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ANALYTICAL INVESTIGATION OF POST-ACCIDENT
CONTAINMENT ATMOSPHERIC STRATIFICATION

by

Vincent P. Manno
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ABSTRACT

The LIMIT computer code is utilized to study the behavior of containment atmospheres following severe core damage accidents. The degree of heterogeneity in passive entity mixing, especially mass stratification, is assessed. Three scenarios are analyzed using a two-dimensional, relatively coarse mesh, computational region as the baseline geometry. Two calculations include steam and liquid fields and all involve hydrogen injection. Some stratification is observed after source injections are terminated. The formation of the stable mass gradients is caused principally by heat removal to structures located in the lower regions. This preliminary study concludes that in the absence of sprays or fan coolers, stratification can occur depending upon the location and heat capacity of energy absorbing/liberating structures.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

The assumption of good atmospheric mixing in the containment during severe core damage accidents is made in many current analyses such as probabilistic risk assessment (PRA) studies [1,2]. This assumption is based, in part, on past experience of performing single or few node lumped parameter analysis of the containment as exemplified by CONTEMPT [3] code computation of post-loss of coolant accident (LOCA) containment pressure and temperature. The degree to which containment atmospheres mix or stratify during actual events remains an open question. It would be unwise to accept the tenet that stratification is not important without further understanding of the conditions during an accident which promote or inhibit it.

Accident sequences which render the well-mixed assumption most suspect involve the loss of containment sprays and fan coolers. The transport transients associated with such events are determined by the dynamic interplay of the following phenomena:

- thermal and mass stratification;
- source strength, location and composition;
- location of heat absorbing (or liberating) structures;
- heat and mass transfer at surfaces and in the bulk flow;
- initial convection patterns; and
- geometrical arrangement of the flow paths.

The mixing and thermodynamic transient is important in assessing the risks associated with combustible gas accumulation

and fission product transport. The phenomenological sensitivities specified above have been borne out in numerous analytical and experimental studies including the Battelle-Frankfurt (BF) Institute and Hanford Engineering Development Laboratory (HEDL) hydrogen mixing studies [4]. While good mixing was observed in many configurations, depressed homogenization was obtained in cases of initial thermal stratification (BF6), constrained inter-region flowpaths (early BF tests) and low source rate transients without blowers (HEDL tests).

A systematic consideration of this aspect of post-accident containment behavior should involve large-scale experiments and computational studies. This is due to the interplay of synergistic effects, not the least of which is the exact accident sequence of events. Nevertheless, the solution of a few prototypic problems utilizing the better estimate analysis tools now available can aid in understanding the important parameters and help validate the evolution of new safety requirements.

This report documents the results of such an investigation. The LIMIT code [5], described briefly in the following section, was employed in the analysis of three problems. A two-dimensional (Cartesian), relatively coarse, continuum computational mesh is employed in all three simulations. Two problems include steam and liquid fields and all three involve hydrogen transport. Nonuniformly distributed steel and concrete heat sinks are included in the model. The results of the three analyses are reviewed and compared, and some preliminary

conclusions are presented in the subsequent sections.

II. LIMIT CODE

The LIMIT code was developed recently at MIT for the analysis of hydrogen transport in reactor containment buildings. The program contains three major modelling options, two continuum models and a lumped parameter model. One continuum formulation is a two-phase, two-fluid model based upon the BEACON [6] code except for the addition of hydrogen gas as an additional component. This fully compressible formulation, which allows interphasic velocity slip, does not include any diffusional mass transport or turbulence effects. The lumped parameter model is based on control volume mass and energy balances and junction flows driven by internodal pressure and density differences and inhibited by frictional and form drag and flow inertia.

The second continuum model, which is used exclusively in this study, is applicable to longer term, slow mixing transients. A "slightly compressible" model is employed in that mass and energy differential transport equations use compressible formulations and the Boussinesq treatment of the momentum equations allows periodic reference state update. A two-equation turbulence model as well as some novel remedies for limiting numerical diffusion errors (see [7]) are included. However, this latter option was not employed in this work due to unresolved problems with its use in situations involving a condensable field. Mixture thermodynamics and mass diffusional effects are included in the formulation.

LIMIT has a model for heat transfer to solid structures which includes both sensible and latent energy transfer. This formulation allows condensation (or evaporation) rates on structures to be calculated on the basis of local conditions and thus yields heat transfer coefficients which are more accurate than the global condition correlations used in most containment analyses (e.g. Tagami-Uchida correlations [9]). The results reported below demonstrate the importance of containment heat sinks and thus further support the use of mechanistic heat transfer models.

III. SIMULATIONS

In light of the phenomena and sensitivities outlined in the introduction, a relatively simple geometry is utilized in the three simulations. The geometry and nodalization is illustrated in Fig. 1. A "stair-stepped" two-dimensional Cartesian coordinate mesh is utilized to represent a "slice" through the region of a large dry containment above the operating deck. There are 84 fluid cells, each having a free volume of 25 m^3 ($5\text{m} \times 5\text{m} \times 1\text{m}$), yielding a total free volume of 2100 m^3 which is roughly 3-4% of the free volume of a typical containment. Symmetric concrete heat sinks are located along the vertical surfaces below the simulated dome region. Each concrete structure has a surface area of 45 m^2 and a volume of 22.5 m^3 . A steel heat sink is located asymmetrically along the lower left-hand horizontal surfaces. This heat sink, which is included to simulate large components and ancillary metallic equipment, has an exposed

surface area of 25 m^2 and a volume of 25 m^3 . In all three problems, the injected component (i.e. hydrogen and/or steam) is added into the three cells in the right lower corner of the region. This type of introduction mimics the ingress of these contaminants through gratings, stairways or other open passages.

Problem 1 - Steam and Hydrogen Injection into an Air Atmosphere

The first problem is formulated to represent a slowly degrading core accident in which a relatively weak steam source precedes a substantial hydrogen inflow into an initially uniform air atmosphere over a period of many minutes. The initial conditions and imposed transient are described in Table 1 and Figure 2, respectively. The heat sinks are in thermal equilibrium with the atmosphere at the time the steam injection commences. The integrated hydrogen addition of 9 kg represents approximately 35-40% cladding oxidation. The analysis proceeded for an additional 300 seconds after hydrogen inflow ceased yielding a total simulation period of 1500 seconds (25 minutes). In order to test the separate effect of initial steam injection, a second run was made which included the hydrogen source only (i.e. Case 2).

The maximum vertical velocity component is plotted in Fig. 3 for both cases. The velocity magnitudes decrease as the steam injection becomes lower and increases when the more buoyant hydrogen gas is introduced. After all source flow is terminated, the flow decays to rates typical of natural convection. The hydrogen-only run (Case 2) exhibits qualitatively similar

behavior but two distinctions are noted. First, during the hydrogen inflow, the maximum velocity is higher in Case 2 than in Case 1 (3 m/sec vs 2.7 m/sec). This is due to an imposed stable stratification caused by condensation-driven heat transfer in the lower regions prior to hydrogen injection and the decreased relative buoyancy of the hydrogen after the steam injection.

The flow field during all source injections was typified by a large counterclockwise recirculating region in the non-dome region as exemplified by Fig. 4, which depicts the flow pattern at 600 seconds (Case 1). The recirculation is strong enough to divert the upward flow of the non-corner source cells. The flow field at 1500 seconds, depicted in Fig. 5, is quite different. In the absence of source buoyancy the flow transitions to two natural circulation recirculatory loops driven by heat transfer to the walls.

Figures 6 and 7 depict the average vertical density profiles at various times for Cases 1 and 2, respectively. The two calculations show marked differences. In the case of the steam injection, a stable stratification forms after all sources are removed due to heat removal in the lower region. The behavior of the dome region is noteworthy in that the more buoyant mixture does not penetrate the region until the source-driven recirculation decays. The nearly linear stratification at 1500 seconds represents the equivalent of a 2.0°C positive temperature gradient if the mixture was monocomponent. The Case 2 density stratification is much less pronounced and is characterized by a nearly neutral profile until the dome and then a minor

stable stratification in the upper region. The entire profile is equivalent to a 0.5°C gradient. Case 2 does exhibit the delayed dome penetration described for Case 1.

Condensation at surfaces and in the bulk flow influences strongly the enhanced stratification of Case 1. The vertical liquid density profiles at various times are shown in Fig. 8. The profile produced at 1500 seconds reflects the lower saturation temperature away from the dome and illustrates depressed condensation in the dome region. Between 1200 and 1500 seconds, the top elevation liquid density changes by 8% while the lowest elevation value increases by 50%. The thermal gradients at various times for both cases are plotted in Fig. 9. The Case 1 plots exhibit the increased energy removal to heat sinks as well as the formation of a stable gradient. Figure 10 presents the vertical density profiles of the three gaseous components at 1500 seconds (Case 1). The air density decreases with elevation, indicating the displacement by the less dense steam and hydrogen. The steam profile follows the saturation line given the thermal gradient depicted in the previous figure. Finally, the hydrogen is relatively uniformly distributed except for some preferential collection in the dome. However, the absolute hydrogen volume fraction does not vary more than a few tenths of a percent over the entire field.

This problem leads to the observation that the presence of steam in conjunction with the location of heat slabs can cause some atmospheric stratification. The stratification produced is not very strong in this case and its effect on hydrogen transport

is minimal in that a nearly uniform hydrogen field is obtained in both cases. The results of these analyses lead to the expectation that the stratification which is becoming evident at the end of the simulation would become more stable as time elapsed.

Problem 2 - Hydrogen Injection into High Pressure and Temperature Air Atmosphere

This problem was intended to involve hydrogen injection into an atmosphere composed of air and steam but due to a programming error, an initial pure air atmosphere at elevated pressure and temperature was assumed. Despite the fact that it was an unintended computation, the results produced from this set of initial conditions are interesting and germane to the questions at end. The intended air-steam case is reported later as Problem 3. The initial pressure and temperature of the air in Problem 2 was $2.737 \times 10^5 \text{ N/m}^2$ (39.7 psia) and 385.75°K (235°F), respectively. Heat sinks were at 323.15°K as in Problem 1. Hydrogen is injected at a rate of 0.005 kg/s during the first 1800 seconds of the simulation.

The maximum vertical velocity history over the simulation duration of 20,000 seconds (5.55 hours) is shown in Fig. 11. The plot shows a decay to a natural convection scale velocity. The decay is relatively unaffected by the hydrogen source flow. The flow field obtained is qualitatively similar to those of Problem 1, but the depressed rates are due to rapid early condensation causing an inversion which blocks the rise and diminishes the

upward momentum of the incoming hydrogen. The average density vertical profile at 2000 and 20000 seconds are both plotted in Fig. 12. The two profiles are similar in that the stable stratification of the dome (no heat sinks) region is clearly defined and becomes stronger as time elapses. The stratification is distinct from the Problem 1 experience in that this is nearly stepwise rather than linear with increasing elevation.

The thermal gradients at various times, which are depicted in Fig. 13, are analogous to the density profiles of Fig. 12. The energy removal in the lower area is apparent. The observed temperature decay rates are 0.0011 °C/sec and 0.0003 °C/sec in the lower and upper regions, respectively. Finally, Fig. 14 shows the air and hydrogen densities at the end of the simulation as a function of vertical position. The expected inversion profiles are observed.

Problem 3 - Hydrogen Injection into Steam-Air Mixture

This simulation involved a hydrogen inflow identical to that assumed in Problem 2 into an atmosphere composed of air and steam. These conditions are specified in Table 2. The steam density and thermodynamic state at the beginning of the calculation was based on the assumption of a large LOCA mass and energy source added to the containment atmosphere of Problem 1. The heat sinks were not in thermal equilibrium due to the assumed rapid change in state caused by the LOCA.

The average pressure and temperature histories over the course of the 20000 second simulation are shown in Fig. 15. The

two thermodynamic variables decay rapidly over the first 1500 seconds and then decrease more slowly. As a point of comparison and validation, this pressure and temperature decay as well as the steam quality transient were compared to a large LOCA blow-down analysis using a single node model [10]. Since initial conditions were different for the two analyses, ratios of initial and "final" (at 3600 seconds) values are compared. Reasonable agreement is observed. The rapid atmospheric cooling and depressurization in the early period is due to rapid energy removal by the heat sinks. This is demonstrated by the plots contained in Fig. 16. This figure shows the energy removal rate as well as the integrated energy absorption of the heat sinks. The initial rate of over a megawatt is due to the initial temperature differences (60°K) and high heat transfer coefficients (HTCs). The HTCs of the vertical heat sinks were approximately $500\text{-}600 \text{ W/m}^2 \text{ }^{\circ}\text{K}$ in the earlier period and decayed to roughly $100 \text{ W/m}^2 \text{ }^{\circ}\text{K}$ for the duration of the transient. These can be compared to peak values during Problem 1 of $50\text{-}70 \text{ W/m}^2 \text{ }^{\circ}\text{K}$. The higher values are due to elevated steam partial pressures in this case.

The maximum velocity is plotted vs time in Fig. 17. Three distinct regions are apparent. There is an initial decay until around 1000 seconds followed by a recovery which lasts until the hydrogen source is terminated and finally a transition to a steady state low flowrate. The first transition is the more interesting as it is not observed in the previous problems. An explanation of the physical phenomena causing this behavior is possible after the flow patterns at 1000 seconds, 1750 seconds

and 20000 seconds are studied. These are shown in Figs. 18 through 20. At 1000 seconds, the flow pattern exhibits three different regions. First, a counterclockwise recirculation, reminiscent of the earlier simulations, exists in the lower 15 m. Second, an area of complex flow in the 15 to 45 m elevation exists and, finally, relatively low circulatory flow in the dome. This midregion pattern indicates the competition of the negative buoyancy of the heat sinks and the positive buoyancy of the hydrogen inflow. The flow field at 1750 seconds exhibits a much better defined counterclockwise recirculation spanning nearly the entire non-dome region. The new dominance of the source-induced recirculation is the cause of the velocity recovery observed in Fig. 17. The final field seen at 20000 seconds shows the dual heat sink natural convection pattern found in Problem 1. In addition, the asymmetric horizontal heat sink seems to cause a smaller flow loop in the lower elevations. The dome remains relatively stagnant.

The vertical density profiles depicted in Fig. 21 are similar to the Problem 2 results with a stepwise stable stratification in the dome region. The stratification is decaying (at a diminishing rate) as opposed to the strengthening observed in the shorter term Problem 1 simulation. The temperature profile curves of Fig. 22 reflect this stabilization. An interesting distinction from the first simulation is that after the initial period, the dome region is cooling at a higher rate than the lower region, indicating some mixing at the inversion interface. This is analogous to Test 6 of the BF since where an inversion

degraded slowly over time due to slow penetration of hydrogen gas through a small orifice.

The density profiles of all components at 1750 and 20000 seconds are presented in Figs. 23 and 24, respectively. The scales of the two figures are the same except for a small incremental difference in liquid density. A noteworthy feature of the 1750 second profiles is the hydrogen stratification in the lower 40 m. The profiles at 20000 seconds are similar to the former time except for more uniformity in the nondome areas, decreased dome/nondome gradients and a complete decay of the steam gradient. The cause of the steam homogenization is probably diffusive transport enhanced by steam removal in the lower region due to condensation. The removal of steam is evidenced in the average steam density decreasing from 0.612 kg/m^3 to 0.560 kg/m^3 during this period.

Since flammability limits are best expressed in volume fraction rather than mass fraction, Figs. 25 through 29 are provided. Figures 25 and 26 depict the changing volumetric mixtures as time progresses for a lower elevation and upper elevation, respectively. The decay in hydrogen volume fraction in the case of the former at around 2000 seconds is due to the source termination and subsequent homogenization of the lower elevations. The rapid steam condensation is also apparent. The dome region transient is notably slower and does not exhibit rapid condensation. In fact, the steam fraction decay behaves in a way indicative of some mixing and diffusive depletion. Figures

27 through 29 illustrate the whole filed "wet" hydrogen fractions (wet implies fractions computed to include steam contribution) at 1000, 1750 and 20000 seconds, respectively. The persistence of differences in the lower region during injection as well as the slow ingress of hydrogen to the dome region are noteworthy.

DISCUSSION

The results reported in the previous section demonstrate the importance of the sensitivities noted in the introductory remarks. Thermal and mass stratification is observed in certain simulations but their magnitude and exact spatial definition are sequence dependent. In the first simulation, representing a slowly degrading core sequence, a small but distinct vertically linear stable stratification formed after all sources were removed. The presence of steam and the sequence of source injection encouraged the formation of the stable gradients. This influence is obtained from two separate effects. First, the initial steam injection helped heat the atmosphere and decreased the relative buoyancy of the hydrogen gas. Second, condensation heat transfer at the vertical surfaces increased the energy removal from the bulk flow in the lower region. These heat sinks were the dynamic determinants of the post source flow transient. Despite these modest inhomogeneities, the effect on hydrogen gas transport is minimal in this case.

The second simulation involving only air and hydrogen showed that the heat sink energy removal could dominate the flow transient during source injection. Also, the thermal inertia

of the atmosphere is much lower when the condensible component is not present. Consider that the nondome region average temperature decreased 55°C, while in Problem 3 the decrease was 14°C even though the heat transfer coefficients in the third problem were at least an order of magnitude higher. This second simulation illustrates a scenario which could lead to the initial conditions set in Test No.6 of the BF Phase 1 series (see [14]).

Problem 3 results share many of the second simulation's characteristics including stepwise stable stratification, well-mixed lower volume and dominance of heat sink energy removal. However, this case also possesses a few unique results. The calculated heat transfer coefficients were much higher during this computation due to the large steam mass fractions. The two strongest momentum influences - negative buoyancy due to energy removal and positive buoyancy due to hydrogen inflow - competed during the source injection phase as demonstrated by the velocity magnitude transient and the slow evolution of the flow fields. The eventual smoothing of the vertical steam density profile also demonstrates the importance of diffusive transport when a component removal mechanism (i.e. condensation) is available. The decoupling of the upper and lower regions with respect to hydrogen accumulation is also reminiscent of the BF6 test data.

The relevance of these results to hydrogen flammability considerations is illustrated in Fig. 30 which depicts the trajectories of the three simulations on the triangular hydrogen combustion limit diagram. The curves indicate that flammability limits can be violated from a variety of initial conditions,

different subregions can differ in their flammability potential and pre-chemical reaction thermo-fluid dynamic transient determines the severity of postulated burns. The impact of detailed containment behavior on fission product transport is not addressed quantitatively in this work but the results should still be noted. A particularly important aspect is the steam density profiles observed and their potential effect on fission product removal mechanisms such as diffusiophoresis.

A number of sensitivities have not been studied although they are clearly important. First, the presence of sprays and fan coolers would alter the outcomes dramatically. Second, various geometries must be analyzed in order to characterize this influence. Higher priority variations include three-dimensional arrangements, different heat sink configurations and computational mesh changes. A number of different accident sequences and their resultant contaminant injection transients should be simulated with the goal of distinguishing which accidents are susceptible to nonuniform containment conditions and thus require more detailed treatment than they currently receive in safety studies.

V. CONCLUSIONS

The results of this modest investigation lead to two major conclusions. First, analysis of a few prototypic post-accident containment transients using better estimate analysis tools indicates that atmosphere stratification and depressed mixing can be obtained. This observation is relevant to assessing safety

regulatory requirements for the mitigation of severe core damage accidents in that these results affect both fission product transport and combustible gas control. Second, the physical constraints that encourage or discourage atmospheric homogenization include heat sink placement, source flow, initial state and geometrical arrangement. Much remains to be done before clear understanding of this problem is obtained. The purpose of this contribution is to stimulate attention to this important nuclear safety question.

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Table 1

Initial Conditions for Problem 1

Atmospheric pressure - $1.0135 \times 10^5 \text{ N/m}^2$ (14.7 psia)

Atmospheric temperature - 323.15°K (122°F)

Composition - 100% air

Initial Velocity Field - stagnant

Initial Heat Sink Temperature - 323.15°K

Table 2

Initial Conditions for Problem 3

Atmospheric pressure - $2.737 \times 10^5 \text{ N/m}^2$ (39.7 psia)

Atmospheric temperature - 385.75°K (235°F)

Composition - 56% air, 44% steam by mass

44% air, 56% steam by volume

Initial velocity field - stagnant

Initial heat sink temperature - 323.15°K (122°F)

PROBLEM GEOMETRY

FIGURE 1

PROBLEM 1 SOURCE SPECIFICATION

FIGURE 2

PROBLEM 1 MAXIMUM VERTICAL VELOCITY TRANSIENT

FIGURE 3

FIGURE 4

FLOW FIELD AT 600 S DURING
PROBLEM 1 SIMULATION

$U_{\max} = -1.10 \text{ M/S}$ $V_{\max} = 1.47 \text{ M/S}$

FIGURE 5
FLOW FIELD AT 1500 S DURING
PROBLEM 1 SIMULATION

$U_{\max} = 0.30 \text{ M/S}$ $V_{\max} = 0.39 \text{ M/S}$

FIGURE 6

DENSITY STRATIFICATION OF PROBLEM 1 - CASE 1

FIGURE 7

DENSITY STRATIFICATION FOR PROBLEM 1 - CASE 2

VERTICAL LIQUID DENSITY PROFILES
DURING PROBLEM 1

FIGURE 8

FIGURE 9

THERMAL STRATIFICATION DURING PROBLEM 1

FIGURE 10

VERTICAL DENSITY PROFILES OF CASEOUS
COMPONENTS AT 1500 S OF PROBLEM 1

MAXIMUM VERTICAL VELOCITY TRANSIENT
FOR PROBLEM 2

FIGURE 11

DENSITY STRATIFICATION DURING PROBLEM 2

FIGURE 12

THERMAL STRATIFICATION DURING PROBLEM 2

FIGURE 13

FIGURE 14
VERTICAL DENSITY PROFILES OF AIR AND HYDROGEN DURING PROBLEM 2

AVERAGE TEMPERATURE AND PRESSURE DURING PROBLEM 3

FIGURE 15

FIGURE 16

HEAT SINK ENERGY REMOVAL RATE AND INTEGRATED ENERGY ABSORPTION
DURING PROBLEM 3

MAXIMUM VERTICAL VELOCITY TRANSIENT DURING PROBLEM 3

FIGURE 18

FLOW FIELD AT 1000 S DURING

PROBLEM 3. SIMULATION

$U_{\max} = 0.60 \text{ M/S}$ $V_{\max} = 0.52 \text{ M/S}$

FIGURE 19

FLOW FIELD AT 1750 S DURING
PROBLEM 3 SIMULATION

$$U_{\max} = 0.45 \text{ M/S} \quad V_{\max} = 0.79 \text{ M/S}$$

FIGURE 20
FLOW FIELD AT 20000 S DURING
PROBLEM 3 SIMULATION

$U_{\max} = 0.13 \text{ M/S}$ $V_{\max} = 0.23 \text{ M/S}$

DENSITY STRATIFICATION DURING PROBLEM 3

FIGURE 21

THERMAL STRATIFICATION DURING PROBLEM 3

FIGURE 22

FIGURE 23

VERTICAL COMPONENT DENSITY PROFILES AT 1750 S DURING
PROBLEM 3 SIMULATION (ALL IN KG/M^3)

FIGURE 24
 VERTICAL COMPONENT DENSITY PROFILES AT 20000 S DURING
 PROBLEM 3 SIMULATION (ALL IN KG/M³)

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VOLUME FRACTION TRANSIENT FOR LOWER RIGHT HAND NODE DURING
PROBLEM 3 SIMULATION

FIGURE 25

VOLUME FRACTION TRANSIENT FOR DOME REGION CELL DURING
PROBLEM 3 SIMULATION

FIGURE 26

FIGURE 27

HYDROGEN VOLUME % PROFILE AT 1000 S DURING
PROBLEM 3 (WET & INCLUDING STEAM)

			0.09	0.11			
		0.25	0.26	0.30	0.33		
	0.38	0.44	0.45	0.55	0.54	0.54	
0.65	0.66	0.66	0.68	0.83	0.89	0.89	0.89
0.71	0.77	0.76	0.79	1.03	1.03	1.01	0.94
1.39	1.44	1.49	1.54	1.70	1.72	1.70	1.67
1.34	1.54	1.64	1.79	1.97	1.92	1.78	1.63
1.58	2.12	2.22	2.30	2.31	2.31	2.31	1.77
1.83	2.28	2.38	2.47	2.51	2.48	2.38	2.21
1.94	2.24	2.35	2.45	2.47	2.58	2.88	3.43
1.89	1.86	2.22	2.42	2.59	2.85	3.20	3.52
1.85	1.81	1.77	1.77	1.90	2.38	2.67	3.20

FIGURE 28

HYDROGEN VOLUME % PROFILE AT 1750 S DURING
PROBLEM 3 SIMULATION

			0.21	0.21			
		0.43	0.45	0.46	0.47		
	0.57	0.63	0.61	0.63	0.68	0.69	
1.37	1.47	1.54	1.74	1.77	1.71	1.63	1.57
1.39	1.70	1.97	2.15	2.25	2.36	2.42	2.51
3.40	3.42	3.42	3.42	3.44	3.62	3.90	4.09
3.37	3.51	3.69	3.77	3.83	3.95	4.07	4.11
3.31	3.43	3.63	3.74	3.81	3.92	4.04	4.13
3.24	3.38	3.64	3.66	3.75	3.84	3.80	4.14
3.19	3.31	3.44	3.54	3.63	3.70	3.70	4.18
3.11	3.20	3.29	3.36	3.44	3.52	3.64	4.28
2.94	2.98	3.02	3.08	3.16	3.69	4.12	4.59

FIGURE 29
HYDROGEN VOLUME % PROFILE AT 20000 S DURING
PROBLEM 3 SIMULATION

			1.52	1.52			
		1.83	1.83	1.83	1.83		
	2.17	2.08	2.09	2.09	2.08	2.16	
3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14
3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
3.15	3.15	3.15	3.15	3.14	3.14	3.14	3.14
3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
3.16	3.16	3.16	3.16	3.17	3.17	3.17	3.17
3.18	3.18	3.18	3.19	3.19	3.18	3.18	3.18

TRAJECTORIES OF THREE SIMULATIONS PROJECTED
ON HYDROGEN-AIR-STEAM FLAMMABILITY
MAP

FIGURE 30

Appendix - Computer Application Information

These simulations were run on the Duke Power CDC Cyber 176 computer by Richard Jenny of Duke. The hard copy output of these runs is held by the authors. The job names and run dates are:

Problem 1	0-300 s (Case 1)	ACGAACOH	4/26/84
	300-600 s (Case 1)	ACGAABFS	5/3/84
	600-1500 s (Case 1)	ACGAAAIG	6/20/84
	0-600 s (Case 2)	ACGAAAIU	6/20/84
Problem 2	0-20000 s	ACGAAAMB	7/6/84
Problem 3	0-20000 s	ACGAAATB	7/16/84

The execution time and efficiency statistics are summarized below.

<u>Job</u>	<u>Simulated Time (s)</u>	<u>CPU Time (s)</u>	<u>CPU time duration-cell*</u>
COH	300	476	0.01888
BFS	300	316	0.01254
AIG	900	764	0.01011
AIU	600	744	0.01476
AMB	20000	3958	0.00236
ATB	20000	5061	0.00302
 TOTAL	 42100	 11319	 0.00320

*84 fluid cells