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Hydrogen Burn Survival: Preliminary Thermal Model and Test Results

W. H. McCulloch, A. C. Ratzel, S. N. Kempka, D. T. Furgal,
J. J. Aragon

This report documents part of the Hydrogen Burn Survival (HBS)
Program being conducted by Sandia National Laboratories

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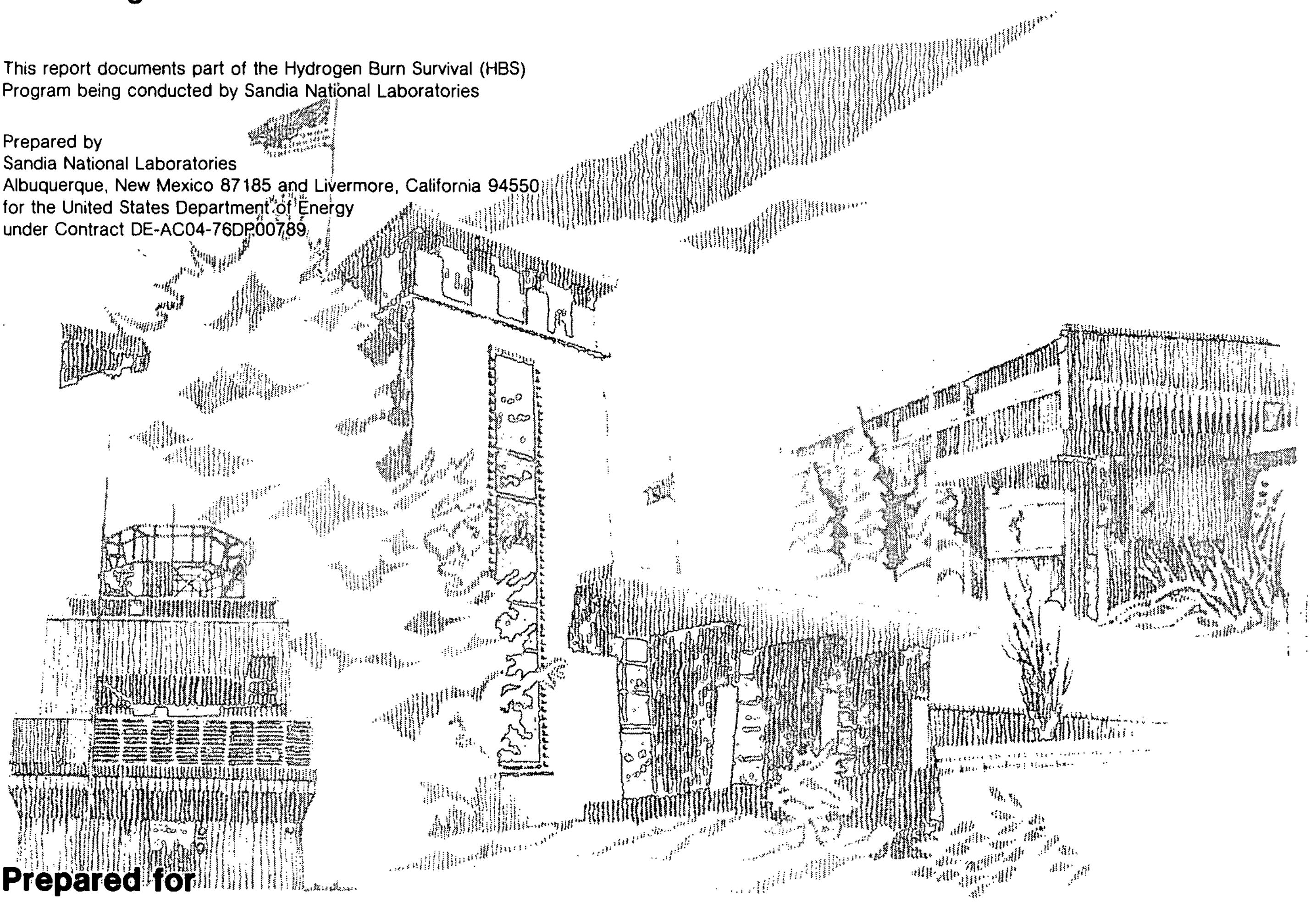

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HYDROGEN BURN SURVIVAL: PRELIMINARY THERMAL MODEL AND TEST RESULTS

W. H. McCulloch, A. C. Ratzel, S. N. Kempka,
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ABSTRACT

This report documents preliminary Hydrogen Burn Survival (HBS) Program experimental and analytical work conducted through February 1982. The effects of hydrogen deflagrations on safety-related equipment in nuclear power plant containment buildings are considered. Preliminary results from hydrogen deflagration experiments in the Sandia Variable Geometry Experimental System (VGES) are presented and analytical predictions for these tests are compared and discussed. Analytical estimates of component thermal responses to hydrogen deflagrations in the upper and lower compartments of an ice condenser, pressurized water reactor are also presented.

EXECUTIVE SUMMARY

The Hydrogen Burn Survival (HBS) Program is focused on the study of hydrogen deflagration (non-explosive burn) effects on the performance of safety-related (Class 1E) equipment in nuclear power plant containment buildings. A major objective of this program is to develop analytical methods to aid the Nuclear Regulatory Commission (NRC) in the evaluation of component survivability analyses. The analytical models address a loss-of-coolant accident (LOCA) scenario in which the reactor core is uncovered and a significant amount of hydrogen is released into containment. The released hydrogen builds up to concentrations high enough to allow for accidental or deliberate deflagrations in the containment.

The HBS Program at Sandia proceeds from the hydrogen research work characterizing containment building deflagration environments. The first phase of this program consisted of studies to assess the complexity of the equipment survivability problem. This report summarizes the activities and presents the results of those early scoping efforts. As advances in the experimental program and analytical model development are made, the information contained in this report will be supplemented.

In support of model development, a series of deflagration tests with varying hydrogen concentrations were conducted in the Sandia Variable Geometry Experimental System (VGES). The VGES tests were designed to provide data for characterizing the physical mechanisms involved in hydrogen deflagrations. Black aluminum cubes were also exposed to hydrogen combustion environments to acquire data on the thermal response of three-dimensional objects. These thermal response data were compared to analytical model predictions. The CORASPN and CINDA-3G computer codes were used to simulate the experiments. CORASPN, developed at SNLA, models the convective and radiative heat transfer from the products of combustion. CINDA-3G is a general purpose heat transfer code used for modeling conduction heat transfer in multi-dimensional geometries.

The results of experimentation and analysis to date have indicated that under some conditions the hydrogen burn environment is a credible threat to the survival of safety-related equipment. (As an interim criterion for survival in this program, it is assumed that there is reason for concern if expected component temperatures exceed those encountered in LOCA qualification tests. While some components could certainly withstand temperatures beyond this limit, testing in addition to present LOCA qualification programs would be required to demonstrate the continued performance of equipment during and after such exposures.) Analytical estimates of temperatures for equipment fully-exposed to hydrogen deflagrations in containments indicate that components may exceed LOCA qualification temperatures (approximately 433 K (320°F)).

Equipment is not usually installed so that it would be "fully-exposed" to hydrogen burns, i.e., components would frequently realize significant thermal protecton from nearby structures and hardware. Experience to date suggests that consideration of such protection in the safety analyses of critical equipment may alleviate any need to redesign components to tolerate higher temperatures or to demonstrate (with "qualification" tests) survival at higher temperatures.

Future HBS tasks will be focused towards determining more precisely the environmental conditions and component responses produced by hydrogen deflagrations and identifying those accident conditions which produce potentially threatening environments. It is important to note that the results presented in this report are based on single hydrogen burns. In reality, multiple burns are expected for plants equipped with deliberate ignition systems. Depending upon their magnitudes and timing, multiple hydrogen burns could make the threat more severe than indicated by the single burn analyses. Development of the capability to analyze multiple burns will be a part of the future HBS effort. The overall effort will require: 1) additional experimentation to characterize hydrogen burn phenomena and 2) continued development and verification of analytical models used to calculate response of safety-related components to hydrogen deflagrations in containment. The analytical models will also be used to calculate expected input heat flux profiles for components in full scale reactors. The calculated heat fluxes will be used in the SNLA Radiant Heat Facility to subject some safety-related components to simulated thermal environments typical of postulated accidents.

ACKNOWLEDGEMENTS

The Hydrogen Burn Survival Program involves personnel from several SNLA organizations. The authors gratefully acknowledge Susan Dingman, John Cummings, Allen Camp, Michael Wester, Martin Sherman and Marshall Berman of Division 9441; Lou Cropp, Vince Dandini and Beth Richards of Division 9445; and Bill Benedick and Charles Daniel of Division 1131 for their contributions to this effort.

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1.0 INTRODUCTION

A possible consequence of a serious nuclear power plant accident is the release of hydrogen into the reactor containment building. In some postulated accident scenarios, the quantity of hydrogen released into the containment building is sufficiently large to create concentrations which could result in a hydrogen explosion or fire. During the 1979 Three Mile Island accident, a hydrogen deflagration (i.e. non-explosive burn) did occur in containment. Although the over-pressure created by the deflagration was not sufficient to breach containment, there was evidence of damage as a result of the severe thermal environment [1].

In a proposed modification to its regulations [2] regarding improved hydrogen control capability in light water reactors, the Nuclear Regulatory Commission (NRC) addressed means of minimizing the threat to containment integrity caused by hydrogen release. One proposed method of alleviating the dangers of containment failure for ice condenser pressurized water reactors (PWRs) is to deliberately ignite the hydrogen/air mixtures using glow plugs. This method is intended to burn off hydrogen at low concentrations ($\leq$ 10% hydrogen by volume) rather than allowing the hydrogen concentration to build up to levels which might cause containment failure if ignited. Licensee analyses indicate that glow plug activation during an accident would subject the equipment inside containment to repeated hydrogen burns. For this reason, it is important to determine whether safety-related components can function adequately when exposed to hydrogen combustion and post-combustion environments.

To address this problem, the Hydrogen Burn Survival (HBS) Program was initiated at Sandia National Laboratories, Albuquerque, New Mexico (SNLA), in the last half of FY '81. Most of the effort to date has been directed towards developing experimental and analytical techniques for predicting the response of safety-related equipment in ice condenser PWR containments when exposed to hydrogen deflagrations. The interactive and concurrent analytical and experimental efforts are a unique feature of the SNLA program. Experimental data obtained in small-scale test chambers can be used to develop and validate analytical models before they are applied to larger containment volumes.

The purpose of this report is to present:

1. Preliminary comparisons of analytical and experimental results obtained for small-scale hydrogen/air deflagrations

2. Preliminary temperature profiles for fully exposed equipment in the post-combustion environment in a nuclear reactor containment building

3. Component thermal response estimates which demonstrate important differences between deflagrations in small test vessels and large-scale containments.

This report focuses on the insights and conclusions reached through February 1982. It should be noted that the results to be discussed here illustrate the development of a hydrogen burn survival analysis methodology. Further, this work is not intended to define specific criteria for the survivability of safety-related equipment in hydrogen deflagration environments.

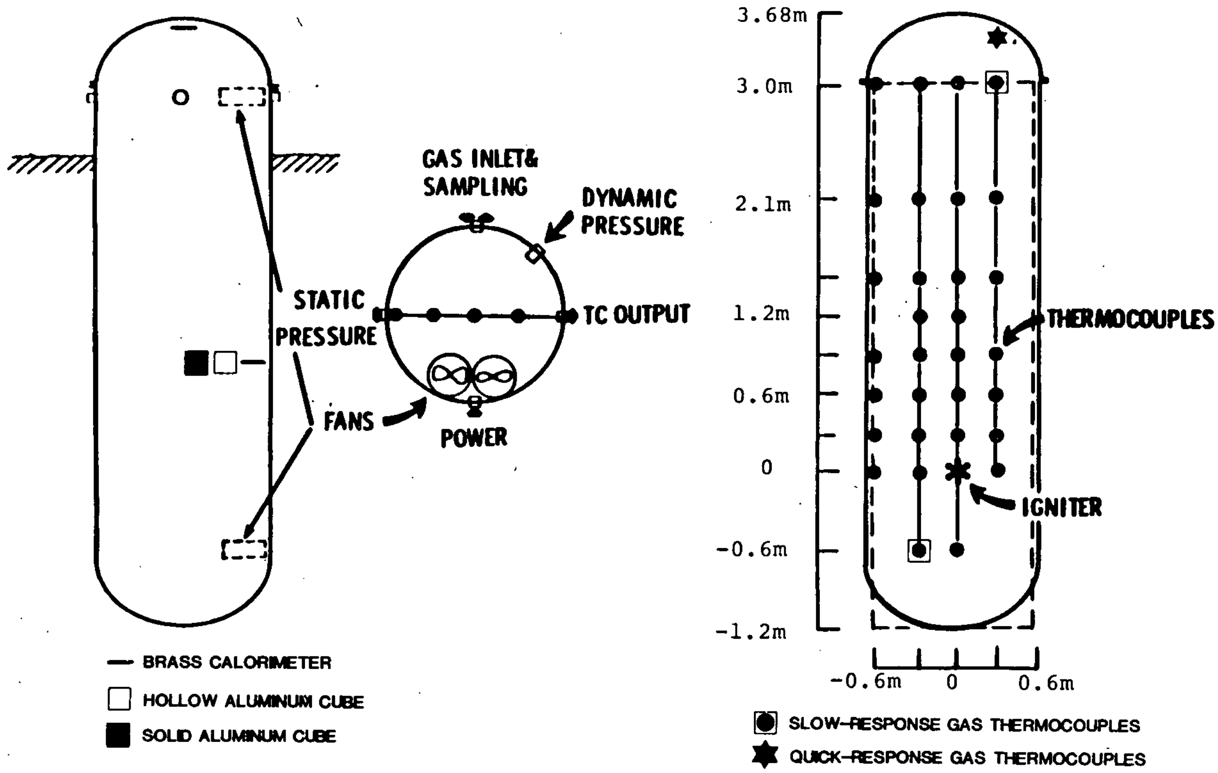
2.0 EXPERIMENTAL PROGRAM DESCRIPTION

The experimental investigation of component response to hydrogen burns began with a series of tests conducted in the Variable Geometry Experimental System (VGES) at SNLA during November 1981. The VGES facility, shown schematically in Figure 2-1, is a partially buried steel vessel (5.7 m^3 volume) instrumented with: 1) pressure transducers, 2) an array of thermocouples to detect flame front arrival and 3) several calorimeters for monitoring the thermal response of components to hydrogen/air deflagrations [3]. The tank is a vertical cylinder with domed ends, approximately 4.9 m (16 ft) high and 1.2 m (4 ft) in diameter. One of two ignition sources, a glow plug or a spark plug, was used for each of the six HBS experiments. The ignition source was located on the tank axis 1.2 m (4 ft) from the bottom. Figure 2-1 indicates the location of the calorimeters and other instrumentation.

Steam is an important constituent in the containment atmosphere before, during and after hydrogen/air burns. However, because the VGES tank is partially buried and is not insulated, the tank remains very near the soil temperature so that steam added prior to ignition would condense. For this reason, carbon dioxide was injected into the VGES tank as a non-condensing substitute for steam in two of the six tests. The tank is also equipped with fans to thoroughly mix the gases before each test. The fans may be left on during testing to increase turbulence during burns.

2.1 Test Specimens

At the time the tests were conducted, samples of typical safety-related components found in nuclear reactors were not available. Instead, several flat-plate and three-dimensional hollow and solid calorimeters were exposed in the VGES tank. These calorimeters were representative of equipment in containment and were selected for their simple geometries, known thermophysical properties, and availability. In addition, several thin, flat-plate, brass calorimeters (Figure 2-2) from another project at SNLA were readily available. These calorimeters were originally used as passive measurement instruments and therefore had several temperature-indicating tapes affixed to the back (protected) surface. Thermocouples (RdF model 20112) were also



(a) Location of Components

(b) Thermocouple Array

Figure 2-1. Variable Geometry Experimental System (VGES)

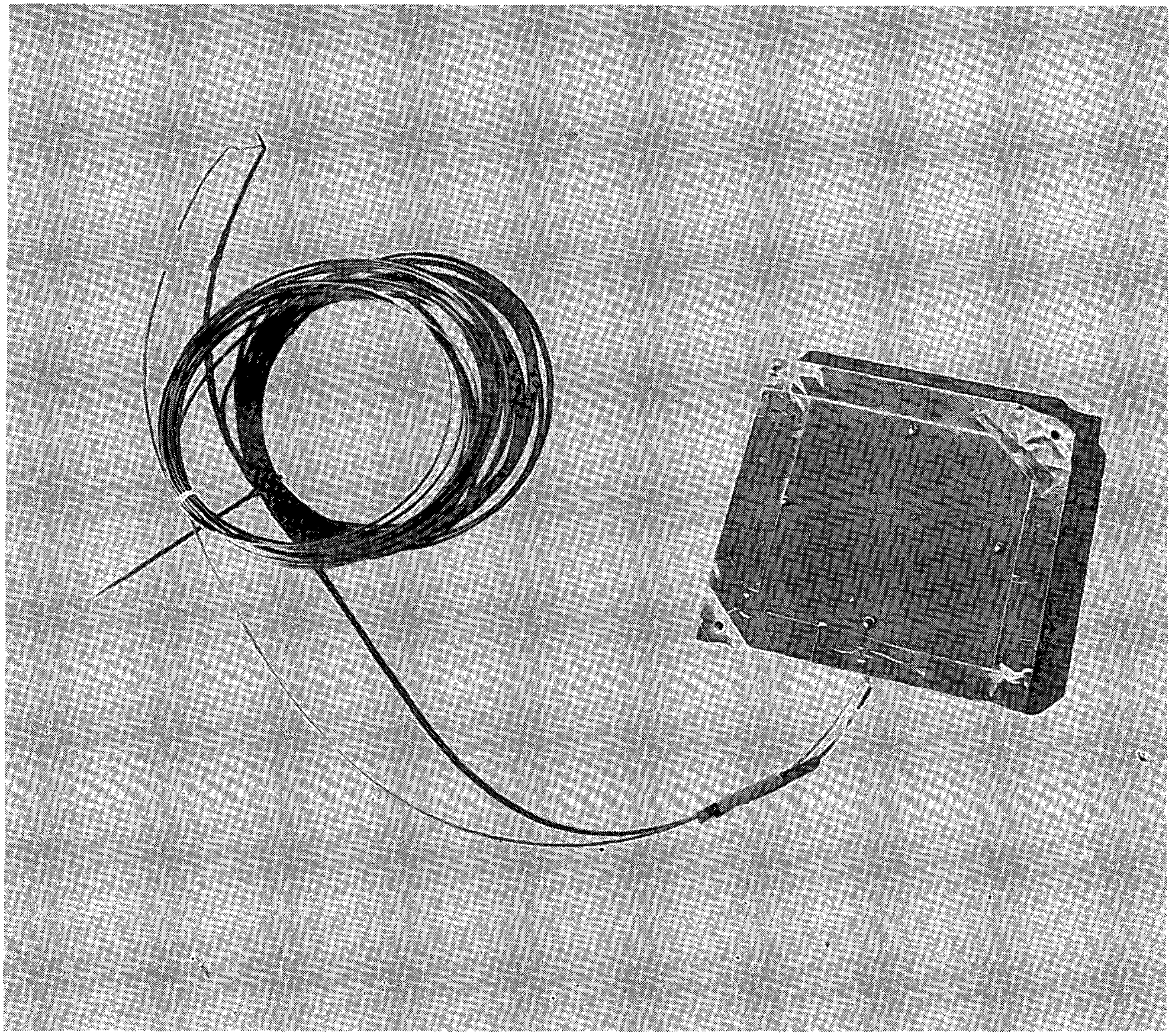


Figure 2-2. Flat-Plate Calorimeter

Table 2-1 Component Description and Pertinent Property Data

Type	Location	Size	Length Scale Used In Convective Modeling (m)	Thermal Conductivity (W/m-k)	Thermal Diffusivity (m/sec²)	Surface Treatment	Thermal Emissivity
Calorimeter #1 Brass plate w/insulation backing	Along cylinder surface 1.52m from base	15.24 cm on a side, 0.635mm thick with 0.635cm insulation backing	0.1524	128.0	$3.4(10^{-5})$	Pyromark paint	0.95
Calorimeter #2 Brass plate w/insulation backing	Centered at top of test section	15.24cm on a side, 0.635mm thick with 0.635cm insulation backing	0.1524	128.0	$3.4(10^{-5})$	Pyromark paint	0.95
Component #1 Hollow aluminum cube	Along cylinder surface 1.52m from base	10.16cm on a side with 0.3175cm thick walls	0.1016	206.0	$8.42(10^{-5})$	Anodized Aluminum	0.95
Component #2 Solid aluminum cube	Along cylinder surface 1.52m from base	10.16cm on a side	0.1016	206.0	$8.42(10^{-5})$	Anodized Aluminum	0.95
Steel Containment Vessel	Lower 3/4 of tank buried	1.22m diameter, 4.88m long with 1.59cm thick walls	2.44	36.0	$1.39(10^{-5})$	Highly oxidized surface	0.70

attached to the back side of these flat-plate calorimeters. The exposed faces were spray painted with a high-temperature, flat-black paint to maximize heat transfer (absorption of the radiative flux) from the combustion gases.

The three-dimensional calorimeters were fabricated to represent components which might be found in reactor containments. Their simple geometries were selected to facilitate analysis of the test data. A hollow aluminum cube (~3.2 mm (~ 0.13 in) wall thickness) 10.2 cm (4.0 in) on a side was used to characterize components with low heat capacitance. A solid aluminum cube was fabricated to represent the more massive components expected to be found in containment. To maximize heat transfer (i.e., the absorption of radiative flux) these calorimeters were black anodized. Additional geometry and thermophysical property data for the calorimeters and components used in the experimental modeling effort are summarized in Table 2-1.

2.2 Test Information and Insights

Six tests were conducted with varying hydrogen and carbon dioxide concentrations, ignition sources, and gas mixing as indicated in Table 2-2. Selected maximum temperature and pressure data recorded during the tests are also shown in the table. Several observations can be made based on the results given in Table 2-2. These observations are summarized below.

1. Obviously, burning at higher hydrogen concentrations produces higher gas temperatures and pressures and this results in higher component temperatures.

2. The presence of carbon dioxide significantly lowered the measured peak gas temperature but had little impact on reducing the maximum temperatures reached by the components. (A possible explanation is that though the carbon dioxide absorbed some of the energy from combustion (i.e. energy sink) holding the gas temperature down, it also increased the post-combustion radiation heat transfer from the gas to the tank walls and to the components because it increased the emittance of the gas. Noncondensing steam in large containment volumes would be expected to have a similar effect on component temperatures.)

3. Operating the mixing fans during combustion had no discernable impact on the peak gas temperatures but significantly increased the measured gas pressure. (We would have expected the gas temperatures to increase when the fans were operating. There were not enough redundant gas temperature measurements (from quick response thermocouples) to verify this expectation).

Table 2-2 Test Descriptions and Maximum Calorimeter Temperatures

	B88	B89	B90	B91	B92	B93
% H_2	10.4	10.5	10.1	10.1	15.2	15.0
% CO_2	0	0	10.0	10.1	0	0
Mixing Fans	OFF	ON	OFF	ON	OFF	ON
Igniter	Spark	Spark	Glow Plug	Glow Plug	Glow Plug	Spark
MAXIMUM TEMPERATURES (K)*						
Gas	1200	1200	1060	1075	1505	1475
Flat Plate	420	420	430	400	460	455
Hollow Cube	325	330	330	335	340	345
Solid Cube	310	305	305	310	---	305
MAXIMUM PRESSURE (ATM)						
Transducer	2.6	3.6	2.6	2.8	3.5	4.9

* The temperatures measured were obtained from unreferenced, uncalibrated chromel-alumel thermocouples of different wire diameters and different thermocouple junction sizes. The accuracy of these measurements is unknown.

4. The temperatures measured for the flat-plate calorimeters exposed to an environment resulting from a 10% hydrogen deflagration in VGES are very close to LOCA qualification temperatures. As will be discussed later, the time required for the gas to cool-down in these tests was very short compared to that expected in containment deflagrations. This means that the environment of the small test chamber is much less severe than that in large containment buildings. Therefore, we are concerned that deflagrations in large scale containments will produce component temperatures in excess of LOCA qualification specifications.

The VGES facility was designed to study hydrogen burn propagation and the included thermocouple array was utilized to indicate flame front location. Since the data of interest were the arrival times of the hydrogen flame (as indicated by the onset of an increase in the thermocouple output), the thermocouples were made of relatively heavy gauge wire to withstand repeated exposures. In the HBS Program there is more concern for the actual gas temperatures, suggesting smaller, more responsive thermocouples. The VGES facility included one such thermocouple mounted near the wall at the top of the tank (see Figure 2-1). Its proximity to the wall may have caused significant deviation from the actual gas temperature. Future experimental activities will include efforts to identify more suitable thermocouples and mounting techniques for the measurement of gas temperatures.

In analyzing the experimental data, it became apparent that a heat flux gauge capable of responding to rapid thermal transients is needed. Instrumenting calorimeters with additional thermocouples would also assist in verifying the accuracy of component thermal responses through redundant measurements. These data are necessary for estimating the energy transfer to the components from the combustion gas products to provide inputs for future Radiant Heat Test Facility experiments.

Future experimental efforts will be conducted in the Fully Instrumented Test System (FITS) at SNLA (shown in Figure 2-3). The use of the FITS facility provides the following extensions to the experimental program:

- More extensive instrumentation
- Observation of the condensation phenomenon
- Inclusion of steam injection in the initial gas mixture at saturated or superheated conditions
- Elevated initial gas and wall temperatures more typical of actual conditions resulting from reactor accident scenarios

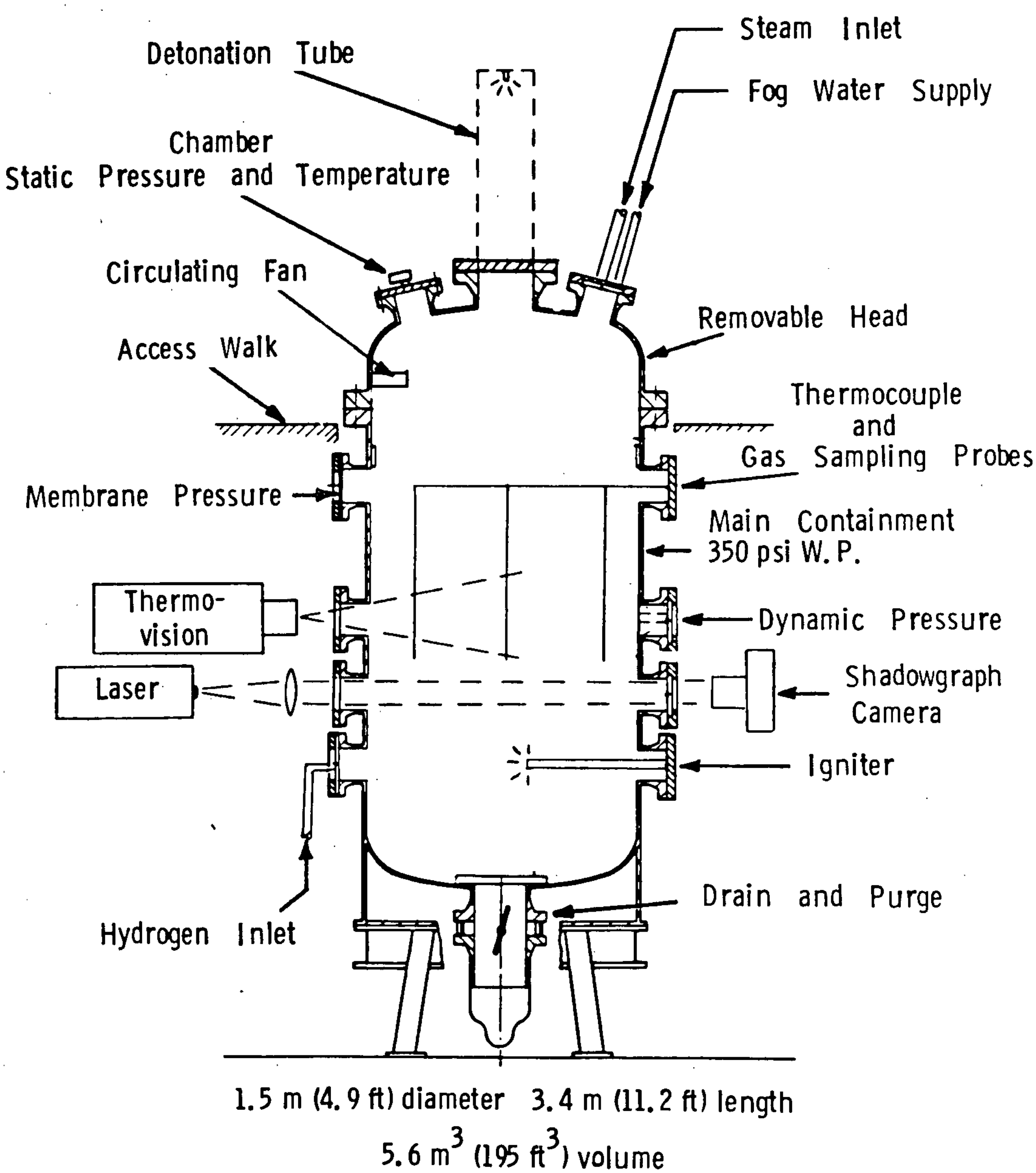


Figure 2-3. Fully Instrumented Test System (FITS)

- Possible implementation of gas velocity measurement techniques.

In general, the VGES tests provided valuable information for understanding the hydrogen combustion phenomena and associated heat transfer processes. The tests have also provided insight into the experimental procedures and apparatus required to obtain more meaningful data in future tests. Further discussion pertaining to VGES results will be presented in Section 5 of this report.

3.0 THERMAL ANALYSIS

3.1 Analytical Methods

The modeling effort used an SNLA developed computer code, CORASPN, which predicts post-deflagration thermal responses in a containment vessel. CORASPN assumes a uniform isothermal gas volume for radiative and convective energy transfer and accounts for possible steam condensation on containment and component surfaces. All components and surfaces comprising the containment are modeled as flat plates with adiabatic back surfaces. The net energy transfer from the gas is assumed to be uniform over each surface area. CORASPN models the transient energy processes as quasi-steady-state energy exchanges during each time step and uncouples the radiative, convective and conductive effects in obtaining a total energy balance. Note that CORASPN is the first generation computer simulation model from which the code HECTR has evolved [3]. The latter code will be used in future analytical modeling efforts.

The most important early time energy transfer mechanism following combustion is radiative exchange from the combustion products to the containment surfaces. Radiative transfer calculations for the gaseous participating media are accomplished using the exponential wide band models for steam and carbon dioxide summarized by D. K. Edwards in a monograph entitled "Molecular Gas Band Radiation" [4]. Necessary inputs to these models include the steam and carbon dioxide partial pressures and temperatures and the effective 'beam' (path) lengths between surfaces. Though the enclosure surfaces are significantly cooler than the gas in the early times of the analysis, radiative transfer from the enclosure surfaces is included for gray diffuse walls using the net radiation method described by Siegel and Howell [5].

Convective energy transfer may also be included in CORASPN, depending upon user preference. Natural and forced convective heat transfer coefficients are computed for each time step and the larger contribution is used. A major shortcoming in the convective analysis requires that the user must provide an estimated uniform free-stream gas velocity since the hydrodynamics are omitted from modeling. In addition, the convective heat transfer correlations used may be inappropriate when the free stream gas temperature is significantly different from the enclosure temperature. Steam condensation is accounted for using an infinite diffusion rate, air-steam Nusselt film condensation model. The effect of noncondensables and the omission of possible drop-wise condensation are major shortcomings of this condensation model.

Finally, in order to account for multi-dimensional effects in the hollow and solid cubes and in an actual pressure transducer commonly used in many reactors, a series of CINDA 3-G [6] thermal models were developed. CORASPN was modified into a subroutine package to provide gas temperatures and radiative and convective heat inputs to the surfaces of the three-dimensional component models. By utilizing the CINDA 3-G models, the unrealistic backside adiabatic boundary condition is eliminated in the analyses and temperature distributions within the components can be predicted.

3.2 Code Application

The conditions modeled by CORASPN result from a hydrogen deflagration in a S_2D accident sequence in the Sequoyah ice condenser PWR. The "S_2D" designation refers to a specific loss-of-coolant accident (LOCA) where coolant is lost through a small break in the primary cooling system and the emergency core cooling system is inoperative. The pre-combustion containment environment and the conditions resulting from an isochoric (constant volume), adiabatic (no heat loss) combustion of the gas mixture are summarized in Table 3-1. These pre-ignition conditions were obtained at SNLA from an S_2D LOCA simulation using the computer code MARCH [7] developed by Battelle Laboratories. The isochoric, adiabatic combustion environment given in Table 3-1 provided the initial conditions in the CORASPN analyses.

Our analyses considered hydrogen deflagrations in both the upper and lower compartments of the Sequoyah containment. A schematic of this reactor containment is given in Figure 3-1. These analyses assumed that the spray cooling system was inoperative. Expansion of lower compartment combustion gases through the ice condenser units and the influx of cool (310 K (99°C)) upper compartment air into the lower compartment were simulated in the lower compartment analysis. An upper compartment deflagration represents the more severe accident scenario since there is no gas recirculation (constant volume process).

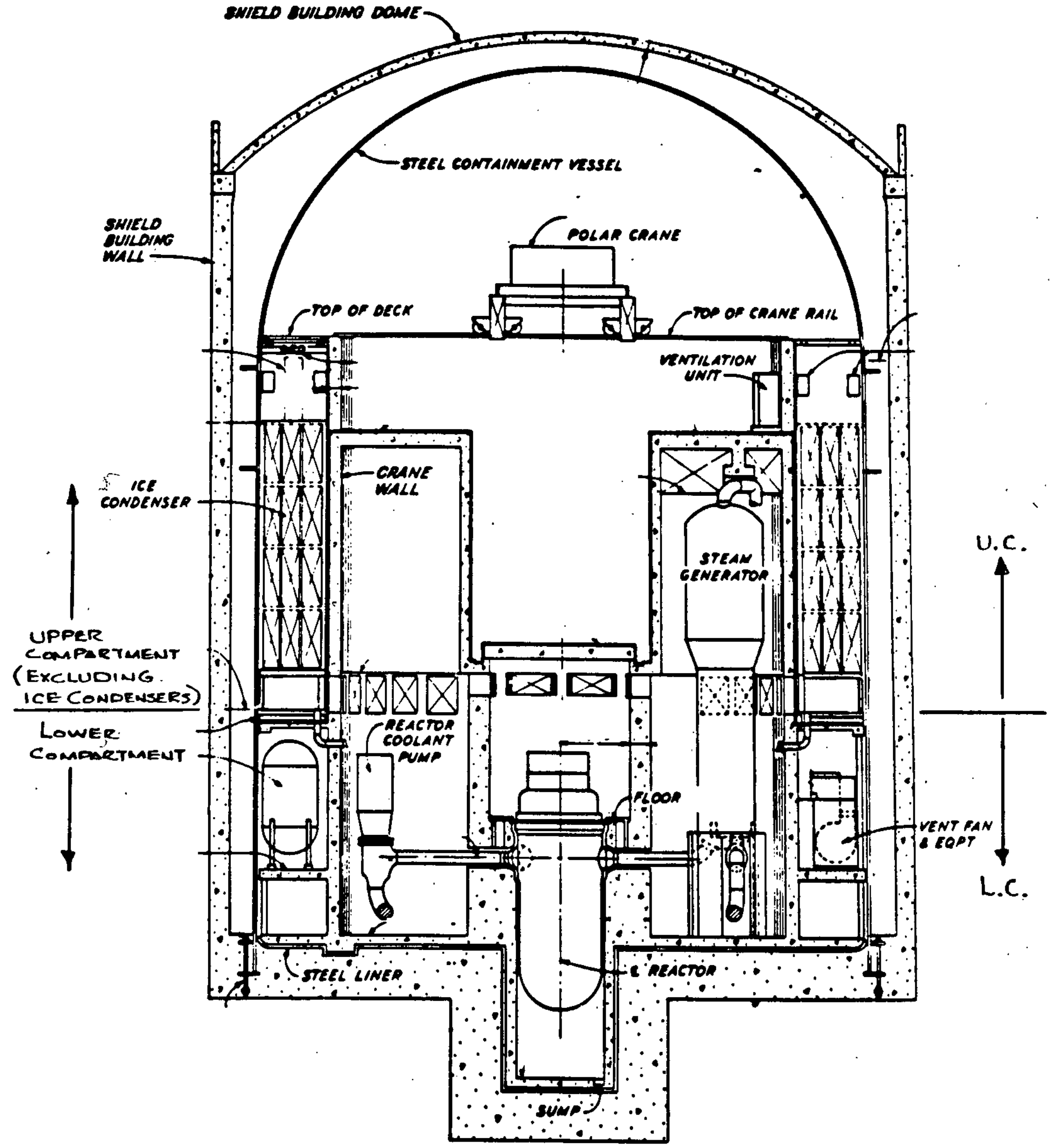


Figure 3-1. Sequoyah Ice Condenser Pressurized Water Reactor Containment Building

Table 3-1 Sequoyah Pre- and Post-Combustion LOCA Conditions Assumed in Modeling Effort

Conditions Prior to Ignition	Post Combustion Conditions
~310 K gas temperature	1353 K gas temperature
~1.5 atm gas pressure	6.6 atm gas pressure
~0.05 steam fraction	0.158 steam fraction
0.10 hydrogen fraction	

Time after accident initiation 1.3 hours

Upper compartment surface area	3781 m^2
Lower compartment surface area	9693 m^2
Upper compartment total volume	20000 m^3
Lower compartment total volume	10980 m^3

To estimate component response to the Sequoyah upper and lower compartment burns described above, the solid and the hollow aluminum cubes described in Section 2.1 were analyzed using CORASPN and CINDA-3G codes. The results of these analyses are shown in Figures 3-2 through 3-5. In the CINDA-3G analyses, the entire surface area of each component is exposed to a uniform heat flux obtained from CORASPN calculations. Figure 3-2 shows that the hollow cube in the upper compartment, with sprays inoperative, experiences a maximum temperature of 722 K (840°F). In the lower compartment analysis the hollow cube experiences a lower maximum temperature of 580 K (584°F) as shown in Figure 3-3 resulting from the gas recirculation. The gas temperature profiles to which these components are exposed are also shown in the figures. When the solid cube is exposed to the same post-combustion environments, peak temperatures of 437 K (327°F) in the upper containment and 372 K (211°F) in the lower compartment result (see Figures 3-4 and 3-5). These analyses suggest that a component in the Sequoyah containment fully-exposed to a 10% hydrogen burn could experience a wide range of maximum temperatures (between 372 K and 722 K (211 and 840°F)) depending upon its thermal mass and its location in containment (i.e., upper or lower compartment). Note that if the spray systems were operative these maximum temperatures would be significantly reduced.

A post-combustion thermal analysis was also applied to a typical pressure transducer found in containment. This piece of equipment was comprised of a 0.6 cm (0.25 in) thick carbon steel casing which encloses a printed electronic circuit board and a bourdon gauge. Figure 3-6 shows the thermal response of this pressure transducer in the upper compartment, subject to deflagration conditions defined in Table 3-2. The computer model predicted that the carbon steel casing and printed circuit board would reach temperatures of 477 K (400°F). Again, these results were obtained assuming that all surfaces were exposed to the post-

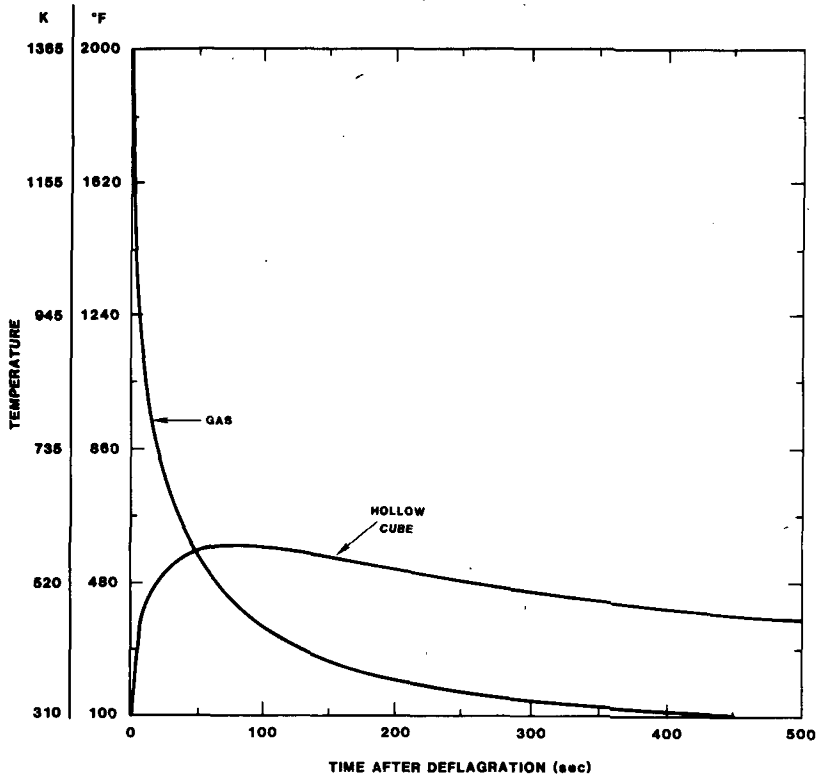


Figure 3-2. Temperature Profiles of Gas and Hollow Aluminum Cube Resulting From a 10 % Hydrogen Burn in the Sequoyah Upper Compartment

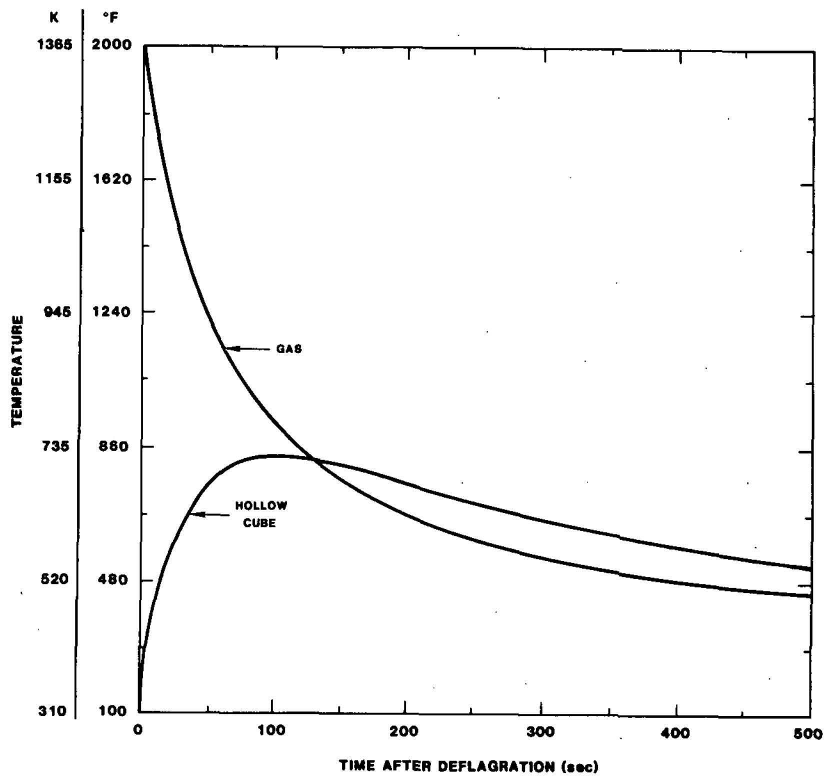


Figure 3-3. Temperature Profiles of Gas and Hollow Aluminum Cube Resulting From a 10% Hydrogen Burn in the Sequoyah Lower Compartment

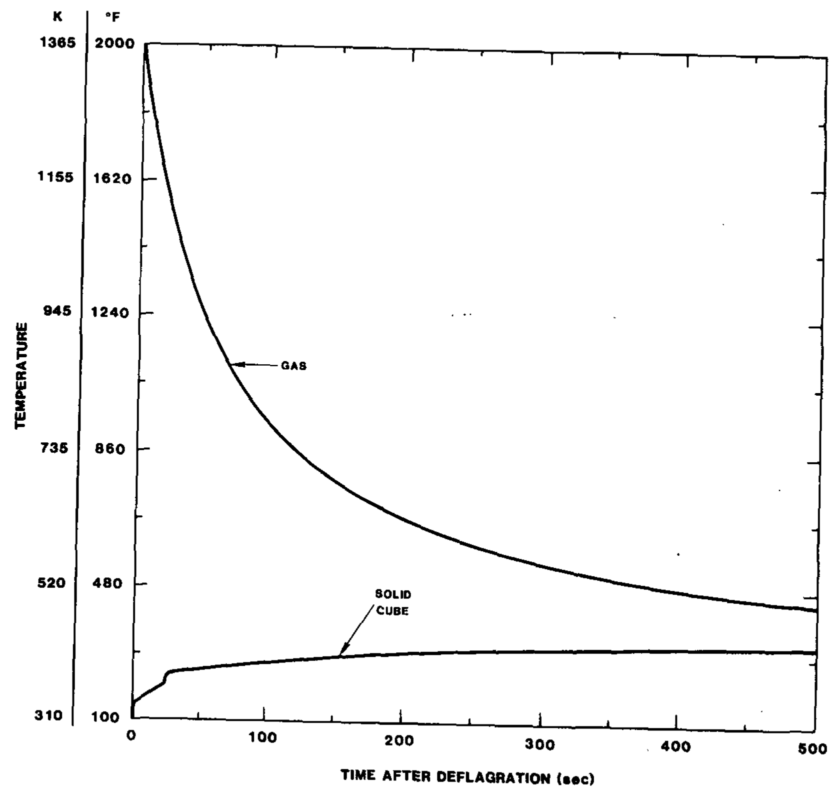


Figure 3-4. Temperature Profiles Gas and Solid Aluminum Cube Resulting From a 10% Hydrogen Burn in the Sequoyah Upper Compartment

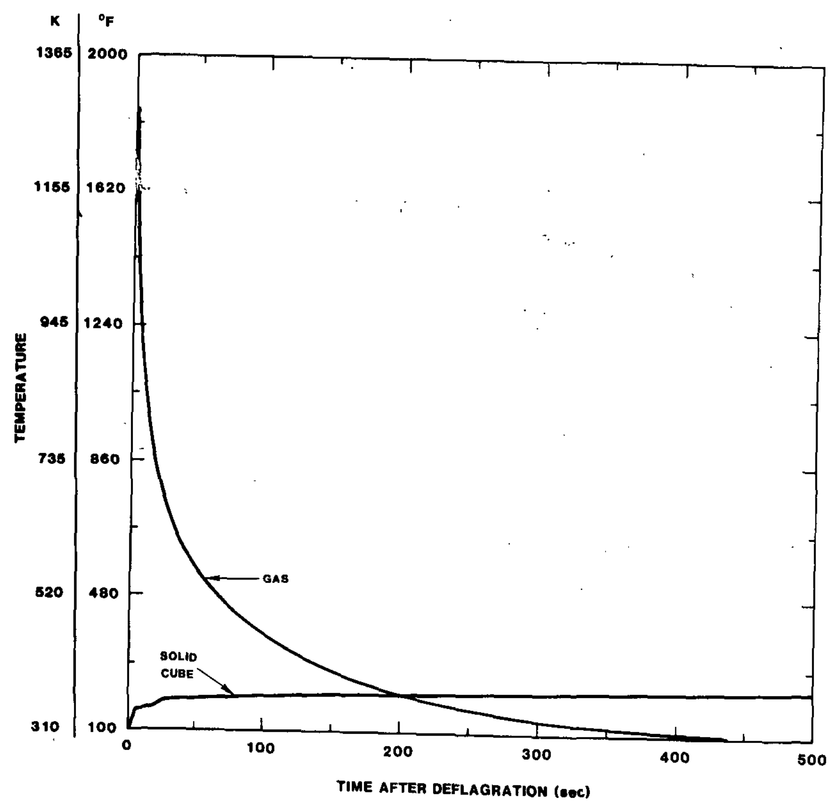


Figure 3-5. Temperature Profiles of Gas and Solid Aluminum Cube Resulting From a 10% Hydrogen Burn in the Sequoyah Lower Compartment

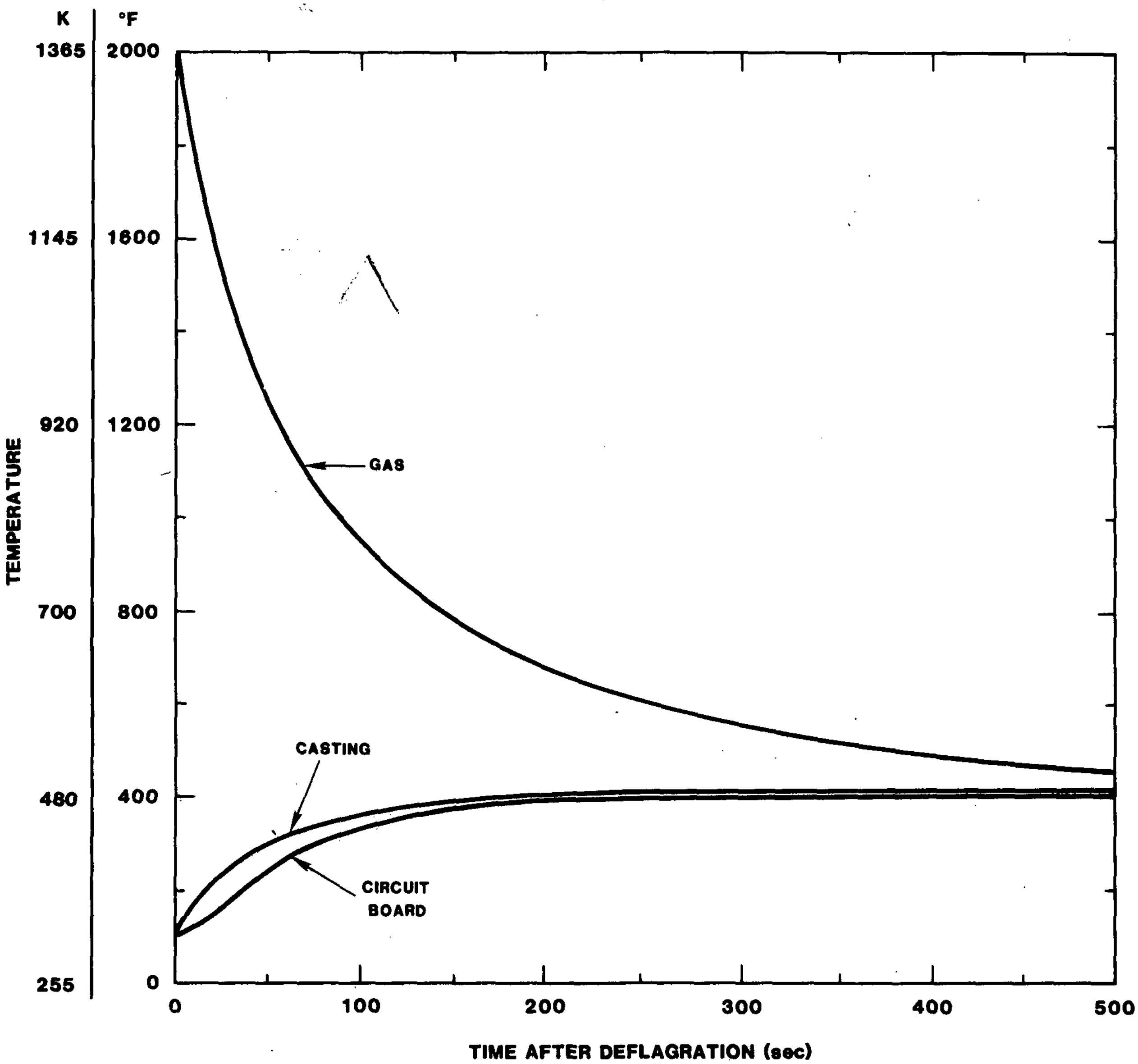


Figure 3-6. Temperature Profiles of Gas and Pressure Transducer Resulting From a 10% Hydrogen Burn in the Sequoyah Upper Compartment

combustion environment. Thermal shielding of any transducer surface would be expected to reduce the maximum temperatures reported here.

Overall, these analyses indicate that the continued operation of safety-related equipment could be impaired if these components are fully-exposed to thermal environments resulting from a 10% hydrogen/air combustion. CORASPN simulations of component thermal responses have demonstrated two factors to consider in component survival analyses. First, component casings can provide substantial protection to internal component instrumentation if the thermal mass of the casing is large. Low thermal mass (i.e., thin-wall) components, conversely, could be expected to exceed LOCA qualification temperatures (approximately 433 K (320°F)). Second, the component location (upper or lower compartment) is significant. Analyses for the same component in the two compartments resulted in a higher maximum temperature for the upper compartment case since the environment there is more severe. Note that the local proximity of these components to containment structures has not been included in this work and hence thermal shielding effects have not been taken into account.

4.0 COMPARISON OF ANALYSIS AND EXPERIMENTS

As with any analytical method, validation of predicted results through experiments is extremely desirable. In this instance, however, test facilities approaching the volumes of reactor containment buildings are not readily available for experimentation. Therefore, verification of analytical (numerical) models must be conducted in scaled-down facilities to gain confidence in phenomenological modeling. The heat transfer phenomena involved (principally radiation) are not subject to conventional scaling laws. Hence results obtained from small-scale tests cannot be extrapolated directly to larger containment volumes (the ratio of containment volumes to the volume of the test facilities like VGES are of the order of 4000-15000 to 1). Rather, they serve only to verify the analytical models.

Experimental data obtained in VGES tests were compared with CORASPN results. Initially, experimental results from the entire test series were evaluated to determine thermocouple response uniformity from test to test. Thermocouple performance appeared consistent under similar fan circulation conditions during the tests (fans on/fans off). It was observed that gas circulation (fans on) during the post-deflagration period tended to increase the rate of gas temperature cool-down as would be expected. Following this cursory evaluation, the 15% hydrogen deflagration test conducted on November 12, 1981 was selected for detailed comparison with CORASPN predictions. Initial conditions for the experiment and the associated input conditions to CORASPN are summarized in Table 4-1.

Table 4-1 Initial Conditions for VGES Experimental and Comparative Studies

Initial Experimental Conditions for VGES Test of November 12, 1981

Gas Pressure	0.971 ATM
Gas Temperature	297 K
Hydrogen Content by Volume	0.1504
Moisture Content	0.001 humidity ratio (assumed)
Ignition Time	3:25 PM
Igniter System Used	70 V glow plug
Circulating Fans Turned off Prior to ignition	

Post-Combustion Input Conditions to CORASPN

Isochoric Temperature	1803.5 K
Isochoric Pressure	5.43 ATM
Steam Volume Fraction	0.163
Average Gas Velocity	0.3 m/sec (assumed)
Component and Containment Temperature	297 K
Spray Mitigation Scheme	Inoperative

Figure 4-1 shows a comparison of CORASPN—calculated gas temperature profiles and measured temperature profiles for a 15% hydrogen deflagration in the VGES chamber. The gas temperatures calculated by CORASPN approach experimental results after 20-25 seconds. However, even though the adiabatic assumption precludes heat loss during combustion, shortly after ignition, the calculations underestimate actual measurements. At the beginning of the burn, the dominant energy transfer mechanism is radiative cooling. Since radiation is proportional to the fourth power of temperature, underestimating the gas temperature during this period could produce significantly lower peak component temperatures. The difference between predicted and measured temperatures for the two brass flat-plate calorimeters (described in Table 2-1) is illustrated in Figure 4-2. The measured maximum temperatures significantly exceed the CORASPN calculated maximum. Similar trends were noted in analyzing the solid and hollow aluminum cubes, though the differences between experimental and analytical results were smaller.

In interpreting these discrepancies, it appears that significant energy is prematurely removed from the hot combustion gases in the analytical model immediately after the deflagration is completed. We believe this may be attributed to post-combustion initial conditions and/or to the condensation model employed by

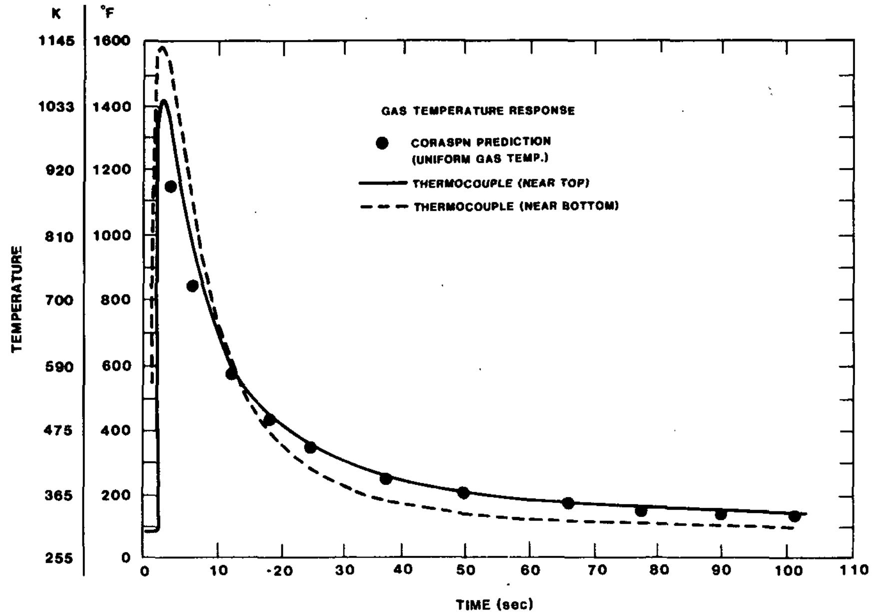


Figure 4-1. Gas Temperature Response Resulting From a 15% Hydrogen Burn in VGES - Predicted vs. Thermocouple Measurements.

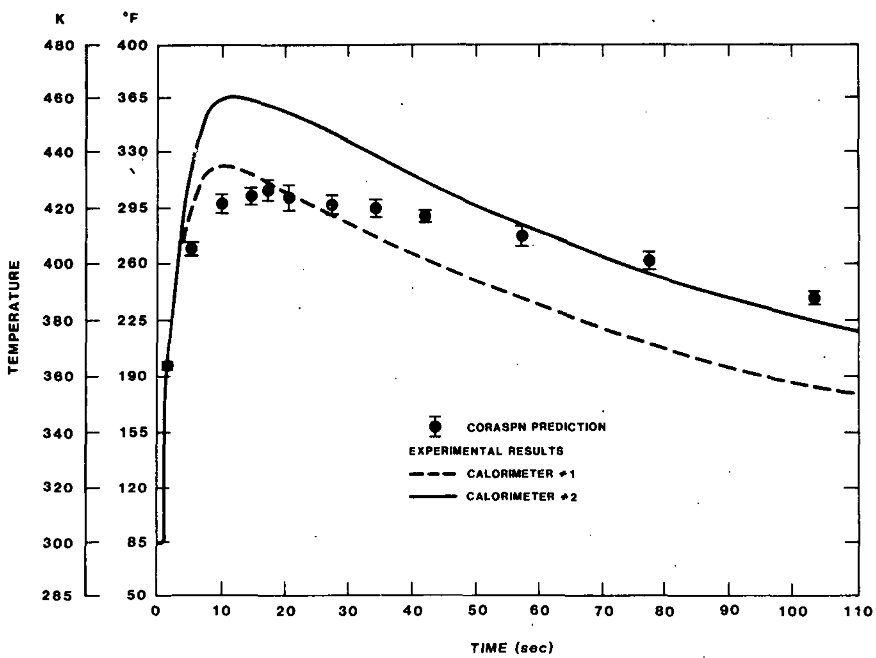


Figure 4-2. Gas Temperature Response Resulting from 15% Hydrogen Burn- Predicted vs. Flat-Plate Calorimeter Measurements.

CORASPN. Initially, the uniform gas temperature in CORASPN is equal to the adiabatic, isochoric combustion temperature. Although it has been reported in the literature that this temperature may be used as an average gas temperature following combustion, there may be local maximums substantially exceeding the adiabatic, isochoric combustion temperature. For example, Garforth and Rallis [8] found that temperatures for stochiometric methane combustion in an 8-cm (3.2 in) radius spherical vessel varied by ± 500 K (440°F) from the adiabatic isochoric temperature. This non-uniformity is attributed to compressive heating of the gas during the combustion process through the volume. Previous work (e.g., Takeno [9]) has demonstrated that for combustion in spherical vessels, the gas temperature near the ignition source in the absence of heat loss from the gas will be 100-300 K (180-540°F) higher than at the flame front location. We suspect that this variation may be even more significant for nearly planar flame propagation such as is expected in the VGES test chamber. It should be noted that while the gas temperature may vary in the test chamber, the pressure created by the burn will be essentially uniform as assumed in CORASPN and measured in the VGES experiments.

In general, the adiabatic, isochoric combustion temperature used as the source temperature for heat transfer may not represent the maximum credible threat to components in containment. If a component is near the ignition site, it could be exposed to gases substantially hotter (hundreds of degrees Kelvin) for short periods of time. We note that most of the previous work on hydrogen deflagrations in reactor containments has addressed the pressure rise and decay phenomena where this temperature discrepancy is of no major consequence.

Added difficulties in interpreting the analytical and experimental results arise from uncertainties pertaining to the condensation process. The VGES facility has a large surface area to gas volume ratio and the walls are cool; thus condensation effects are critical. The condensation model incorporated in CORASPN predicts immediate steam condensation following combustion. In the analytical model, the condensate is instantaneously diffused to the containment walls, blanketing the surfaces with a highly absorbing film (water absorptivity is 0.94). This condensation phenomenon removes significant quantities of thermal energy from the gas and causes the gas temperature and pressure to decrease rapidly. The radiative heating of the calorimeters and other components is correspondingly reduced. It should be noted that the condensation problem is not trivial, as the process depends not only on the gas and wall temperatures, but also on the gas hydrodynamics, on the steam concentrations and on the quantity of noncondensable gases. Additional review of the condensation process is planned to determine if a more suitable model may be developed.

As a programmatic note, it should be pointed out that the HBS Program tasks were originally defined based on the premise that the hydrogen burn environment had been well defined and characterized. As indicated above, the understanding of relevant mechanisms and the representation of the phenomena in computer codes are actually in a state of continuing development. This will have some impact on the format and content of the analytical procedures (i.e., algorithm) eventually produced by this effort. Specifically, the algorithm must include flexibility to encompass variables previously thought to be relatively fixed.

5.0 CONCLUSIONS

During the development and evaluation of HBS Program results, several conclusions became apparent. They are summarized below.

1. In comparing analytical results from VGES and Sequoyah modeling, we noted that gas transient cool-down periods differed by several orders of magnitude, as is shown in Figure 5-1. This implies that a component in a nuclear reactor containment would be exposed to elevated gas temperatures for a much longer period of time (depending on the size of the containment volume) and would thus reach substantially higher temperatures than in a smaller test facility. This phenomenon is illustrated in Figure 5-2 which shows a component thermal response given the experimental and containment environments depicted in Figure 5-1. The apparent scale effect must be considered when evaluating data from small-scale test facilities.

2. Analyses using the CORASPN code estimated component thermal responses in a nuclear reactor containment subject to a 10% hydrogen deflagration with inoperative spray systems. The range of computed maximum and minimum gas and component temperatures (taken from Figures 3-2 and 3-5) are summarized in Figure 5-3. The component thermal response results were obtained assuming that the components were fully exposed to a single, hydrogen/air deflagration in the Sequoyah containment. The upper limit (Curve #2) is the calculated response of a low-thermal mass component in the upper compartment (a severe thermal environment with no sprays and no recirculation). The lower limit (Curve #4) is the response of a high-thermal mass component in the lower compartment (less severe environment with gas recirculation). The wide range of temperature extremes is the result of covering contingencies in component mass, component location and availability of sprays. The conclusion is that under some conditions a low-thermal-mass component could reach temperatures well above the LOCA qualification specifications. Furthermore, depending upon their magnitudes and timing, multiple burns could make the threat even worse.

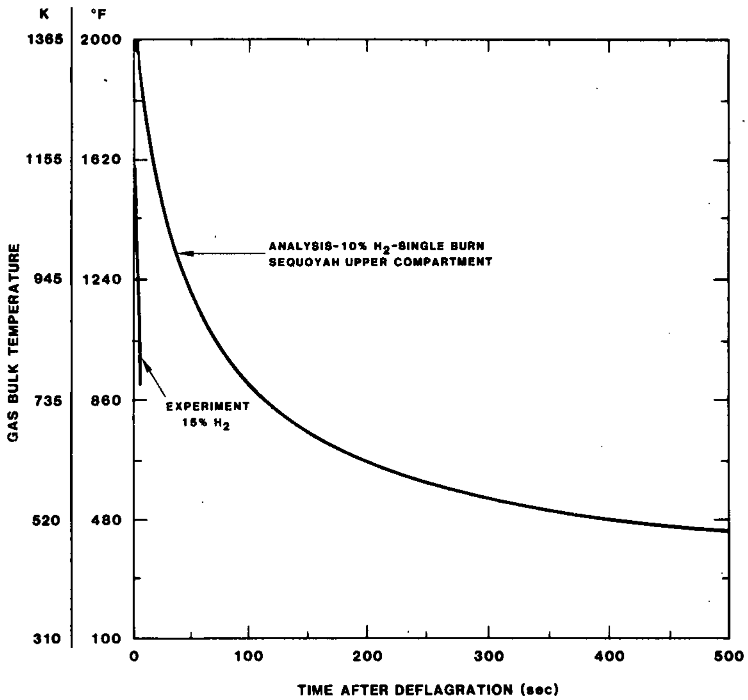


Figure 5-1. Comparison of Temperature Profiles Obtained From VGES Experiments and Sequoyah Upper Compartment Analysis

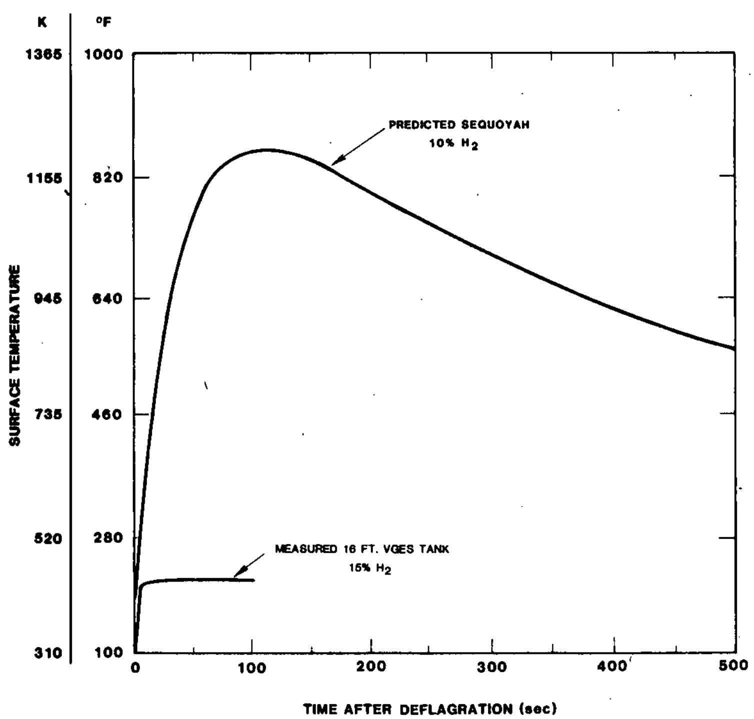


Figure 5-2. Comparison of Hollow Aluminum Cube Thermal Response Obtained From VGES Experiments and Sequoyah Upper Compartment Analysis

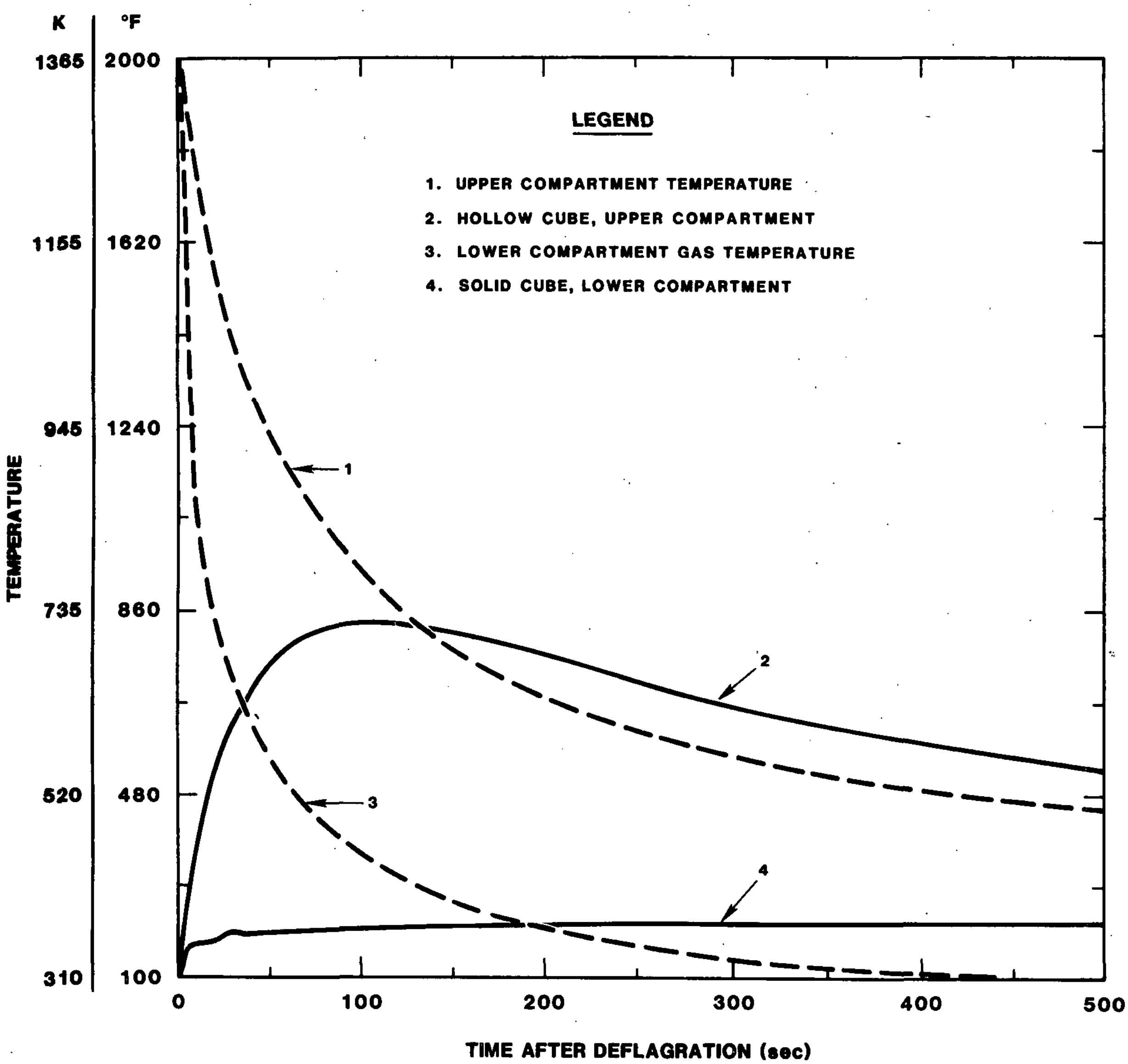


Figure 5-3. Predicted Sequoyah Gas and Hypothetical Component Profiles Resulting From a 10% Hydrogen Burn in the Sequoyah Containment

3. It is possible that localized areas in containment will experience temperatures in excess of those calculated in these analyses if the gas temperature field is non-uniform. The analytical models used to characterize hydrogen burn environments usually assume that the maximum temperatures and pressures achieved are those resulting from adiabatic, isochoric deflagrations. While this approach yields satisfactory average gas temperatures and pressures, comparison of such calculations with VGES test data gives reason to suspect that temperatures in certain localized areas could be in excess of the isochoric combustion temperature. Therefore, until this possibility has been given further consideration, the analyses presented should not be regarded as an absolutely conservative upper limit of expected component temperatures. Also, note that in our analyses every component surface was exposed to the post-combustion thermal environment. Thermal shielding from nearby structures and equipment would be expected to limit the exposure of at least some component surfaces to these environments. This would result in reduced maximum component temperatures. The degree of protection would be determined by detailed thermal analyses of each application.

In summary, preliminary HBS Program efforts suggest that under certain conditions component temperatures higher than LOCA qualification specifications can be expected as a result of single or multiple hydrogen deflagrations. The response of components to these challenging environments is dependent upon their location and configuration in containment and must be evaluated with detailed specific analyses. Continuing HBS Program analytical and experimental efforts will be directed towards the definition of conditions under which components might be threatened and towards the continued development of reliable thermal models for analyzing safety-related components in hydrogen deflagration environments.

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