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March 2, 1982

NUCLEAR PRODUCTION DEPARTMENT

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

Attention: Mr. Harold R. Denton, Director

Dear Mr. Denton:

SUBJECT: Grand Gulf Nuclear Station
Units 1 and 2
Docket Nos.: 50-416 and 50-417
File: 0260/L-8600/0756
Report on "Study of Hydrogen Control in
the Grand Gulf Nuclear Station"
AECM-82/25



Enclosed is one copy of the subject report which has been prepared by Bela Karlovitz and Bernard Lewis of Combustion and Explosives Research (COMBEX), Inc. In this report, COMBEX concludes that "The presently designed igniter system is adequate to prevent dangerous accumulation of flammable H₂-air mixtures in the containment." COMBEX further concludes that "...the Grand Gulf Nuclear Station (GGNS) as designed can contain safely the pressures which may develop during burning of hydrogen released by safety relief valves or by a small LOCA. There is no danger of transition of deflagration to detonation because large volumes of H₂-air mixtures with a composition within the detonable range are not allowed to accumulate in geometrical configurations conducive to transition." The enclosed report also contains some recommendations with respect to igniter locations and testing (see Section 9).

As described in Section 4 of the enclosed COMBEX report, hydrogen released into the wetwell either through safety relief valve spargers or through the vents from the drywell will mix with air in the wetwell and burn in the form of a turbulent diffusion flame. This turbulence results in a lower flame height than observed in previous tests in nonturbulent regimes. This lower height is due to an increased burning rate caused by turbulent mixing or entrainment with air. Combustion will continue as long as the supply of hydrogen and oxygen is adequate. In the case of a pipe break in the drywell, as air is introduced into the steam and hydrogen rich drywell atmosphere via the purge compressors or vacuum breakers, combustion will take place in the form of an inverted flame at the air inlet locations.

Combustion such as described above will result in insignificant pressure excursions. However, localized thermal loadings must be carefully evaluated for potential impact on essential equipment. The tests proposed in the attachment to the COMBEX report will provide the necessary data to evaluate the localized thermal environment in the wetwell region. (Performance of

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these recommended tests is under consideration by the BWR Mark III Hydrogen Control Owners Group.) The localized thermal environment in close proximity to the air inlet locations in the drywell is not a concern because no essential equipment is near those locations.

The CLASIX-3 computer program has been utilized by Offshore Power Systems, under contract to Mississippi Power & Light Co., to evaluate the GGNS containment pressure and temperature response to hydrogen deflagration. The nature of the combustion process as modeled in CLASIX-3 is in some respects different from that described in the enclosed COMBEX report and summarized above. The following paragraphs describe these differences and explain the purpose of the CLASIX-3 analyses.

In the CLASIX-3 modeling of hydrogen combustion in the GGNS containment, hydrogen is assumed to be uniformly mixed within any single volume. Ignition is assumed to occur when the hydrogen volume concentration reaches a predetermined value and the oxygen volume concentration is at least 5 percent. This modeling of the combustion process in CLASIX-3 results in many sequential burns in the wetwell volume and in some cases a single burn in the containment volume. Cases which model a drywell pipe break also exhibit a single burn in the drywell volume late in the transient sequence.

Modeling of the combustion process as is done in CLASIX-3 provides conservative pressure calculations for evaluation of the GGNS containment functional capability. It also corresponds, in a conservative way, to the nature of combustion expected to occur if hydrogen flow rates are very low and, therefore, insufficient to support a continuous flame. The CLASIX-3 calculations also allow evaluation of the consequences of hydrogen combustion in various regions of the containment, thereby bounding the range of combustion threats which might be postulated.

Except for localized temperature effects, CLASIX-3 calculations can be used to assess equipment survivability since the integrated energy of combustion is an important parameter over the time frame considered.

In light of the recommendations of Section 9 of the enclosed report, MP&L intends to evaluate each area of consideration. These areas include: 1) location of Ignitors, 2) Evaluation of the phenomena associated with the burning of hydrogen, 3) Tests in rich Hydrogen-air mixtures, and 4) Burn testing above the suppression pool. The above tests are described in a separate transmittal, however MP&L intends to perform such testing in order to address each recommendation of the subject report. It is MP&L's desire to resolve each of these issues in our test program described in AECM-82/60 dated March 2, 1982.

In conclusion, the expected nature of hydrogen combustion in the GGNS containment is described in Section 4 of the enclosed COMBEX report and summarized in the second and third paragraphs of this letter. The CLASIX-3 calculations incorporate a somewhat different modeling of the combustion

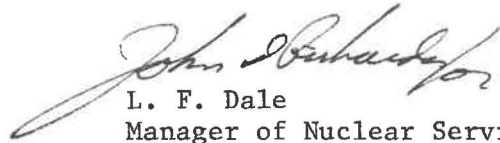
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process which provides conservative pressure calculations for the evaluation of containment functional capability. The CLASIX-3 calculations also provide information for assessing equipment survivability, when supplemented by test results for evaluation of localized temperature effects.

Yours truly,


L. F. Dale
Manager of Nuclear Services

SHH/JDR:rg

Attachments

cc: Mr. N. L. Stampley (w/a)
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REPORT ON STUDY OF HYDROGEN CONTROL
IN THE GRAND GULF NUCLEAR STATION

By

Bela Karlovitz and Bernard Lewis

November 25, 1981

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Combustion & Explosives Research, Inc., has evaluated the use of a distributed ignition system for the control of hydrogen hazards which may exist in the containment building of the BWR Mark III Containment of the Grand Gulf Nuclear Plant of Mississippi Power & Light Company.

1. Mark III Containment System

a.) Description

The Boiling Water Reactor sits in the center of the Drywell of the Mark III Containment. The drywell is formed by a cylindrical concrete wall and a flat concrete roof, the center opening of which is closed by a removable hemispherical steel cap. The drywell is surrounded by the wetwell which extends to the cylindrical steel shell of the containment. The bottom of the wetwell contains the suppression pool having a normal high water depth of approximately 18 ft. 10 in. The drywell communicates with the wetwell through three rows of horizontal vent openings. Each row contains 45 vent openings of 4.28 ft.² distributed around the circumference. The water is prevented from flowing into the drywell by a circular weir wall. Gases can flow from the drywell into the wetwell through an annular channel existing between the weir wall and the wall of the drywell. In case of pressure development in the drywell due to steam and/or hydrogen evolution the water in the annular channel is depressed until the horizontal vent openings become exposed.

Above the roof of the drywell is an upper pool containing water. This pool, which covers only a section of the total area of the containment building extends from elevation 184 ft. 6 in. to 208 ft. Above the pool is the dome of the upper containment which houses the crane for refueling operation. The volume of the

Drywell = 270,128 CF

Wetwell = 151,644 CF

Upper Containment = 1,248,588 CF

the total volume being 1,670,300 CF.

b.) Accidental Release of Steam and H₂ in the Containment.

In case of accidental overpressure within the reactor, steam and hydrogen may be vented by safety relief valves through spargers submerged in the suppression pool. There are 20 spargers distributed circumferentially in

the suppression pool, each sparger having 4 horizontal perforated discharge arms. The discharge arms cover a 9 ft. diameter circle. The discharge is at approximately 98 feet elevation, that is 14 feet below the normal high water level of the suppression pool. In the case of a small LOCA, steam and hydrogen may be released directly into the drywell from a pipe break. Such steam and H_2 pass through the horizontal vent openings into the suppression pool. In either case steam would condense out in the water and hydrogen would bubble up and emerge from the surface of the suppression pool.

c.) Vacuum Breakers and Drywell Purge System.

The pressure in the drywell may increase above atmospheric by venting steam and H_2 into the drywell or it may decrease below atmospheric due to steam condensation. To prevent development of excessive vacuum in the drywell 2 vacuum breakers are provided with a total flow area of 0.545 ft.² to allow flow of air from the upper containment into the drywell. In addition there are 2 purge compressor blowers with a total capacity of 1,180 CFM per compressor. These compressors can be initiated manually or automatically after a LOCA signal and after the drywell pressure falls to within 1 psi above the containment pressure.

2. Accident Scenarios Considered

Base Case SORV	Considers a stuck-open relief valve. According to Table D-2 of the June 19, 1981 report of Mississippi Power & Light to the NRC the maximum H_2 release rate is given as 1.0415 lb/sec. with a total H_2 release of 2,585 lbs.
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Base Case SORV with 4 x H_2 Release Rate	Considers a stuck-open relief valve with a hydrogen release rate, 4 times larger than for Base Case. The total amount of H_2 released remains the same - 2,585 lbs.
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In both these cases steam and H_2 are vented through 7 to 9 spargers into the suppression pool where steam is condensed and H_2 bubbles up above the 7 to 9 spargers over approximately 8 ft. diameter circles due to contraction of the bubble stream.

Base Case	Considers a small-break LOCA in the drywell, the maximum
Small Break	H ₂ release rate being 1.0415 lbs/sec. and the total H ₂
with no SRV	release being the same - 2,585 lbs.
Release	

In this case steam and hydrogen are vented from the drywell through the partially exposed first row of vent holes into the suppression pool where the steam is condensed and H₂ bubbles up near the wall above the 45 vent holes. Also considered is the case of H₂ release at very low flow rates through the spargers.

3. Hydrogen Ignition (Mitigation) System

To prevent accumulation of large volumes of H₂-air mixtures, potentially with high H₂ concentrations, a large number of igniters are installed over the entire containment system the aim being to ignite and burn the H₂ mixtures as they become flammable. The igniters are General Motors AC Division Model 7G Glow Plugs which are identical to those being used at the Sequoyah and McGuire plants. These plugs have been extensively tested by Fenwal, Inc., and gave reliable ignition in every case tested. The igniter system is designed to operate for a minimum of 168 hours after initiation following an accident. There are two independent sets of igniters and power supplies, the design criterion being that if only one igniter system is operative the maximum distance between igniters shall not exceed 60 ft. The igniters are deployed in sets above the suppression pool and in the drywell at several elevations, also in the upper containment. Two redundant igniters are located in all small chambers where there exists a potential for high concentration of hydrogen to be formed. There are a total of 90 igniters in the entire containment. Of the 90 igniters, 9 igniters constitute the lowest set in the wetwell, approximately 21 ft. above the normal high water level.

4. Hydrogen Flames

a.) Wetwell

The hydrogen released from 7 to 9 spargers or from 45 vent openings into the wetwell bubbles up through the water and emerges from the water surface as a pure hydrogen stream at rather low velocity. The H₂ stream entrains air as it rises and is ignited when a flammable mixture reaches an ignition source. The flame then spreads from the ignition source through the

volume of flammable mixture. Subsequently, H_2 emerging from the water burns as it mixes with air in the form of a turbulent diffusion flame.

Diffusion flame designates a type of flame which is formed when a stream of fuel gas issues into air, entrains and mixes with air and burns at a rate which is determined by the rate of mixing. When the magnitude of the fuel stream exceeds some minimum mixing becomes turbulent which accelerates the burning rate and shortens the flame. The height of the flame is determined by the size of the gaseous stream (orifice size) and the flow velocity.

Experimental data available for the flame height of turbulent diffusion flames relate to small orifice diameters and high flow velocities, i.e., fractions of an inch orifice diameter and up to several hundred feet/sec. gas flow velocity. Therefore, these data can provide only very approximate information for the height of turbulent diffusion flames in this case where the diameter of the H_2 stream is several feet and the flow velocity is of the order of 1 foot/sec.

Assuming a total discharge of H_2 of 1 lb/sec. through 8 spargers the average velocity of the H_2 stream emerging from the water surface above each sparger over approximately an 8 foot diameter circle would be about $\frac{1}{2}$ ft./sec. For 4 lbs/sec. H_2 flow rate the average H_2 flow velocity would be about 2 ft./sec.

Air required for the continued burning of hydrogen must flow down from the upper containment through the wetwell to the suppression pool. The minimum crosssectional area between the wetwell and the upper containment is approximately 2,100 ft.² The total area of the 8 H_2 streams emerging from the water is

$$8 \times \frac{\pi (8)^2}{4} = 402 \text{ ft.}^2$$

Consequently, sufficient crosssectional area is available for unimpeded downward flow of air.

The height of the turbulent diffusion flames may be estimated approximately from model experiments carried out by Thompson and Boncore at Aerojet General on bouyancy-controlled turbulent diffusion flames.* The empirical relationship for flame length given in this study is

$$L = 3.73 (wT)^{0.4}$$

where L is flame height in feet

w is H₂ flow rate, lbs./sec.

T = H₂ temperature, °R.

For a total flow of 1 lb. H₂/sec. through 8 spargers, w = 1/8 lb/sec. With T = 600°R (60°C) the flame height is calculated to be 21 feet. For a total flow of 4 lbs. H₂/sec. the calculated flame height is 36.5 ft.

In the Thompson-Boncore experiments the flames were burning above a pool in the open atmosphere at a low turbulence level. In the containment the downward flow of air is somewhat restricted and the turbulence level will be higher than in the open atmosphere. Consequently, the flames will be shorter than calculated above.

In the case of a small LOCA in the drywell, steam and H₂ would be forced through the top row of 45 vents. At a maximum total H₂ flow rate of 1 lb/sec. = 180 CF/sec. the water level will be only partially depressed in the vent holes and H₂ will bubble through about 6 ft. of water close to the wall. The circumference of the inner wall of the wetwell is 261 ft. and the distance between center lines of vent holes is 5.8 ft. The vent diameter being 2.33 ft. the distance between the holes is 3.47 ft. The H₂ stream through the vent holes covers 40% of the circumference.

Assuming as before .5 ft./sec. average H₂ flow velocity at the water surface the H₂ jets would extend about 3.5 ft. from the wall. As access of air to this row of H₂ columns is restricted essentially to one side we multiply the H₂ flow rate per column by a factor of 4 for estimation of the flame height. Therefore,

$$w = \frac{1 \text{ lb/sec.} \times 4}{45} = .10 \text{ lb./sec.}$$

Then,

$$L = 3.73 \times (.1 \times 600)^{0.4} = 19 \text{ feet.}$$

*Report by W. R. Thompson and C. S. Boncore, Aerojet General Corp., "Design and Development of a Test Facility for the Disposal of Hydrogen at High Flow Rates". Advances in Cryogenic Engineering, Vol. 12.

Because of uncertainty in the estimation of flame height we recommend suitable experiments which would allow measurement of the flame height. At the same time the tests would demonstrate stability of the flames. The proposed tests are described in the attachment to this report.

Once ignited, the flames will continue to burn as lifted turbulent diffusion flames stabilized at some distance above the water surface. Combustion takes place in diffusion flames at locations where the mixture ratio is near stoichiometric. In such mixtures the laminar burning velocity is about 8 ft./sec. In a stream where the average flow velocity is less than the laminar burning velocity, the flame will always move upstream to the point where the mixture becomes flammable. The root of the flame will move up and down randomly above the water surface depending upon local variations of mixture composition and velocity.

Ignition of the H_2 -air stream will involve some transient pressure development as the flame travels from the igniters through accumulated flammable mixture. The first row of igniters in the wetwell is designed to be about 21' above the normal high water level in the middle region of the annular wetwell. However, upper pool dump, operation of the purge compressors and blowdown from the vessel cause an increase in the normal pool depth of about seven (7) feet prior to significant H_2 release, leaving about 14 feet above the pool surface to the first row of igniters. At the time when a near-limit mixture reaches the igniters an appreciable volume of H_2 -air mixture will have accumulated above the water surface. The composition of this mixture will range from 100% H_2 to 100% air. Only a small fraction of this volume is near-stoichiometric. To estimate the transient pressure due to flame passing through this accumulated mixture we assume, conservatively, a volume of stoichiometric mixture covering half of the pool surface and extending to a height of about 14'. The volume of this mixture,

$$V = \frac{6,667}{2} \times 14.0 = 46,669 \text{ CF}$$

which is 3.3% of the 1,400,000 CF of the wetwell and upper containment.

The pressure rise in the entire system due to adiabatic burning of the assumed 46,669CF stoichiometric mixture would be

$$\frac{46,669 \times 106.6 \text{ psia} + 1,353,331 \times 14.7 \text{ psia}}{1,400,000} = 17.76 \text{ psia} = 3.06 \text{ psig},$$

where 106.6 psia is the adiabatic combustion pressure of the stoichiometric

mixture. The open crosssectional area connecting the wetwell with the upper containment is sufficiently large to allow pressure equalization during the burning. While this transient pressure rise upon ignition is moderate its magnitude could be substantially reduced by arranging igniters closer to the surface of the water level and closer to the inner wall.

For a considerable length of time early into an accident H_2 is released at a very low rate, about .01 lb/sec. at 3,600 sec., rising to about .05 lbs/sec. at 4,200 sec. This flow rate amounts to 18 lbs. H_2 in 600 seconds which could form 32,000 CF of 10% H_2 -air mixture. Upon ignition the entire volume of slowly emerging H_2 would be burned and there would not be sufficient H_2 flow to maintain continuity of the flame. Such a low H_2 release ratio would result in a succession of mild ignition puffs. As in the case of large H_2 flow rate the magnitude of the transient ignition pressure would be greatly reduced by placing igniters closer to the water surface above the spargers.

b.) Drywell

In the case of a small LOCA which occurs in the drywell, first steam and later, steam and H_2 flow into the drywell from a pipe break. In the first 2,000 seconds steam enters the drywell at an average flow rate of about 150 lbs/sec. amounting to 6×10^6 CF steam. During this time the 270,000 CF air in the drywell is displaced by steam and blown through the horizontal vent openings into the wetwell and upper containment. After 4,200 seconds the H_2 flow rate increases from very low values to about 0.3 lb./sec., and after 4,800 seconds to about 1 lb/sec., continuing at this rate to approximately 7,800 sec. The total amount of H_2 released is 2,585 lbs. The H_2 -containing atmosphere in the drywell is nonflammable since the air content is negligible. Air can enter the drywell from the upper containment through the 2 vacuum breakers or through the 2 purge compressors, each compressor having a maximum flow rate of 19 CF/sec. As air enters the drywell containing a mixture of H_2 and steam at some unknown volume ratio the H_2 concentration in the mixing air jet will change along a straight line such as shown on the attached H_2 -steam-air flammability diagram (figure 1). As seen, the composition line may pass through the flammable range. To prevent accumulation of substantial volumes of flammable mixture in the drywell, ignition sources should be placed judiciously near the air inlet ducts.

5. Vitiation of Air by H₂ Burning

The total amount of H₂ released is given as 2,585 lbs. equal to 464,000 CF. The total amount of air in the containment building is

Drywell = 270,000 CF
Wetwell = 151,600 CF
Upper Containment = 1,248,600 CF
1,670,000 CF

The amount of air required to burn all the H₂ is 1,110,000 CF. It would appear that all the H₂ could be removed by burning. However, as the combustion products of the flames are mixed with the remaining air the air gradually becomes vitiated i.e., oxygen deficient, as the burning proceeds. The following table gives the O₂ concentration in the remaining "air" after burning given fractions of the total H₂ with or without condensation of the water vapor produced by combustion.

TABLE

Total H₂ = 464,000 CF
Total Air = 1,670,000 CF (349,000 CF O₂)
Assume H₂ and air at same T and P

<u>Fraction of</u> <u>H₂ burned</u>	<u>% O₂ in Vitiated Air</u>	
	<u>Without Condensation</u> <u>of Steam</u>	<u>With Condensation</u> <u>of Steam</u>
50	13.0	15.0
60	11.6	13.7
70	10.2	12.4
80	8.8	11.0
90	7.5	9.6
100	6.2	8.2

Water vapor released from the reactor and water vapor generated by burning hydrogen is ultimately condensed out. Vitiation of air by nitrogen remains. The table shows that the O₂ concentrations in the nitrogen-vitiated air exceed the minimum O₂ concentration of 5.2% for burning H₂ in nitrogen-vitiated air (Figure 1).

The above calculation assumes the air contained in the drywell is fully involved in burning H_2 . In reality this may not be the case depending upon the scenario.

6. Vacuum Created in Containment by Burning of Hydrogen

Burning of hydrogen reduces the total gas volume by an amount equal to one-half of the hydrogen burned when the water remains in vapor form and one and one-half times the hydrogen when the water is condensed.

Releasing H_2 into the containment increases the absolute pressure which is then reduced by consumption of oxygen by the burning H_2 and eventually by condensation of water vapor.

Releasing a total of 2,585 lbs. H_2 = 464,000 CF would increase the pressure in the containment from 1 atm abs to 1.278 atm. abs. equal to 4 psig. Burning all the H_2 released and assuming total condensation of water vapor would result in an absolute pressure of .86 atm = 2 psi vacuum. To restore the pressure to 1 atm. abs. 232,000 CF of air will have to be introduced into the containment.

7. Heat Absorption in the Water Stored in the Suppression and Upper Pools

Upper heat of combustion of 2,585 lbs. of H_2 is 40×10^6 kcal.

Heat content of approximately 453,000 lbs. of steam released is 140×10^6 kcal.

Water contained in wetwell and drywell is

$$(6,667 \text{ ft.}^2 + 553 \text{ ft.}^2) \times 18.33^* \text{ ft. height} = 132,300 \text{ CF}$$

Added makeup volume from the upper pool is 36,380 CF

Total CF of water is 168,680 CF = 4,784,000 Kg. H_2O

Temperature rise of the pool water after absorption of the heats of combustion and condensation of water vapor is

$$\frac{180 \times 10^6}{4.784 \times 10^6} = 38^\circ\text{C}$$

It appears that the water contained in the suppression pool, after the upper pool dump, can absorb the total heat released in a small LOCA with a moderate temperature rise.

*conservative low value

8. Conclusions

Our analysis shows that the Grand Gulf Nuclear Station as designed can contain safely the pressures which may develop during burning of hydrogen released by safety relief valves or by a small LOCA.

There is no danger of transition of deflagration to detonation because large volumes of H_2 -air mixtures with a composition within the detonable range are not allowed to accumulate in geometrical configurations conducive to transition.

9. Recommendations

1. Location of Igniters

The presently designed igniter system is adequate to prevent dangerous accumulation of flammable H_2 -air mixtures in the containment. Nevertheless, some relocation of igniters or the addition of a few more igniters is recommended to reduce further the modest peak pressures which may develop during ignition of hydrogen streams bubbling from the suppression pool. Installation of additional igniters is advisable at the air inlet openings in the drywell.

2. Some consideration should be given to the fact that burning of all hydrogen released in the system may result in a vacuum of the order 2 psi.

3. The reliability of the glow plug igniters has been extensively tested during the past year in lean H_2 -air mixtures. Some additional tests should be carried out for the ignition of rich H_2 -air limit mixtures and also for establishing the reliability of the igniters exposed to splashing water and sprays.


4. Estimation of the height of turbulent diffusion flames under conditions in the wetwell is subject to uncertainties. We recommend a full-scale test involving a single sparger and three horizontal vent holes in a 20' x 20' x 50' high chamber open at the top including an 18 ft.-deep pool.

This would allow a 1 to 1 scale testing of hydrogen diffusion flames, their ignition and stability. Temperature and hydrogen distribution along the flame should also be measured.

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COMBUSTION & EXPLOSIVES RESEARCH, INC.


Bernard Lewis


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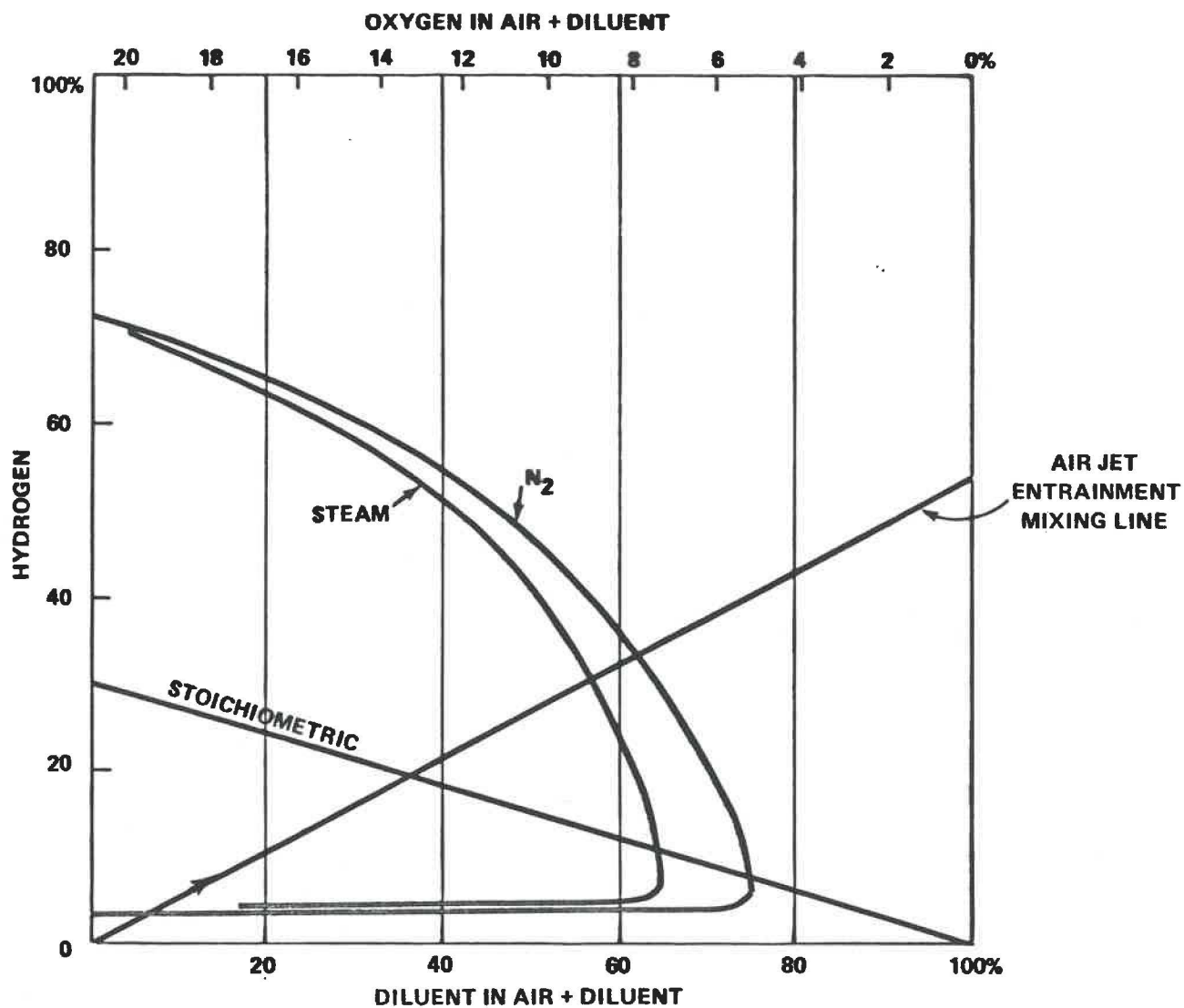


FIGURE 1
FLAMMABILITY DIAGRAM OF H₂ + AIR + DILUENT

ATTACHMENT A

Experimental Study of H_2 Diffusion Flames Burning Above a Pool of Water

While the general character of H_2 diffusion flames burning above a pool of water with restricted air supply can be predicted there is considerable uncertainty regarding the height of such flames. An experimental study of these flames is proposed which will allow the measurement of flame height and temperature, and observation of ignition by glow plugs and of flame stability.

The maximum H_2 flow rate through a single sparger is .5 lb/sec. Thus it is possible to do the experiment at full scale and avoid the scaling problem.

The experimental arrangement would consist of a 20' x 20' x 50' high concrete structure open at the top and containing an 18 foot deep pool of water. A single full scale sparger would be arranged in a position similar to that in the wetwell with three horizontal vent holes representing the connection between the drywell and wetwell (Figure A-1).

Glow plug igniters will be placed at locations corresponding to those in the wetwell. Observation windows and sampling ports will be arranged in the side walls for measurement of flame height, temperature and H_2 distribution along the flame.

In order to measure the transient ignition pressure the top of the structure may be closed temporarily with a cover containing an appropriate vent opening.

The experimental system described above will also be suitable to study the effect of splashing water and water sprays on the igniters and on the flame. Also tests of equipment survivability will be possible.

For safety the tests should be carried out at an open site with remote controls.

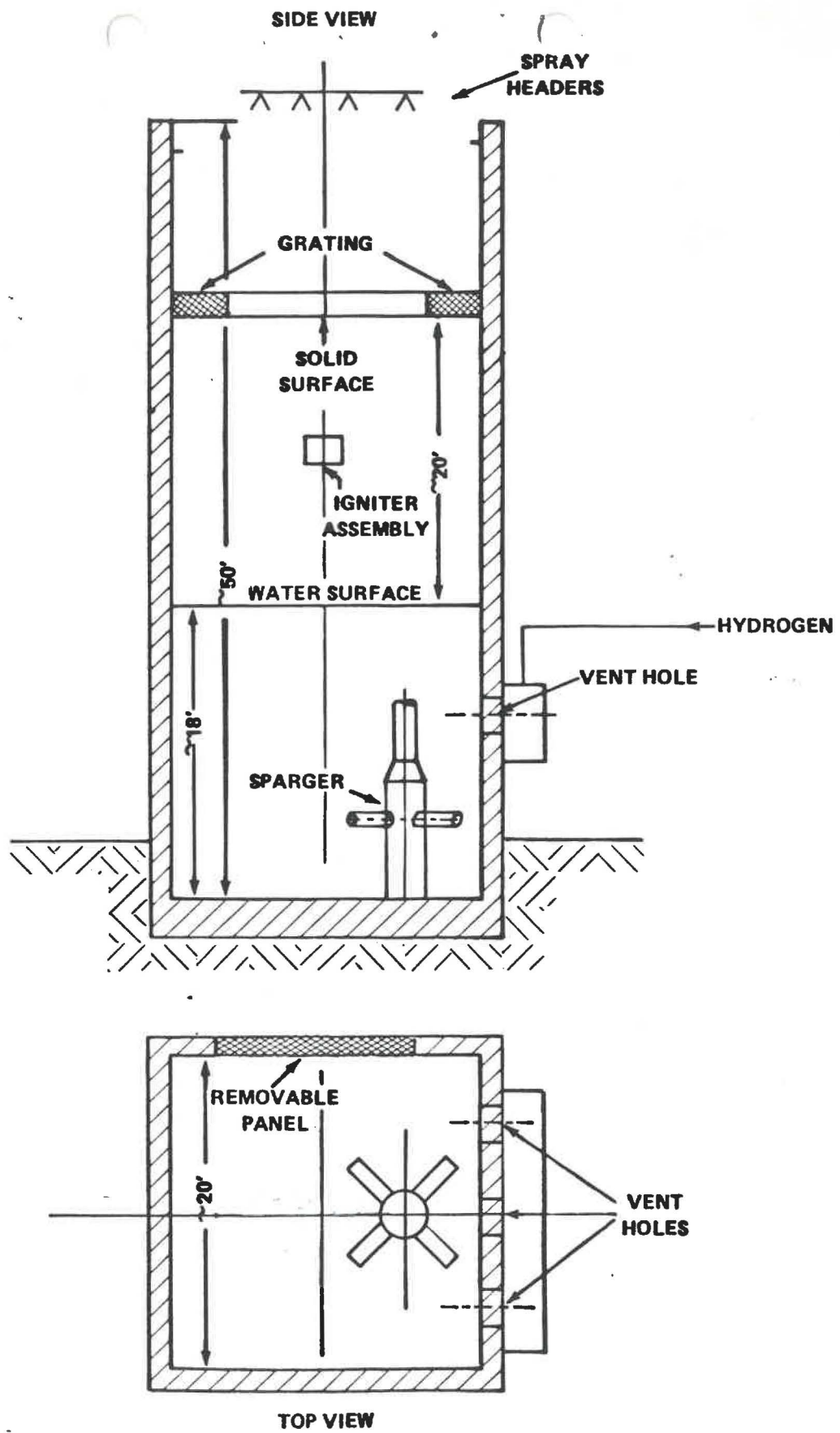


FIGURE A-1
WETWELL TEST CHAMBER