SOME HYDROGEN CONTROL CONSIDERATIONS FOR ICE-CONDENSER NUCLEAR PLANTS

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I. INTRODUCTION

During the accident at Three-Mile Island in 1979, significant quantities of hydrogen gas were produced by the reaction of the zirconium cladding with hot steam. The Nuclear Regulatory Commission (NRC) has been rightly concerned that reactors currently operating should be safe if hydrogen generated during an accident were the same amount that actually was generated at Three-Mile Island. The plants of most concern have been the ice-condenser plants because the volume of their containment is considerably smaller than standard plants. The proposal of the Tennessee Valley Authority (TVA) for coping with this problem in its Sequoyah ice-condenser plant was to put in place glow-plug igniters so that any hydrogen that is evolved during an accident could be burnt before accumulating into a dangerously large mass. Since it was desired to install these igniters in the Sequoyah and other plants as quickly as possible, the NRC asked the Lawrence Livermore National Laboratory (LLNL) to carry out some experiments on these igniters to delineate the region of their applicability.

The present report is an outgrowth of a subcontract from LLNL to R & D Associates (RDA) for assistance in part of this work. Section II deals with analysis and discussion of the data generated by LLNL and some possible difficulties and problems that may be encountered in application. Section III discusses alternative means of coping with the hydrogen problem and the further steps required for their assessment.

II. ON CONTROLLED IGNITION OF ACCUMULATED HYDROGEN IN A STEAM-RICH ATMOSPHERE

1. ANALYSIS AND INTERPRETATION OF LLNL HYDROGEN IGNITER TESTS

The LLNL has tested the performance of glow-plug igniters in mixtures of hydrogen, air, and steam (Refs. 1 and 2). RDA has analyzed some of the test data to locate the initial state-points on a ternary mixture chart and to relate the observed igniter efficacy to the state-point. An anomaly was reported in References 1 and 2 in which ignition failed to occur in a mixture of marginal ignitability because it contained a substantial quantity of steam, but which entered the assumed region of detonability as steam condensed. We studied this anomaly and its import to the general question of controlled ignition of hydrogen in a nuclear reactor containment building.

In tests where steam was mixed with hydrogen and air, the precise location of the state-point in the traditional ternary mixture chart was uncertain, primarily because temperature gradients in the test vessel made difficult the specification of the steam quantity. At the suggestion of LLNL, we calculated an effective average temperature, t_e , at which the sum of the vapor pressure of saturated steam plus the partial pressure of the hydrogen and air would equal the experimentally observed total pressure. Some details are given in Appendix A. The assumption that the steam in the mixture is effectively saturated (rather than being superheated) is believed to be justified because steam is supplied to the insulated vessel at the rate required to sustain the desired total pressure, while liquid water accumulates at the bottom of the vessel. No heat is added, other than that provided by the steam. The steam is provided in pulses through an on-off solenoid valve, from a boiler at about 6 atm total pressure. Temperature variations (spatial) of as much as 10°C in the test vessel are

reported. Table 1 shows the calculated effective mixture temperature for the eight initial test conditions considered, and for the final state of the mixture in Test 43 where no ignition occurred.

At the calculated effective temperature, t_e , the specific volume of saturated steam was then obtained from a curve-fit to the "steam tables," and steam of this density was assumed to fill the entire vessel volume of 300 l. This determined the number of moles of steam, N_s , in the vessel. The number of moles of gas, N_g , was determined from the initial pressure and temperature, p and t_1 , shown in Table 1 as obtained in Reference 2. Reference 1 cites the hydrogen-air ratio by which the number of moles of hydrogen, N_H , was calculated. The mole fractions $N_H/(N_g+N_s)$ and $N_s/(N_g+N_s)$ thus calculated are tabulated in Table 1 as F_H and F_s respectively. Mole fractions corresponding to the various initial conditions are plotted in Figure 1. The state-points in Table 1 and Figure 1 essentially confirm the original estimates in Reference 1. The ratio of partial pressure of steam (at temperature t_e) to total pressure is also given in Table 1, and is found to be essentially the same as the mole fraction of steam in the mixture.

References 1 and 2 provide gas sample analyses prior to and subsequent to ignition. The fractions of hydrogen consumed shown in Table 1 (and the percent combustion in Figure 1) were calculated from the reduction in the number of moles of hydrogen, preignition to postburn, as outlined in Appendix A. It can be seen in Figure 1 that except for Tests 34 and 43, the extent of combustion varies according to the location of the initial state relative to the limits of combustion previously postulated by Shapiro and Moffette. In general, the farther inside the limit boundary, the greater the extent of combustion. Tests 34 and 43 are exceptions. In Test 34, the

TABLE 1. MEASURED CONDITIONS FOR LLNL TESTS WITH STEAM-AIR-HYDROGEN MIXTURES AND CALCULATED EFFECTIVE MIXTURE TEMPERATURES AND COMPOSITION

Test #	35	36	27	38	39	40	34	^a 43
<u>Before steam injection</u>								
p_1 , gas pressure (lb/in ² gauge)	1.92	2.37	2.97	1.98	2.8	3.32	4.2	4.2
t_1 , gas temperature (°F)	67	153	180	172	185	179	130	120
H ₂ /air mole ratio	0.128	0.162	0.218	0.15 ^a	0.209	0.259	0.360	0.407
<u>After steam injection, before ignition</u>								
p_t , total pressure (lb/in ² gauge)	14.0	10.6	11.0	13.1	14.5	16.5	31.0	27.0
t_e , effective mixture temperature (°F)	184.8	179.6	182.4	195.4	198.9	203.6	236.1	226.0
Mole fractions:								
F_S , steam	0.30	0.30	0.31	0.38	0.39	0.40	0.52	0.47
F_H , hydrogen	0.08	0.10	0.12	0.08	0.10	0.12	0.13	0.15
P_S/P_T , steam pressure/total pressure	0.29	0.30	0.31	0.38	0.39	0.40	0.51	0.47
<u>After ignition and burning</u>								
S, mole fraction H ₂ in residual dry gas	0.007	0.073	2.6×10^{-3}	0.085	0.084	0.0065	0.166	0.28
C, fraction of H ₂ consumed	0.46	0.54	0.99	0.42	0.60	0.98	~0.5	~0
<u>Final state</u>								
t_e , effective temperature (°F)								181.4
F_S , steam fraction								0.272
F_H , hydrogen fraction								0.210

^aStoichiometric mixture

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S, mole fraction H ₂ in residual dry gas	0.067	0.073	2.6×10^{-3}	0.084	0.0065	0.066	0.166	0.28
C, fraction of H ₂ consumed	0.46	0.54	0.99	0.60	0.98	0.75	~0.5	~0
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Figure 1. Initial state points of LLNL test mixtures for tests with steam, including the nonburning trajectory of test no. 43.

igniter was "on" continuously, while steam condensed and the state-point migrated toward a drier condition. No combustion was detected until the end of the test when the circulating fan was activated. Combustion at that time produced a small pressure rise ($\sim 1 \text{ lb/in}^2$) in the vessel. The gas analysis was somewhat anomalous (Ref. 2), so that interpretation of Test 34 is impaired. In Test 43, no combustion occurred, and the data are sufficient to permit the trajectory to be plotted in Figure 1. The final point of the trajectory is defined in Table 1 and was determined with the total pressure and the initial composition.

That ignition did not occur at the initial state-points of Tests 34 and 43 is consistent with the expectation provided by the Shapiro and Moffette combustion limit (Ref. 3) in the region of high steam content. However, we can be confident of the trajectory of the Test 43 mixture (since there are no significant anomalies in the measurements), and this trajectory traversed well inside the state-points of Tests 35, 36, 27, 38, 39, and 40. Furthermore, the mixture of Test 43 actually reached the "assumed detonation zone" without combustion. Although the cause of the failure to ignite is still conjectural, the failure to ignite might be the most important experimental finding of the test program, especially if a containment atmosphere could have similar conditions.

At present, it is our conjecture that a dense condensation fog existed in Tests 34 and 43, but not in the other tests (for reasons unknown). Many consider fog to be an effective suppressor of ignition of hydrogen, and this is being studied as a possible safety measure. Of all the tests, 34 and 43 had the greatest quantity of steam present, and a fog is more likely. LLNL reports observations of optical obscuration in nonburning experiments subsequent to Test 43 with 50 percent

steam concentrations.* Also, the method of injecting steam is qualitatively consistent with the generation of aerosol nuclei. Whether or not a fog was responsible in Tests 34 and 43, the conjecture points to a paradox in the simultaneous consideration of igniters and fog generators as devices for coping with accumulations of hydrogen in reactor containments. This paradox is discussed in the next section.

2. DISCUSSION OF A POSSIBLE RELIABILITY PROBLEM FOR IGNITERS

In Reference 4, it is recognized that a fog may occur in a post-LOCA atmosphere in a containment building. In an ice-condenser containment, conditions appear especially conducive for the generation of fog by bulk condensation of moisture in saturated air (i.e., growth of condensation nuclei in the bulk fluid) as the warm saturated air flows through the ice compartment. If fog does indeed suppress ignition, there would appear to be an important set of conditions for which igniters in a containment building would not be effective, and might be countereffective by introducing a spurious hope or distraction.

There is a possibility that while an accident-caused fog might interfere with intentional ignition of hydrogen, the fog might be short-lived, thereby permitting the igniters to be used when needed. One postulated mechanism for fog removal is the containment spray, which could scavenge fog particles. For a spray-water volumetric flow rate $\dot{W}$, and with the spray

* In those optical measurements, the dense fog abruptly cleared as the steam concentration diminished to between 40 percent and 30 percent, which leaves a mystery as to why ignition failed to occur in Test 43 as the mixture approached its final state of 27 percent steam. The answer may lie in the possibility that although the optical length of the fog had increased in the post-43 optical measurements, there was still a sufficient concentration of fog to suppress ignition.

droplets having a uniform radius R and terminal velocity U , the volume of spray water falling through height H at any instant would be:

$$V_s = \frac{\dot{W}H}{U}$$

The number of falling droplets N_D and the volumetric rate at which this spray would "sweep through" the contained atmosphere would be:

$$N_D = \frac{V_s}{\frac{4\pi R^3}{3}}$$

N_D = number of droplets
of radius R

$$Y = N_D \pi R^2 U$$

Y = volumetric displacement rate of falling droplets

$$Y = \pi R^2 U \frac{V_s}{\frac{4\pi R^3}{3}} = \frac{3}{4} \frac{UV_s}{R}$$

Let the relevant containment compartment volume be V_c . Then the fractional rate of "sweeping" of the containment compartment volume would be

$$\frac{Y}{V_c} = \frac{3}{4} \frac{UV_s}{RV_c}$$

If the fog-particle collection efficiency is ϵ , and the particle concentration is γ , the rate of removal of fog particles is

$$\frac{d\gamma}{dt} = -\epsilon \frac{Y}{V_c} \gamma$$

or

$$\gamma = \gamma_0 \exp \left[- \frac{3\epsilon}{4} \frac{UV}{KV} \frac{t}{c} \right]$$

The fog-clearing effectiveness of the containment spray is indicated by the magnitude of the decay constant: the larger the constant, the more effective the clearing. The relaxation or e-folding time for fog clearing is:

$$\tau = \frac{4RV}{3 UV} \frac{c}{\epsilon}$$

Consider a total containment spray-water flow rate of $3 \times 10^5 \text{ cm}^3/\text{s}$, a droplet radius of 0.1 cm, a terminal velocity of 10^3 cm/s , and a containment compartment volume of $2 \times 10^{10} \text{ cm}^3$. These numerical values are believed approximately valid for the Sequoyah containment systems. For this example, and for time τ in seconds,

$$\begin{aligned} \tau &= \frac{(4) (0.1) (2 \times 10^{10})}{3 \times 3 \times 10^5 \times 10^3} \left(\frac{1}{\epsilon} \right) \\ &= \frac{80}{9} \frac{1}{\epsilon} \approx \frac{10}{\epsilon} \text{ s} \end{aligned}$$

Depending on how many exponential factors of reduction are required to bring the fog concentration down to an ignitable level, that many τ intervals are required. A relaxation time of a few minutes is probably acceptable, whereas a time of a few hours is probably not. For the particular assumptions used in this example, a value of ϵ less than about 3×10^{-2} would cause for doubt that the containment spray could clear sufficient fog prior to intentional hydrogen

ignition. The value of ϵ depends upon the fog particle size and the spray droplet size, and magnitudes as small as 10^{-3} and 10^{-2} are reported in the literature on aerosol coagulation. Further work to define the conditions would be necessary before there could be confidence that the containment sprays could assist igniters by clearing whatever fog that might exist.

Other mechanisms might assist in reducing a fog concentration promptly. Particle agglomeration by Brownian motion does not appear very helpful, however, because for particle concentrations on the order of 10^5 cm^{-3} (which would be quite dense, optically) the particle half-life would be many hours. "Plating out" on cold surfaces (e.g., ice) would be of some help, but a quantitative assessment does not appear easy. Turbulence in the air-steam mixture would also provide some increase in agglomeration rate, but would again be difficult to assess.

At present, we consider the reliability of igniters to be in doubt because of (1) the experience of Tests 34 and 43, (2) the above arguments on fog coagulation by containment sprays, and (3) an apparent lack of other reliable methods for prompt reduction of condensation fog.

III. POSSIBLE ALTERNATIVES TO THE USE OF IGNITERS

Control of oxygen availability is a positive method of hydrogen control in reactor containment buildings. It has received little consideration so far because experience with fully inerted buildings has shown many difficulties, higher costs, and possibly impaired overall safety from insufficient access for maintenance. However, the possibility exists of inerting the containment only upon demand, after an accident has occurred. Such methods would offer the highest prospects for effective hydrogen control with minimum cost and inconvenience.

Three different approaches are possible for rapid reduction of combustibility: (1) use up the oxygen chemically, (2) dilute the oxygen with another substance, and (3) segregate or confine the oxygen so that it is not available for combustion. Described below are examples of each type which appear to meet the requirements and which merit fuller investigation.

1. CHEMICAL REMOVAL OF OXYGEN

a. Gas turbine combustor system--Hydrogen control in a reactor containment building through rapid depletion of the oxygen in the building atmosphere is a completely practical operation that can be carried out using commercially available equipment and simple, automatic controls. The equipment required consists of a small gas-turbine engine generator set, appropriate ductwork, a supply of fuel, a spray tower, a heat exchanger, and two pumps with piping. When started, the system would draw the containment atmosphere (which under accident conditions consists of air, radioactive gases, and possibly steam and hydrogen) through the gas-turbine combustor where a fuel such as kerosene or natural gas would be ignited. The turbine would provide power for circulating the atmosphere

and driving the pumps. Additional fuel would be burned in an afterburner to further deplete the oxygen. Any hydrogen in the inlet stream would be burned in the flame and assist in depleting the oxygen. The exhaust stream would be cooled rapidly in a spray tower and then discharged in the containment so as to minimize recirculation to the inlet.

The size and capacity of this system can be chosen to suit any likely set of requirements for rate of oxygen removal. The example considered here is capable of reducing the oxygen concentration by about 75 percent in 30 min in a building the size of the Sequoyah containment. The engine would continue to run until the inlet gas no longer supports combustion, whereupon it would stop by itself. During operation, the heat of combustion produced must be removed to the outside of the containment to avoid contributing to the overpressure that may exist from release of primary reactor water and stored core heat. This heat must be removed without releasing any radioactive materials.

The heat quantities involved are substantial: for the Sequoyah plant, to pass all the containment air through the turbine in 30 min requires a throughput of $2,000,000 \text{ ft}^3/\text{h}$, or $550 \text{ ft}^3/\text{s}$. Complete depletion of the oxygen in one pass would require burning fuel at the rate of 2.9 lb/s for kerosene and 2.5 lb/s for natural gas. Assuming on the average that only 75 percent of the oxygen is consumed, which seems readily attainable in practice, the fuel consumption is 2.2 lb/s for liquid fuel, producing heat at the rate of 49.5 MW, or 1.87 lb/s and 52.2 MW for natural gas. If hydrogen is present in the containment atmosphere, the engine controls will sense the higher heat input and reduce fuel flow accordingly. Thus the energy developed in consuming the oxygen will remain about the same.

During this time the reactor core may be producing decay heat at the rate of 40 MW or so, and if hydrogen is formed there is still more heat from the zirconium-steam reaction, as well as the energy in the pressurized hot water released in the escape of the primary reactor fluid. In this illustration it is assumed that the ice condenser, the containment cooling sprays, and other emergency systems are capable of handling these heat releases, but not the gas-turbine combustion energy. Therefore, the description that follows treats the oxygen depletion system as a separate, independent system with its own heat rejection means. Detailed analysis may show that existing systems could be readily modified to accept the additional cooling load. Alternatively, if other systems were deemed marginal in capacity, the gas-turbine cooling system could be readily enlarged to assist in controlling containment pressure at the most crucial time.

The effect of the gas-turbine operation upon the containment pressure is small but in a favorable direction: operation of the system serves to replace oxygen in the building atmosphere with CO_2 and H_2O . For kerosene fuel the reaction is: $\text{CH}_2 + 1.5 \text{ O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$ while for natural gas it is: $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$. Since the water vapor formed is condensed by the heat removal system, the effect of 75 percent combustion of oxygen is to replace 0.2 atm of oxygen with 0.05 atm of unburned oxygen and 0.1 atm of carbon dioxide, a net reduction of 5 percent in containment pressure. For methane fuel, the reduction in pressure is 7.5 percent.

The presence of carbon dioxide has an important effect upon the flammability limits for hydrogen because it is a much more effective diluent than nitrogen alone. Drell and Belles (Ref. 5) state that no mixture of hydrogen, air and nitrogen can propagate a flame if it contains less than

4.9 percent oxygen, while mixtures of hydrogen, air and carbon dioxide require 7.5 percent oxygen to propagate. Although it may be possible to adjust the engine to consume more than 75 percent of the oxygen, this value seems readily attainable with realistic ducting arrangements and simple controls. It also seems to be an adequate value, in view of the carbon dioxide produced, to give effective inerting to hydrogen in all concentrations.

The gas turbine required for the flow-rate assumed is about 4 feet in diameter and 12 feet long, with additional space required for the gearing and generator set. The hot turbine-afterburner exhaust gas is cooled rapidly by passing it into a spray tower which might be 7 feet in diameter and 30 feet tall, for example. Water is sprayed down this tower at a rate of about 800 gal/min, collected at the bottom, and pumped through a heat exchanger and back to the spray nozzles. The heat exchanger is required to pass the heat collected to the exterior of the containment without releasing any radioactive materials, which must be assumed to have contaminated the interior of the building. For the assumed capacity a heat exchanger about 36 inches in diameter and 65 feet long would suffice, although the equipment can be arranged in other proportions to fit the space available, and can be either vertical or horizontal. A second water circuit in the shell side of the exchanger picks up the heat, passes through the containment wall, and is circulated by a second pump to an auxiliary cooler, which might be the main cooling tower of the plant. This water circuit does not get contaminated.

Except for the ductwork needed to control the intake and discharge points of the air, the system is compact in size and flexible in arrangement. It is described here as being located within the containment, since it will be expected to become contaminated, and containment penetrations are to be avoided if possible. However, if space inside were too

limited, the system could be located outside with some shielding around it if it were permissible to bring the air ducts (30 inches in diameter) through the containment wall. The water pipes are only 6 to 8 inches in diameter.

The above illustration represents the equipment needed to meet the assumed goal of producing an inert atmosphere in the containment within 30 min. The engine-generator set is the most expensive item, estimated at a little under \$1 million. The additional equipment would cost less than \$0.5 million more, exclusive of installation, but the installation costs and the cost of plant shutdown time may tend to dwarf the equipment costs. If the time required for inerting is relaxed to 60 min, for example, all the capacities given above could be halved, and the cost reduced. The apparatus could be more compact and installation might be easier.

The gas-turbine inerting system is a highly practical approach to hydrogen control, once installed, but the question of its feasibility may depend upon the extent to which it can be programmed for installation during plant operation or during scheduled shutdowns. At \$600,000/day, only two or three extra shutdown days would generate down-time costs that exceeded the equipment costs.

b. Recombiners--The ideal way to remove hydrogen and oxygen is, of course, to cause them to react or recombine directly and to condense the resulting steam. This method would treat the hydrogen problem directly and simply. There has been extensive industry research on hydrogen recombiners, with the first unit installed on the Los Alamos Water Boiler reactor in the early 1950s. Much of the work has been done on catalytic recombiners; however, they are subject to poisoning in some circumstances, and the preference for commercial units is for a thermal recombiner, in which a heated furnace

wall instead of a catalyst causes the reaction to proceed. Complete with a blower and a cooling spray system, the recombiner operates in much the same way as the jet engine system except that it introduces no additional gases to the containment atmosphere.

Unfortunately, the largest commercially available system operates at about $150\text{-ft}^3/\text{min}$ throughput, so it would require 100 h to treat the Sequoyah containment of $1,000,000\text{ ft}^3$. Alternatively, 50 units could be used to make one pass in 2 h. The air stream is heated by electric heaters to about 1300°F , requiring 5 MW of electric input for the 50 units. If the requirement was for one complete pass in 30 min, as hypothesized for the jet-engine case, 200 recombiners drawing 22 MW would be required, probably an impractical goal in both cost and power supply.

To compare the jet engine with the recombiner, one should note that if the requirement is for very rapid inerting of the containment, only the jet-engine seems practical. If a slower treatment rate is permissible, either could do the job. However, the operation of the jet engine removes oxygen from the containment whether or not there is any hydrogen present at the time, while the recombiner accomplishes nothing unless hydrogen is present in the air stream.

2. INERTING BY DILUTION

An otherwise combustible mixture of air and hydrogen can be diluted below the flammable limit by adding an inert gas such as carbon dioxide. However, under conditions where hydrogen formation can be expected, the containment building would already be close to its maximum pressure, and the inert gas would tax it even more. If hydrogen should reach 10 percent by volume, for example, the building pressure would have to be nearly doubled to produce a nonflammable mixture with CO_2 .

A more efficient diluent is Halon 1301, a well-known fire-extinguishing agent. Halon 1301 is a member of the freon family of halogen-substituted methanes. It is nontoxic and inert generally, but in a flame front it reacts efficiently with the free radicals which propagate the flame and cause it to go out. With ordinary hydrocarbon fuels as little as 5 percent by volume will extinguish a flame, while 7.7 percent renders a highly flammable mixture completely inert. With hydrogen it is not as effective, requiring about 31 percent for a completely inert system. The required concentration would be 0.13 lb/ft^3 , or 130,000 lb for the Sequoyah containment. At \$8/lb, the chemical alone would cost over \$1 million, with approximately an equal amount for installation.

The cost of a Halon system does not seem high in comparison with the jet engine or recombiner systems, for example, but the necessity of adding 30 percent to the containment pressure at a time when it may be near its operating pressure limit gives one some pause in recommending its use for plants with small containments. For a new reactor, which could be designed with a beefier containment building, further study may show it to be one fairly convenient, sure, and low-cost way to inert the containment on demand.

3. SEGREGATION OF OXYGEN BY FOAM

The use of foam for rapidly inerting a containment building has not been previously considered, although it is well-proven for use on fires. Foam works in two ways to prevent combustion: first, it immobilizes the oxygen or air, and second, it provides a persistent form of dispersed water. The first effect would be most important for containment use. A foam generator uses water detergent and air to produce a heavy, stable foam made up of bubbles about 2 mm in size and containing 200 to 1000 volumes of air per volume of liquid

water. The practice is to completely fill the room or compartment to be protected. The foam flows freely and rapidly around, under and behind all obstructions during filling, but once full the air is held stationary and segregated in a semi-rigid mass, so that all convection is suppressed.

To be effective, foam would have to be in place in the containment before much hydrogen was formed. The foam generators work very rapidly, however--present installations already have the capacity to fill the Sequoyah containment in 10 min or less. Careful study and testing would be needed to determine the course of events when a stream of steam and hydrogen escapes into a foam-filled containment. It is certain that the immediate pathway between the source of steam and the ice condenser would be swept clear of foam, and the air in that flow volume would be mixed with the hydrogen. A quick calculation indicated that as much as 90 percent of the oxygen would still remain immobilized, but as was noted earlier in the discussion of gas turbines, removal of only three-fourths of the air seemed to be adequate for an inert system.

By properly choosing the location of the foam generators and the connecting openings between compartments, the pathway of the hydrogen could perhaps be controlled and the point of hydrogen accumulation chosen. One possible sequence, which would have to be verified, is that steam blow-down to the ice condenser would create a pathway through the foam, that the hydrogen-steam mixture would follow during the core-dryout stage, and would reach the ice with probably little additional admixture of air. As the steam condensed, one would expect the hydrogen to form a pocket of highly enriched gas which could slowly rise through the foam in the upper compartment to lodge on the ceiling of the dome, still without mixing.

The foam mixture developed for fighting large industrial fires persists only for a few hours, which is desirable since fairly rapid reentry is needed. Perhaps a more persistent form can be found for containment use, but at best the segregation of the hydrogen and air effected by the foam would not be long lasting. Some active means would be needed to drain off or recombine the hydrogen without danger of burning or explosion. In concept, the simplest of these would be to conduct or pump the hydrogen to a compartment which has been freed from ignition sources and which could be isolated for the duration of the accident.

It is clear that the use of foam to control containment hydrogen cannot be assessed without more detailed study. In particular, the interaction of containment cooling sprays and foam is not clear. In some fire-fighting situations, foam and sprays are used together to produce a heavier, denser foam, yet a heavy jet of water will knock down foam. If some of these questions can be answered, the foam system has important qualities:

1. The equipment is simple and well-proven. A foam generator consists of a source of water under pressure, a supply of detergent and a metering device, a water turbine driving an air blower, a spray nozzle, and a wire netting that establishes the size of the bubbles. It is set in operation by turning on the water, which drives the turbine and blower, and sprays water and detergent into the air stream ahead of the netting.
2. It is safe. An accidental or false alarm release of foam would not be dangerous to persons trapped in it (although they could not see to walk) and the foam causes little or no water damage compared to a spray system.

3. It is very quick (~10 min to fill).
4. It is commercially available.
5. Indications are that it would be less costly than any other proposed system except the igniters.

APPENDIX A. CALCULATION METHODS FOR TABLE 1

1. DETERMINATION OF EFFECTIVE MIXTURE TEMPERATURE

A numerical iteration was performed, varying the effective mixture temperature t_e until the total pressure in Eq. (1) agreed with the observed total pressure to within an error of 0.004 atm.

$$P_T = P_1 \frac{T_e}{T_1} + P_S(T_e) \quad (1)$$

Capital symbols are the absolute pressures and temperatures corresponding to p_1, t_1 , and t_e .

$P_S(T_e)$ is the function defined by the "steam tables" for saturated steam. An empirical curve fit was used for $P_S(T_e)$. This relation is given in Reference 6.

2. DETERMINATION OF STEAM FUNCTION

Let F_S represent the steam function. The specific volume of saturated steam is $v(T_e)$ (empirical curve fit from Reference 6, l/gm):

$$\text{Vessel volume} = V$$

$$\text{Mass of steam} = V/v(T_e)$$

$$N_s = \text{Moles of steam} = \left(\frac{1}{18}\right) \left[\frac{V}{v(T_e)}\right]$$

$$N_g = \text{Moles of gas} = \left(\frac{V}{22.4}\right) \left(\frac{273}{T_1}\right) \left(\frac{P_1}{1}\right)$$

$$\frac{N_S}{N_g} = \frac{22.4}{(18) v(T_e)} \left[\frac{T_1}{273 P_1} \right]$$

$$\frac{N_S}{N_g} = 4.558 \times 10^{-3} \frac{T_1}{P_1 v(T_e)}$$

$$F_S = \frac{N_S}{N_S + N_g} = \frac{N_S/N_g}{1 + N_S/N_g}$$

3. EXTENT OF COMBUSTION

If the final number of moles of hydrogen in the vessel is $\bar{N}_H$, the fraction of combustion C is defined as:

$$C = \frac{N_H - \bar{N}_H}{N_H} = 1 - \frac{\bar{N}_H}{N_H}$$

N_H is obtainable from N_g , the initial moles of hydrogen and air, since the ratio of hydrogen to air is given in Reference 1. In order to obtain $\bar{N}_H$ from the final gas analysis in Reference 1, wherein the fraction of hydrogen in the final noncondensable gas is given, it is assumed that no gas is lost (or dissolved), and that for every two moles of hydrogen removed by combustion, one mole of oxygen is also removed.

Let the initial number of moles of air, hydrogen, oxygen, and nitrogen be:

$$N_a, N_H, N_O, \text{ and } N_N$$

and designate the final number of moles of each by an over-scored symbol. From Reference 1, we know

$$S = \frac{\bar{N}_H}{\bar{N}_N + \bar{N}_O + \bar{N}_H}$$

where S is a mass spectrometer determination. Then

$$\bar{N}_H = \left(\frac{S}{1-S} \right) (\bar{N}_N + \bar{N}_O)$$

But

$$\bar{N}_N = N_N$$

and

$$\bar{N}_O = N_O - 0.5(N_H - \bar{N}_H)$$

Then

$$\bar{N}_H = \left(\frac{S}{1-S} \right) [N_N + N_O - .5(N_H - \bar{N}_H)]$$

$$\bar{N}_H \left[1 - \frac{.5S}{1-S} \right] = \frac{S}{1-S} [N_N + N_O - .5N_H]$$

$$\bar{N}_H = \left[\frac{S}{1-1.5S} \right] [N_N - 1.5N_H]$$

$$\frac{\bar{N}_H}{N_H} = \left[\frac{S}{1-1.5S} \right] \left[\frac{N_N}{N_H} - 1.5 \right]$$

$$C = 1 - \left[\frac{S}{1-1.5S} \right] \left[\frac{N_g}{N_H} - 1.5 \right]$$

$$C = 1 - \left[\frac{S}{1-1.5S} \right] \left[\frac{N_a}{N_H} - 0.5 \right]$$

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