Attachment 1 to AEP:NRC:0500S

HYDROGEN COMBUSTION MODELING ASSUMPTIONS FOR THE D.C. COOK NUCLEAR PLANT

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SUMMARY

The set of hydrogen combustion and control analysis assumptions, presented in Attachment 2 to letter AEP:NRC:05000 (dated March 29, 1985), has been modified to reflect comments received from the NRC staff and recent developments in analytical models. In particular, the criteria for the deliberate ignition of hydrogen/air mixtures have been modified to account for the potential effects of fog generated in an ice condenser containment atmosphere; the correlations for flame speed and burn completeness have also been updated to those recently proposed by Sandia National Laboratories. The revised set of hydrogen combustion parameters, presented in this document, are those to be used in the CLASIX and MARCH computer codes to perform the analyses required under 10 CFR 50.44 (c).

BACKGROUND

Previous base case analyses, to demonstrate the effectiveness of the Distributed Ignition System (DIS) for the D.C. Cook Nuclear Plant, were based on CLASIX calculations which assumed eight volume percent hydrogen for ignition, eighty-five percent completeness of combustion, and a flame speed of six feet per second. Since those analyses were performed, the data base for hydrogen combustion events and related phenomena has improved significantly. The calculations to be performed for final resolution of the hydrogen control issue (10 CFR 50.44 (c)), will be consistent with the improved data base by utilizing modeling assumptions that reflect the current understanding of hydrogen combustion phenomena.

Of particular interest in the current analyses is the ability of the DIS to effectively ignite lean hydrogen/air mixtures in the ice condenser containment. The presence of high concentrations of small-diameter water droplets, or fogs, in the containment atmosphere has been shown in previous analyses to potentially affect the performance of glow plug igniters. The combustion parameters, described below, account for this effect by incorporating the results of the analysis specific to the D.C. Cook Nuclear Plant.

FLAME IGNITION and PROPAGATION CRITERIA

In hydrogen combustion experiments with glow plug igniters operating, combustion is typically found to start well below the eight volume percent previously assumed. In the continuous injection combustion tests, performed at the Nevada Test Site (NTS) by EPRI, ignition occurred when the volume-averaged hydrogen concentration was between three and five volume percent (depending upon hydrogen source injection rate) (1). These results are supported by data from several small scale experiments including those conducted by Sandia in the Fully Instrumented Test System (FITS), Fenwal,

Inc., and the Whiteshell Nuclear Research Establishment (2). In general, the current data base suggests the use of ignition criteria near the lower flammability limit.

One additional factor has been considered, however, in defining our assumptions regarding flame ignition. An analysis performed by Westinghouse (3) (and supported by data from Factory Mutual) concluded that the presence of high concentrations of small diameter (less than 20 micron) water droplets, or fogs, may suppress the ignition of otherwise flammable mixtures. Westinghouse proposed criteria for "fog inerting" of hydrogen/air mixtures and calculated the concentration of fog that would be generated in the D.C. Cook containment during an S_2D[1] accident sequence. This sequence is also one of the three accident sequences to be investigated in the current analysis.

The proposed fog inerting criteria are reproduced in Figures 1 and 2 for 4.76 and 7.2 volume percent hydrogen, respectively. The concentration of fog required to inert the mixture is shown to depend upon the assumed size of water droplets that compose the fog. The Westinghouse analysis recommended a mean fog droplet diameter of 10 microns. If the fog inerting criteria are extrapolated to 10 microns, the minimum fog concentration required for inerting 4.76 percent hydrogen is approximately 8.4×10^{-6}. For 7.2 percent hydrogen the Westinghouse theoretical fog inerting criterion (1.0×10^{-4}) differed from that indicated by Factory Mutual data (2.1×10^{-5}). Both values were considered in our review.

The fog concentration calculated by Westinghouse for each compartment of the D.C. Cook containment during an S_2D sequence is reproduced as Figure 3. A rough schematic of the D.C. Cook containment is given in Figure 4, which outlines the regions that comprise the various compartments considered in this analysis. The upper plenum of the ice condenser is predicted to have the highest fog concentration for most of the time. Following the upper plenum in fog concentration are the dead end regions and the upper compartment.

The times at which the upper plenum hydrogen concentration were calculated to reach 4 and 7 volume percent for this sequence are identified along the time scale of Figure 3; the corresponding fog inerting limits (for 10 micron droplets) are also indicated. Comparison of these limits to the predicted fog concentrations in each compartment leads to the following conclusions:

(i) Following the time at which the hydrogen concentration reaches the lower flammability limit in the upper plenum, the upper plenum is predicted to have fog concentrations exceeding the fog inerting limit. It is uncertain whether flame ignition in the dead end region is limited by fog concentration at the lower flammability limit.

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[1] S_2D is the Reactor Safety Study nomenclature for a small break loss-of-coolant accident with failure of all emergency coolant makeup.

(ii) Ignition of the hydrogen/air mixture in the upper plenum at 7 volume percent is uncertain, therefore, modeling the ignition of hydrogen in the upper plenum should be delayed until 8 volume percent is achieved. The dead end region fog concentration is predicted to decrease with time and is likely to be lower than the fog inerting limit at 6 volume percent.

(iii) All compartments, other than the upper plenum and the dead end region, are predicted not to develop fog concentrations high enough to warrant significant increases in the hydrogen concentration at which ignition may be assumed to occur.

The criteria described above define the range of concentrations of hydrogen/air/steam mixtures which may be ignited by an active glow-plug igniter. Propagation of a flame from the region of the containment containing an igniter into a neighboring gas volume is dependent upon an additional characteristic: the direction (orientation with respect to vertical) the flame must travel. This dependency was observed in the NTS test results where the volume-averaged hydrogen concentration at which a global burn could be initiated by an igniter located at the bottom of the test vessel was lower than that at which a global burn could be initiated by an igniter at the top of the vessel (1). In modeling the propagation of a combustion flame from one region of a containment vessel to another, this directional dependence is accounted for by requiring a higher compartment-averaged hydrogen concentration to propagate a flame against bouyancy forces (downward) than to propagate with the aid of bouyancy forces (upward).

Based upon our review of the available data from relevant hydrogen combustion experiments, and the existing analysis regarding fog inerting in the D.C. Cook containment the following assumptions for modeling hydrogen ignition and propagation are planned:

(1) Ignition in the upper plenum of the ice condenser will occur at a compartment-averaged hydrogen concentration of eight volume percent. Ignition in all other compartments will occur at a compartment-averaged hydrogen concentration of six volume percent. In either case, ignition will be subject to the availability of sufficient oxygen (>5 v/o) and considerations of steam inerting (<55 v/o).

(2) Flame propagation between compartments will be based on the criteria of Coward and Jones (4) (the default values in MARCH) which take into account hydrogen concentrations and orientations of connected compartments. These criteria are:

Upward Propagation	- 4.1 v/o hydrogen
Horizontal Propagation	- 6.0 v/o hydrogen
Downward Propagation	- 9.0 v/o hydrogen

It should be noted that these criteria do not conflict with the combustion limitations associated with high fog concentrations. As discussed above, it is primarily the upper plenum of the ice condenser that is restricted by fog

inerting criteria. The upper compartment is the only compartment from which a flame may propagate into the upper plenum. Since the upper compartment is modeled as a volume above the upper plenum, for a flame to propagate into the upper plenum, it would have to originate in the upper compartment and propagate downward. This would require an upper plenum hydrogen concentration of 9.0 v/o which is greater than the concentration at which the upper plenum mixture is assumed to be ignited.

COMBUSTION COMPLETENESS and FLAME SPEED

Sandia National Laboratories has developed improved correlations for the completeness of hydrogen combustion and flame speed for the HECTR computer code (5). The data base for these correlations is extensive and, in the case of combustion completeness, includes the NTS tests. The most current HECTR models for combustion completeness and flame speed will be used in the D.C. Cook analyses.

A newly developed correlation for combustion completeness, planned for incorporation into HECTR version 1.5, will be used. The new correlation is (6):

$$x_f = \text{Max}\left(\left(1.8777 - 23.4397\, x_i\right) x_i,\ \ 0.005\, x_i\right)$$

x_f = fraction of hydrogen burned
x_i = initial hydrogen mole fraction

This correlation is shown in Figure 5 in comparison to available data and to the old default HECTR correlation (also used as the default in MARCH 2.0).

The correlation for flame speed that will be used is the default model in HECTR version 1.0 ((5), page A-19). This correlation produces flame speeds slightly lower than those calculated with the current default model in MARCH 2.0 (7).

CONCLUSION

The modeling assumptions described above, as well as those presented in Attachment 2 to letter AEP:NRC:05000, form the technical bases for the analyses approved by an NRC letter, dated June 28, 1985 (8). These assumptions are based on the most recent experimental data available and reflect our understanding of proper modeling of the important phenomena in hydrogen combustion and control.

REFERENCES

1. L.B. Thompson, J.J. Haugh, B.R. Sehgal, "Large Scale Hydrogen Combustion Experiments", International Conference on Containment Design, Toronto, Canada, June 17-20, 1984.

2. M. Berman and J.C. Cummings, "Hydrogen Behavior in Light Water Reactors", Nuclear Safety, 25-1, January-February 1984.

3. S.S. Tsai and N.J. Liparulo, "Fog Inerting Criteria for Hydrogen/Air Mixtures", Second International Workshop of the Impact of Hydrogen on Water Reactor Safety, Albuquerque, New Mexico, October 3-7, 1982. (A full report was also submitted to the NRC as Attachment 4 to letter AEP:NRC:0500K, dated Oct. 10, 1983)

4. E.F. Coward and G.W. Jones, Limits of Flammability of Gases and Vapors, Bulletin 503, Bureau of Mines, U.S. Department of the Interior, 1952.

5. A.L. Camp, M.J. Wester, S.E. Dingman, "HECTR Version 1.0 User's Manual", NUREG/CR-3913, Sandia National Laboratories, February 1985.

6. Personal communication from C. Channy Wong (Sandia National Laboratories) to Thomas Crawford (American Electric Power Service Company), letter dated August 12, 1985.

7. R.O. Wooton, P. Cybulskis, S.F. Quayle, MARCH 2 (Meltdown Accident Response Characteristics) Code Desription and User's Manual, NUREG/CR-3988, Battelle Columbus Laboratories, September 1984.

8. NRC letter, dated June 28, 1985, from Mr. Steven M. Varga to Mr. John Dolan (American Electric Power).

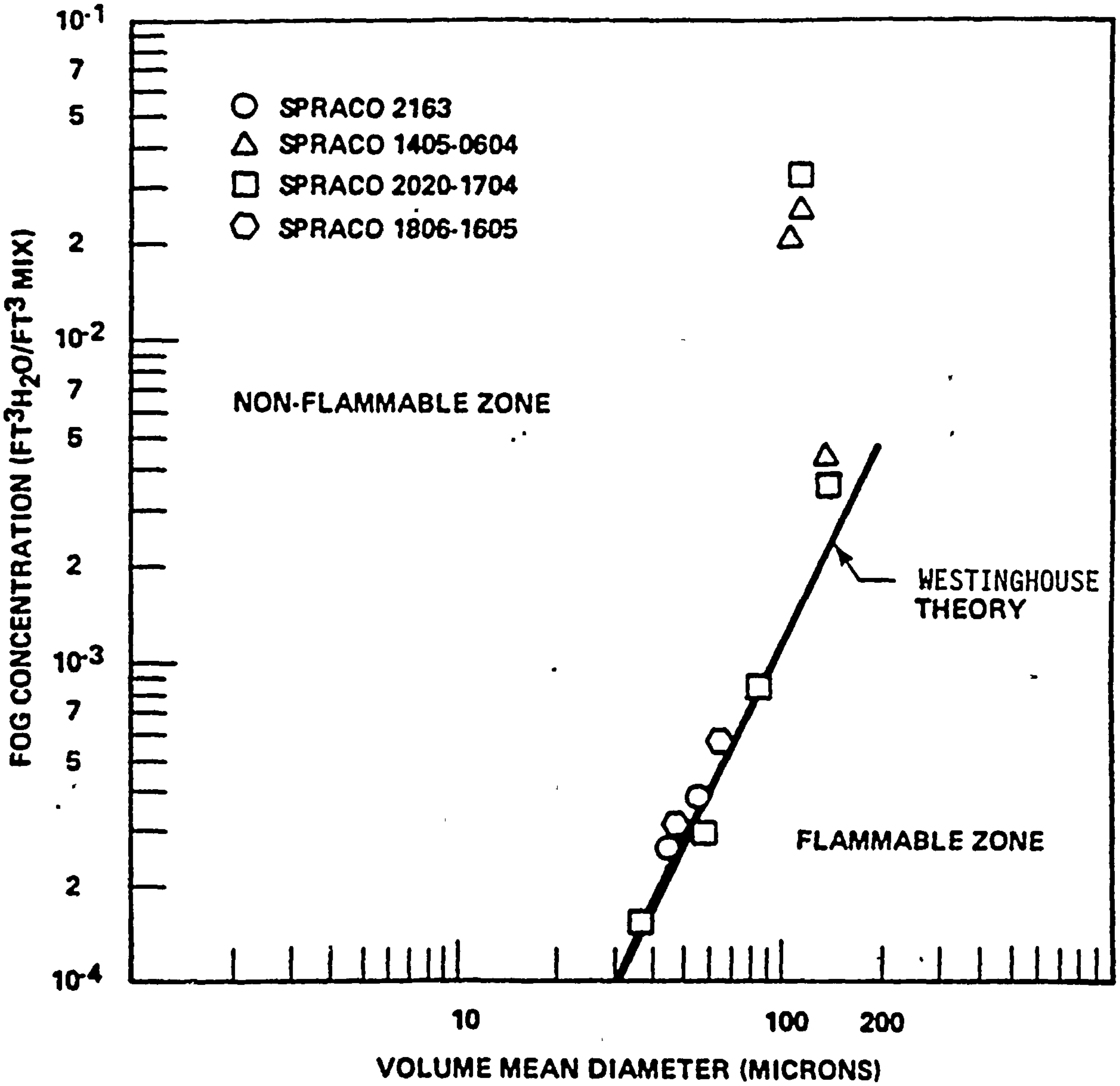


FIGURE 1. COMPARISON BETWEEN THE WESTINGHOUSE THEORY AND FACTORY MUTUAL FOG INERTING EXPERIMENTS ON 4.76 PERCENT HYDROGEN. [3]

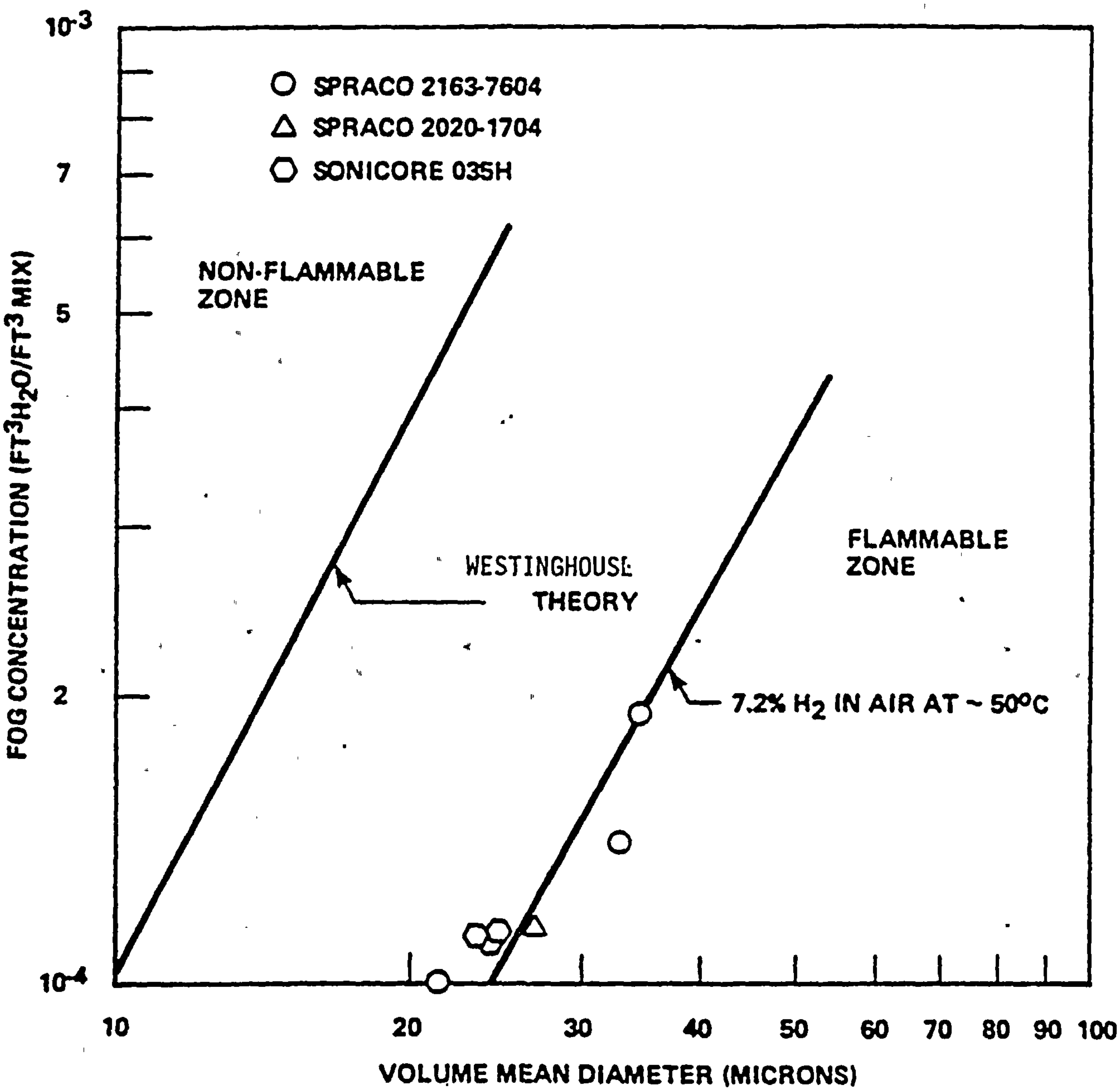


FIGURE 2. COMPARISON BETWEEN THE WESTINGHOUSE THEORY AND FACTORY MUTUAL FOG INERTING EXPERIMENTS ON 7.2 PERCENT HYDROGEN. [3]

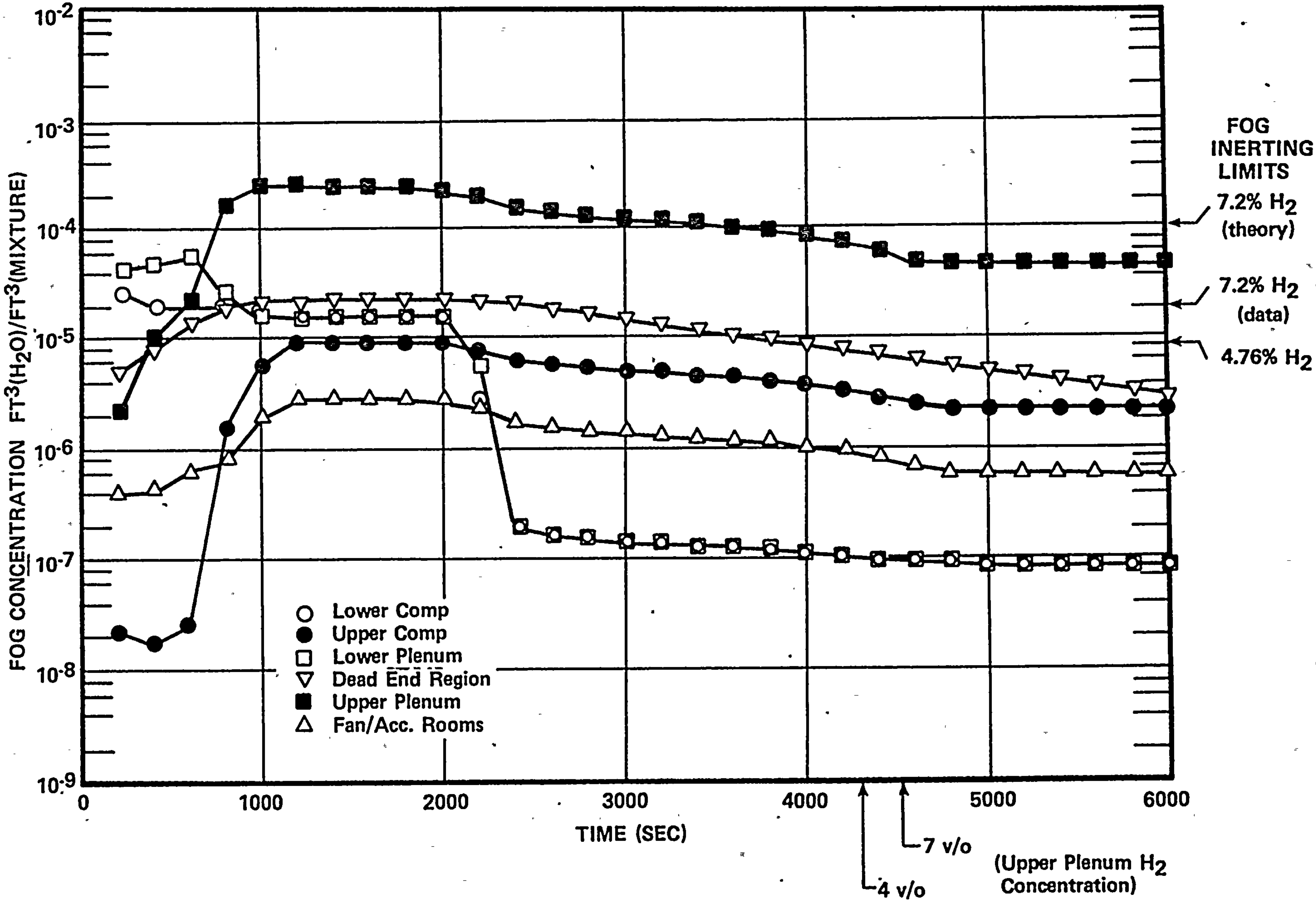


FIGURE 3. FOG CONCENTRATION IN D. C. COOK CONTAINMENT [3]

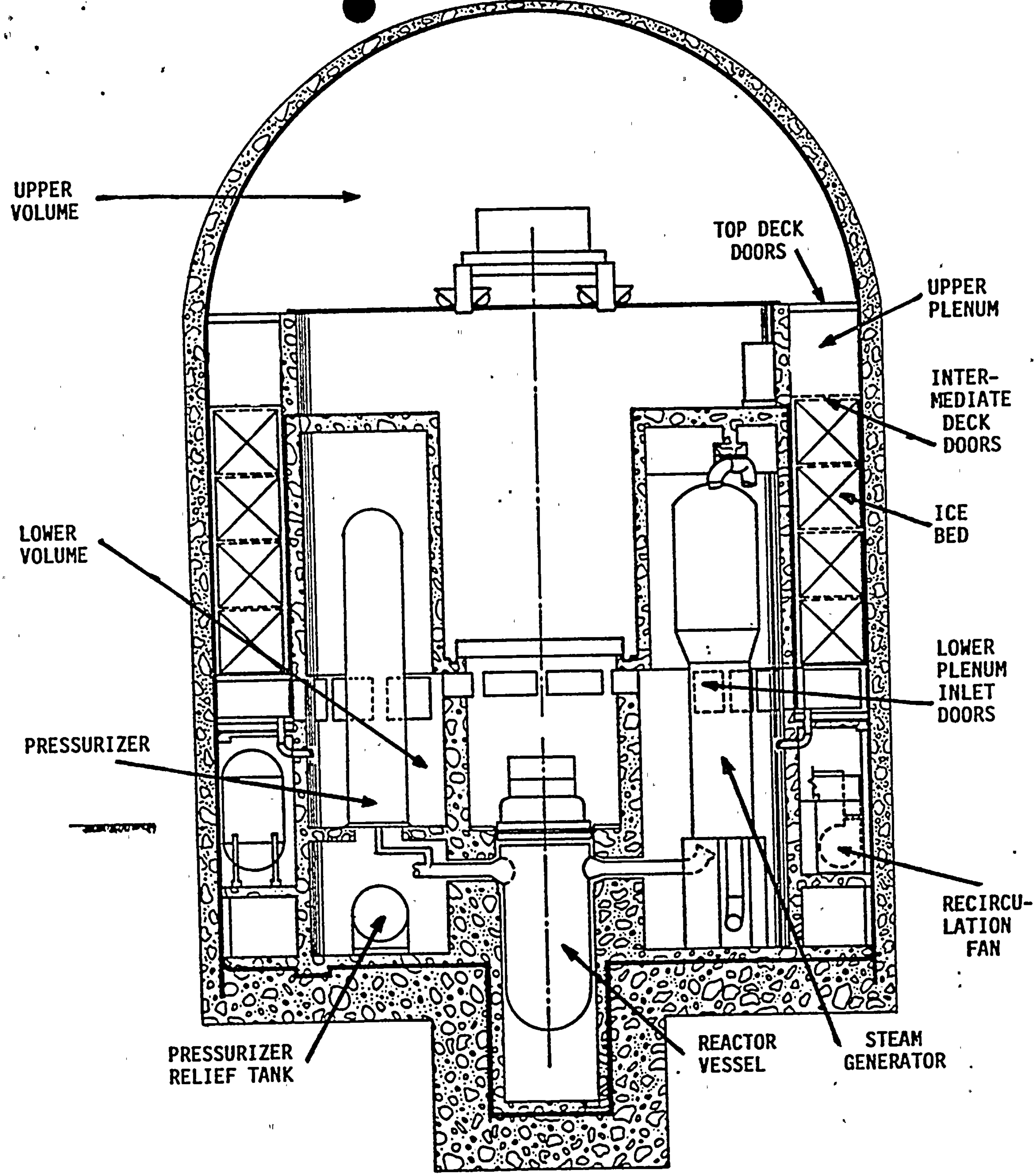
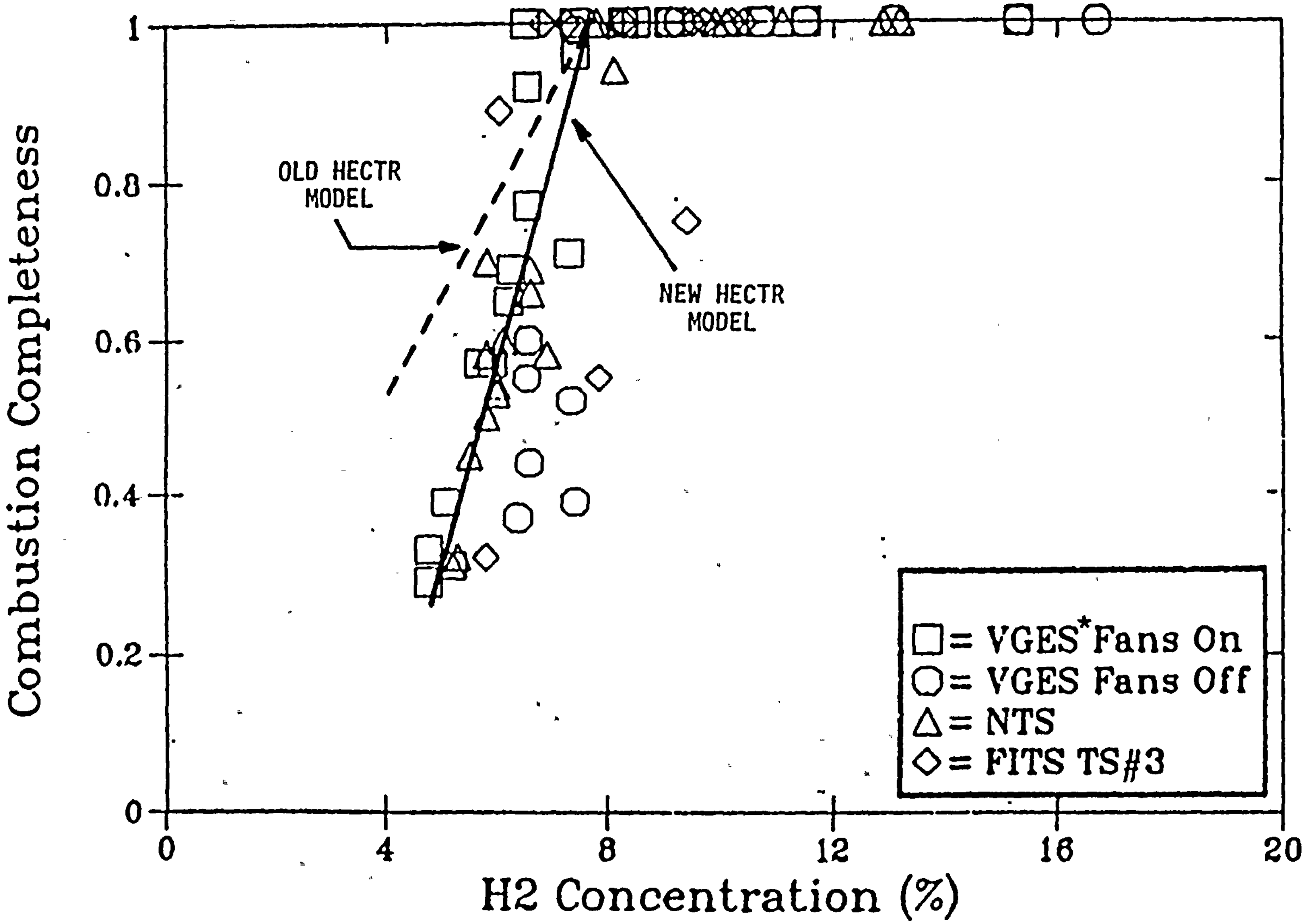


FIGURE 4. SIMPLIFIED DIAGRAM OF ICE CONDENSER CONTAINMENT COMPONENTS



*Variable-Geometry Experimental System (Sandia)

FIGURE 5. HYDROGEN COMBUSTION AS A FUNCTION OF THE INITIAL H_2 CONCENTRATION. [6]

ATTACHMENT 2 TO AEP:NRC:0500S

REFERENCES

1) "An Analysis of Hydrogen Control Measures at McGuire Nuclear Station," submitted by Duke Power Company to Mr. Harold Denton of NRC, February 29, 1984.

2) "Report on the Safety Evaluation of the Interim Distributed Ignition System," prepared by TVA for the Sequoyah Nuclear Plant Core Degradation Program, December 15, 1980.

3) "Containment Response to Degraded Core Events," for Sequoyah Nuclear Plant, November 16, 1981.