIMNEY
FLOW IN BOTH DIRECTIONS
FLOW IN ONE DIRECTION
SPRAY HEADERS

FIGURE 2

Figures 2 through 5 have been excluded due to the proprietary nature of their contents.

Attachment 2
to HGN-111-NP

THE CHARACTERIZATION AND OCCURRENCE OF DIFFUSIVE HYDROGEN COMBUSTION AT LOW HYDROGEN FLOW RATES

TABLE OF CONTENTS

I. INTRODUCTION

In response to questions and comments from the NRC staff in a meeting with HCOG on October 7, 1987, combustion phenomena at low hydrogen release rates, as observed in HCOG's 1/4 Scale Test Facility, are discussed in the attachment. The NRC and its reviewers had questions regarding characterization of the localized combustion phenomenon, effects of containment sprays, effects of the stuck open relief valve (SORV) location, information gained from the video cameras, and the expected effects of hydrogen igniters. Reviewers suggested that a review of the test data could yield insight into the localized combustion phenomenon. This paper characterizes the combustion at low flows, discusses its effect in the containment, and addresses the severity of the associated thermal environments.

Importantly, deflagrations have not occurred in the 1/4 Scale Test Facility (QSTF), other than brief, lightoff burns upon ignition. Instead, combustion phenomena are characterized by diffusion flames, whose stability depends on the hydrogen release rate. As discussed in Reference 1, from 1/4 scale testing, the stable diffusion flame threshold falls within the range of * (full scale). Above this range, the flames are sustained, stable, and are anchored to the pressure suppression pool surface. In this range the flames become intermittent. The pool flame extinction limit (FEL) occurs at flows ranging from * , depending mainly on the background gas hydrogen concentration. The flame extinction limit decreases to about * as background hydrogen concentration increases to about * .

Five tests, S.08, S.09, S.10, S.14 and S.15 were conducted in the 1/4 Scale Test Facility (QSTF) with portions of their hydrogen release near the FEL. During these periods of very low hydrogen inlet flow, pool burning generally ceased, while the effects of combustion were observed elsewhere in the test volume, usually above the HCU floor. This phenomenon has been called localized combustion by the HCOG. Localized combustion has been defined by HCOG as * .

Test facility thermocouples indicate that combustion at low hydrogen flows occurred in the * chimneys, and at the top of the * chimney. Although combustion activity was present, the measurements show that the resultant thermal environments were * . The thermocouple data show that temperatures are * In all cases, the maximum temperatures during periods of combustion at low flows were * produced during peak hydrogen injection.

*Deleted due to proprietary information.

The data taken during low hydrogen release periods from the five subject tests demonstrate certain repeatable trends. For example, areas where thermocouple activity was observed are recurrent and are generally predictable at the low flow rates. Also, the zones of maximum temperatures are recurrent. Furthermore, hydrogen concentrations at low release rates are maintained within predictable bounds and at nearly constant levels.

The localized combustion phenomenon at low hydrogen release rates below the FEL is characterized by

*

. Instrumentation coverage, while not sufficient to track random movement of the combustion zones, is nonetheless adequate to determine the character, the magnitude, and the extent of the energy deposition to the global gas flows in the chimneys. The deposition is

*

. The net result is that local gas temperatures are * , and the combustion phenomenon poses * . Typically, peak temperatures recorded during localized combustion are * . Thermal loads are * . Average gas temperatures are * , and the temperature responses are *

To support the discussion which follows, test data have been reviewed with the intent of identifying zones of combustion at low flows and addressing the potential severity of the resultant thermal environments in these areas.

*Deleted due to proprietary information.

II. CHARACTER OF COMBUSTION AT LOW HYDROGEN FLOWS

Figure 1 shows the hydrogen release history for Test S.10[a], where the release rate is below the FEL for times greater than about 800 seconds. The hydrogen and oxygen concentration data alone are sufficient to establish that combustion is occurring during the low flow period. Figure 2 shows continuous oxygen depletion during this time interval. The hydrogen concentration, on the other hand, remains constant at about * even through the 1/4 scale equivalent of about * full scale is being continuously injected. This indicates that all hydrogen entering the facility at low flows is consumed in the presence of the distributed hydrogen ignition system. Widespread thermocouple responses indicate that * . The overall energy release rate is determined by the inlet hydrogen flow rate, which for the low flow portion of S.10 was about * of the peak reflood hydrogen release rate.

Combustion activity is * during periods of low hydrogen flow. An examination of Test S.10 thermocouple responses indicated * locations, ranging from the * elevation to the * elevation in the test facility. The effects of combustion activity were apparent in the * chimneys at each of the instrumented elevations in the aforementioned range. (Reference 2 provides the appropriate test facility instrumentation plans for the scoping tests).

The * nature of most thermocouple responses suggests that combustion at low flows is * . Figure 3 show a data trace from * , the location of maximum thermocouple response in the * chimney at this elevation. The character of this trace is typical of the response at numerous locations during low flow testing. The * suggest that the energy dissipation * , and that the energy deposition is * .

In Test S.10, with active spargers at * , the local hydrogen concentration was insufficient during the low flow period to enable downward propagation of flames to the hydrogen fuel source and establish pool flames. Figure 4 shows data from T176 (* *) approximately 1 foot above the suppression pool surface. As indicated by this trace, there were no pool flames above the * sparger during the low hydrogen release. This trend, the absence of downward combustion propagation to the suppression pool surface, is generally the case during hydrogen release of about * (full scale equivalent). Exceptions

(a) 8 active ADS spargers, with sprays off.

*Deleted due to proprietary information.

to this are know to have occurred, however, and will be discussed later is this paper. In general, though, sustained pool flames are difficult to establish at * , due to diffusion of the hydrogen over the suppression pool surface by the sparger bubbling action, and because the global hydrogen concentration is maintained near the lower flammability limit.

*Deleted due to proprietary information.

III. VIDEO CAMERA OBSERVATIONS

Wetwell video camera coverage, coupled with thermocouple data, is sufficient in the test facility to identify when pool flames occur. However, combustion activity has not been observed on video displays when pool flames are absent. The cameras respond to wavelengths associated with the high temperatures of stoichiometric diffusion flames. Per Reference 1, the cameras would probably be insensitive to emissions when combustion (or oxidation) temperatures are below about * . Local effects very near the igniters are masked on the cameras due to the high temperature glow plugs. However, the absence of visual flame indications above the HCU floor is at least consistent with the thermocouple data. The following discussion will therefore focus on pool flame characterizations, because this is where the cameras are of greatest use.

The hydrogen release history for Test S.09 is shown in Figure 5. In Test S.09, (8 ADS only, sprays on) video cameras were located both above and below the HCU floor in the * chimney. The * chimney was characterized by plume gas flows during the low flow rate period of Test S.09, more so than by localized combustion. Video cameras were used to establish this characterization, in addition to the thermocouple data. Pool burning was observed above several wetwell spargers at low hydrogen flows on those cameras in the wetwell region. (See Figure 6 for an example of the effects of pool flames). Although thermocouple activity was apparent above the HCU floor, (see Figure 17) there was * camera installed in this region. The camera had a good view of an igniter at the * feet elevation, but * . Considering the visible evidence of pool flames, which burned for most of the tail during S.09, thermocouple activity in the * chimney is primarily due to * . It is significant that plumes usually cause a thermal environment of * compared to localized combustion.

Test facility instrumentation was placed with the primary purpose of measuring the effects of diffusion flames at the pressure suppression pool surface. HCOG did not place instruments with the intent of measuring the peak temperatures during localized combustion. Although the HCOG considers this to be an event of minimal consequence as it relates to equipment survivability, some concern exists over how high peak temperatures could be during localized combustion. It is HCOG's judgement that the peak temperatures arising from localized combustion probably are not very high, and they would occur in a very limited area. The discussion in the next two paragraphs, based on temperatures recorded in pool flame zones, indicates that the net effects on the nearby gas during localized combustion *

*Deleted due to proprietary information.

Regarding pool flame zones at low flow rates, the hydrogen flow rate during the low flow period averaged about * and was low enough for pool flame extinction normally to have occurred. As mentioned, however, pool flames were observed on camera during Test S.09 and were also apparent in the gas thermocouple data. Figure 6 shows thermocouple T178 (* *). This thermocouple is located about * directly above the pool surface over the * sparger, which was active for this test. This thermocouple is located near a flame zone, based on the video camera observations, which indicated no appreciable flame leaning (away from the * azimuth) during the visible flame intervals at about * seconds and about * seconds in Figure 6, thus establishing the proximity of the flame zone to T178.

Note that the measured response at T178 does not exceed * during those pool flames, which occurred at low hydrogen flows. This is not to imply that visible flame temperatures are less than * . It is observed on the camera, however, that the flames

*

Because of efficient mixing, one should expect local hydrogen concentrations elsewhere in the facility to be less that at the suppression pool surface. This factor, coupled with the T178 data trace and the absence of flame indications on cameras above the HCU floor, is not strongly supportive of an hypothesis that *

would be established during hydrogen flows below the FEL.

The test facility was sufficiently well instrumented in the scoping tests to say that regions greater than * from the igniters would experience * temperatures. In later testing, thermocouples as close as * laterally to igniters similarly have indicated * . closer than this, the video cameras and thermocouples do not enable direct characterization of the localized combustion phenomenon.

*Deleted due to proprietary information.

IV. EFFECTS OF CONTAINMENT SPRAYS

The * chimneys all showed widespread thermocouple activity for the tests without sprays, S.08, S.10 and S.15. Containment spray operation affects the combustion patterns at low flows, most noticeably in the open chimneys. For Tests S.09 and S.14, sprays were active, and thermocouple activity in the * chimney was largely eliminated. In the * chimney, a lower level of activity was apparent when sprays were on, based on comparisons of Tests S.14 and S.15 at low hydrogen flow rates. The suppression of combustion activity during spray operation is more obvious in the less obstructed chimneys, and it is probably caused by greater cooling and the inducement of net downward velocities due to spray flow, which would tend to direct any combustible gas toward the hotter zones in the test facility, in this case the updraft, * chimney.

The maximum response for thermocouple T308 (*), is shown in Figure 7 from Spray Test S.14, with the low flow period after * seconds recording the most activity at * during all five of the tests. In S.14, the turbulent fluctuations in the flow are enhanced by the sprays compared to Test S.15 without sprays, both for the sustained pool flame time period (*) and during combustion at lower hydrogen flows (times greater than * seconds), as evidenced by a comparison of Figure 7 to Figure 8. However, even in the presence of spray induced turbulence, the temperatures were * the temperatures recorded elsewhere in the * chimney at this elevation.

Summarizing, containment spray operation suppresses combustion activity in the open chimneys during periods of low hydrogen release due to cooling effects and can cause changes in global flow patterns. In isolated instances, slightly higher temperatures may occur due to spray induced turbulence and enhanced mixing. In the blocked 45° chimney, shielded from direct spray cooling, * was observed when sprays were on. The greater global activity in this area certainly did not * than those caused by pool flames at flows near the FEL, and in fact it did not result in * than those recorded when sprays were off.

*Deleted due to proprietary information.

V. EFFECT OF SORV LOCATION

The * chimney showed a consistently higher level of thermal activity during testing at low release rates compared to the other chimneys. However, the higher activity level could not be correlated to the * . Other effects are more dominant.

For Tests S.08, S.10 and S.15, three different active sparger configurations were used, * * . Thermal activity in the * chimney was qualitatively about the same at the HCU floor (*) and at the * elevation for all three tests, regarding both magnitude of the peak temperatures and the spatial extent of the thermocouple responses (test compared for the same elevations). The zones of highest temperatures were also consistent.

Thermocouple activity in the * chimney is shown in Figures 9 and 10 for Tests S.08 and S.10, respectively, at thermocouple T310 (* *). Making the comparison between * seconds, these two plots illustrate that there is * chimney during the low flow periods. After about * seconds, pool flames were established in the * chimney during Test S.08. There is a slight subsidence in the turbulence in the * chimney after this time, (i.e., the temperature fluctuations about the mean are smaller) for S.08 compared to S.10. This is due to * during the latter part of Test S.08, and weaker localized combustion in the * chimney as a result.

For Test S.15, Figure 11, focusing on the time period beyond * seconds, the data exhibit similar characteristics to Tests S.08 and S.10 in that intermittent, turbulent response is apparent. Due to the lower flow rate, * in Test S.15 compared to about * in Tests S.08 and S.10, the peak temperatures in Test S.15 are lower, even though the SORV was located at the * azimuth in Test S.15. This suggests that the effect of the flow rate *

Based on S.08 and S.10, for those times when pool flames were absent in the two tests, it appears that the SORV location * . Because the * chimney exhibited a more significant level of thermal response compared to the other chimneys, it was the principal location of interest regarding the effects of the SORV arrangement. Effects in the other chimneys were not specifically investigated, because it is believed that they would be even smaller compared to the * chimney.

*Deleted due to proprietary information.

VI. EFFECTS OF THE HYDROGEN IGNITERS

For the five subject tests discussed in this paper, the test facility was well instrumented. There are several instances in which gas thermocouples are located at the same elevation and within * inches of an igniter. In two additional cases, a thermocouple is located * inches above and offset by * inches from the igniter nearby. While these data are not sufficient for detailed mapping of the temperature field in the near vicinity of the igniters, some observations can be useful and are discussed in this section.

The test data suggest that any postulated zones of high temperatures near igniters would be * . Thermocouple response is generally *
away. While combustion is initiated by igniters, it may not remain there. There is evidence that small momentum effects, such as background gas movement, are sufficient to dissipate combustion energy, tending to prevent the establishment of sustained flames at igniters. The data suggest that combustion, rather *
. If the concentration gradient is sufficiently high, then combustion will *
. As mentioned earlier, this has been observed in Tests S.08 and S.09. However, in the subject tests it was more typical that the global movement of combustible gases in the test volume, *
which was influenced but not dominated by the igniters. Because the igniters were numerous and because the convective mixing was very efficient, the combustion energy release was *
.

Comparing the effects of blockages to open flow regions, Figure 12 shows the response beneath a solid blockage at thermocouple T377 (* *) which was * inches laterally from igniter GP21 during Test S.10. Although the influence of the overhead blockage was * at this particular thermocouple, the temperatures beneath the blockage were * . Figure 13 shows another thermocouple response, from Test S.10, at the same elevation as igniter GP16, both at the * feet level in the unobstructed * chimney. Also about * inches from the igniter, somewhat lower temperatures were noted at T330 (* *) in the open chimney, compared to T377 beneath the blockage. Although the blockage had *

In the * chimney for Test S.10, thermocouple T291 was * inches above and offset by less than * inches from igniter GP11. Very intermittent activity was noted at this location, as shown in Figure 14. Benign and intermittent activity for times greater than * seconds was also noted at adjacent thermocouple T292, Figure 15,

*Deleted due to proprietary information.

with no pool flames apparent below the * chimney in this test. In all five tests, T292 registered higher activity than did the thermocouple closer to the igniter, T291. Both thermocouples are no doubt outside the

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. The presence of major structures, as related to large scale turbulence and the positions of the major updrafts in the chimneys, may be a factor of equal importance compared to the thermal influence of the glow plug.

Even those thermocouples which are suspected to be closest to zones of greatest thermal activity exhibit generally * . In the * chimney, thermocouple T210 was located * inches above and offset by only * inches from igniter GP02. This thermocouple, at * degree azimuth and * feet elevation, often registered * other thermocouples in the same vicinity. Thermocouple T210 is offset just enough that it may be inside any thermal plume originating at the glow plug, i.e., the spray shield above the igniter could be expected to divert the upward flow to the side. Figures 16-18 show traces from T210 for Tests S.08, S.09 and S.10 respectively. Of the 17 thermocouples in the 45° chimney at the HCU floor elevation (*), T210 usually was the location of maximum recorded temperature response during low hydrogen flows. However, Figures 16-18 show that the response

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Of the three traces discussed above, the response was more sustained and temperatures were higher in Test S.09. Importantly, flames on the pool probably caused this. In Test S.09, more continuous pool burning at low flows was observed in the * chimney, beneath the steam tunnel, and at the * azimuth as well, so that T210 probably registered hot plume gas flow up the * chimney. If, as expected, a plume originated in the * chimney during the low flow rate portion of Test S.09,

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releases, as indicated by a comparison of Figure 17 to Figure 18. In Tests S.08 and S.10, T210 was proximate to a zone of localized combustion activity, based on the large fluctuations about the mean temperature and on the absence of pool flames in these two tests. It follows that the combustion zone of influence would be

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. The * temperatures also indicate that * . In both cases, thermocouple response driven by plume activity or thermocouples responding to localized combustion zones, the measured combustion effects at low hydrogen flows are * in the containment at vertical distances greater than * inches from the igniters.

*Deleted due to proprietary information.

At overlying elevations, again there is no clear correlation pointing to * in the vicinity of the igniters. A * level of thermocouple activity was generally recorded at the * feet elevation in the * chimney. The thermal response is typically very similar at all five thermocouple locations at this elevation. Thermocouple T308, * inches away and the closest thermocouple to igniter GP13 (also at *) was not usually the thermocouple where the highest temperatures were recorded. Thermocouples T306, T309 and T310, * feet from any igniter, were equally active. Maximum temperatures were about * , and the peaks were intermittent. Typical response near the drywell wall in the absence of pool flames is shown in Figure 19 for times greater than * seconds. As was the case in the * chimney (T292) the major structures appeared to * than did the igniter locations.

*Deleted due to proprietary information.

VII. FLOW MAPPING

To better characterize localized combustion, the turbulent intensity has been mapped during the low flow periods of the five subject tests. The technique is useful to differentiate plume zones from localized combustion zones, to qualify the energy level of the flow, and to improve estimates regarding the effects of test parameters such as hydrogen release configuration and spray operation upon chimney flow behavior.

Flow turbulence increases in flame zones. The level of turbulent fluctuations can be identified by the temperature measurements. It is useful to determine the level of turbulence in known flame zones and to compare it to the turbulence in suspected zones of localized combustion. In this way, the potential severity of the energy releases in localized combustion zones can be brought into perspective.

The turbulent intensity, (T.I.) as defined herein, is calculated by taking * of the temperature departures about a * response, and then normalizing it to the * temperature. Averages are taken during time intervals of similar response, either during plume flows or in localized combustion time periods. That is,

*

For plume zones, in which the response is characterized by temperature oscillations about an elevated, mean response, (e.g., Figure 8) the reference gas temperature is simply the * gas temperature * for the time interval of interest. For localized combustion zones, which are characterized by departures above a background temperature level rather than oscillations about a (higher temperature) mean, the reference temperature is taken as the * gas temperature.

Because of the blockage at the * elevation, the thermal activity is more * chimney compared to the open chimneys, from which the exit gas flow rate (and therefore, the local cooling) is much greater. The behavior near the blockage is also of interest. Therefore, mapping of turbulence has been limited to the * chimney.

*Deleted due to prprietary information.

Figure 20 shows the RMS temperature fluctuations about the mean response, normalized to the * temperature, as a function of elevation above the suppression pool surface for three cases in which pool flames were observed during the time periods of low flow testing.

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Tests S and S.15 exhibit very similar trends. The shape of the curve differs slightly for S.14 due to * above the pool) because of the operation of containment sprays. Discounting the one, spuriously high data point at the * abscissa for Test S.14, the curve shape is very similar to the other two tests. The rightmost data points reflect gas thermocouple T410, beneath the blockage in the * chimney. This curve indicates that * . This is a consistent trend in the plume flows from test to test, but it also occurs repeatedly at T410 during time intervals of localized combustion and will lead to the conclusion that the zones of maximum localized combustion activity are * .

The same technique has been applied to localized combustion time intervals in addition to the plume zones (caused by pool flames) discussed above. Localized combustion has a separate, distinct signature compared to the plume flows, as shown by the curves plotted in Figure 21, for the 45° chimney. Tests S.08, S.10 cod S.14 indicate that there is a * to localized combustion in the 45° chimney and support the conclusion that the * . (Test S.08 was used in lieu of Test S.09 for this portion of the analysis due to an absence of significant localized combustion in Test S.09). The plotted results also imply, that * . The overall trend is tempered somewhat by the S.15 behavior, but the S.15 response is not surprising considering that some degree of randomness in a turbulent flow is expected, on a pointwise basis. Locations nearest the HCU floor, the leftmost points on the graph, reflect * response. The effect of spray induced turbulence, Test S.14, is to * in the vicinity of the HCU floor during localized combustion. However, the combustion induced turbulence at the * elevation (* above the pool surface) dominates the spray induced turbulence.

Similar to the previous discussion concerning T410 and Figure 20, the rightmost points in Figure 21 show that there is a repeatable trend toward decreased turbulence beneath the blockage during localized combustion time intervals. Figure 21 indicates that T410 is in a plume zone, which is caused by localized combustion at lower elevations in the chimney. Figures 22 and 23 show the differences in thermocouple responses beneath the blockage compared to directly below, at the * elevation. Although the collection of warm plume

*Deleted due to proprietary information.

gases beneath the blockage results in * (Figure 22) compared to localized combustion (Figure 23) *

. Note that Figure 21 has been drawn conservatively. Since T410 is in a plume zone, a decay curve similar to Figure 20 is more likely between the * abscissas.

The question of peak temperature locations can be reexamined based on the data presented in Figures 20 and 21. From the discussions in Section III regarding pool flame zone behavior, it is expected that * for the same hydrogen flow rate. Also from those discussions, the peak temperatures during localized combustion at low hydrogen flows are expected to be * . From Figure 20, the pool flame zone turbulence would be expected to * compared to within the chimneys. These flows are buoyant, thus the temperature activity recorded at * indicates that the maximum combustion zone response should occur * . Igniter locations at or below this level support this possibility. An alternate possibility, temperatures above * , is considered improbable based on the preceding buoyancy considerations. The effects of partial blockages in the chimney are * , because tests S.08 and S.10, without spray carryover blockages at the * elevation, exhibit * compared to S.14, where the blockages were present. If localized combustion occurred above * , it would probably be * , based on the repeatable attenuation in turbulence at T410. Given that the localized combustion source strength(s) and the spatial rate of energy decay are not precisely known, further attempts to define the zones of peak temperatures do not appear to be warranted.

To summarize, the technique presented in this section provides a way to characterize the various zones in the flow when coupled with the data plots. Separate and distinct signatures are apparent for plume zones at low flows compared to localized combustion zones. When pool flames occur at low flows, plumes develop. The turbulent intensity of the plume gas flow * .

In localized combustion zones, which are characterized by * , larger values of the turbulent intensity parameter * .

Beneath the * chimney blockage, in both plume flows and during localized combustion time intervals, the turbulent intensity * locations far removed from the pool flames. This

*Deleted due to proprietary information.

indicates that the zones of maximum localized combustion are * , and the turbulence decay curves indicate that these zones occurred lower in the * chimney.

Compared to combustion induced turbulence, effects such as spray operation, the number of active relief valves beneath a chimney, and the presence of spray carryover blockages appear to be * . Finally, it is expected that the maximum localized combustion zone responses should be * , for the same, low hydrogen flow rate.

*Deleted due to proprietary information.

VIII. SUMMARY

The HCOG has reviewed the existing QSTF test data. Both pool flames and combustion activity elsewhere in the facility are possible at low flow rates below the stable diffusion flame threshold. Pool flames at low flows are well characterized, because they are identifiable on video cameras, and there have been thermocouples in sufficient proximity to pool flame zones to establish their net effect on the gas nearby. Pool flames at low hydrogen release rates exhibit

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Due to effective convective mixing, the local hydrogen concentration is in all likelihood * at the pool surface compared to elsewhere in the test facility . Therefore, pool flames at low flows are considered to represent a * for combustion at the low hydrogen release rates.

The main effect of containment sprays is * of localized combustion in the more open chimneys due to cooling. Some enhanced local turbulence was observed in the blocked * chimney during some test with sprays, but the * dominates compared to the * .

With respect to the most active, * chimney, considered the limiting configuration, the intensity of localized combustion is * . Multiple open spargers beneath a chimney, therefore, * within a chimney. This is because, at low inlet hydrogen flows in the absence of pool flames, * .

Hydrogen combustion at low flows in containment regions at or above the HCU floor is considered to be a diffusively controlled phenomenon. The same effects that * in the case of pool flames are still active. * , whether the result of gas velocities, spray operation or combustion itself, * . Because of this mixing, fixed combustion locations exhibiting high temperatures and concentrated, high level energy releases during low hydrogen flow rates * .

Based on a detailed review of all available data, localized combustion is

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hydrogen concentrations lead to the conclusion that peak temperatures during localized combustion should be * . Existing measurements indicate that areas of high temperatures would be quite

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*Deleted due to proprietary information.

IX. REFERENCES

1. Letter from J.R. Langley to Robert Bernero, "Report of Hydrogen Combustion Experiments in a 1/4 Scale Model of a Mark III Reactor Containment", HGN-121 dated July 22, 1987, Attachment 4.

2. Letter from J.R. Langley to Robert Bernero, "Scoping Test Report", HGN-098 dated July 18, 1986.

Figures 1 through 23 have been excluded
due to the proprietary nature of their contents.