MISSISSIPPI POWER & LIGHT COMPANY
Helping Build Mississippi
P. O. BOX 1640, JACKSON, MISSISSIPPI 39205

January 14, 1983

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: Hydrogen Control Owners Group (HCOG) BWR-6 Mark III Information on H_2 Combustion Test Programs
HGN-008

The attached information is submitted by the Mark III Containment Hydrogen Control Owners Group (HCOG) to keep the Nuclear Regulatory Commission (NRC) Staff updated on the HCOG test programs. Summary information concerning overall HCOG program activities which was presented to members of the NRC Staff on September 10, 1982 is included as well as a discussion of current program activities. This submittal includes a description of the 1/20th scale hydrogen combustion facility, a draft test matrix, details of scaling relationship as well as a progress report on the 1/4 scale test program.

As work proceeds in the HCOG test program, further appropriate submittals will be made to the NRC Staff.

If you need clarification on any of the material submitted please contact me.

At the present time, the testing program is proceeding expeditiously in order to meet the requirements of licensing schedules. NRC comments on the HCOG test program, if any, are therefore needed as soon as possible.

Yours truly,

John D. Richardson, Chairman
Hydrogen Control Owners Group

Y601

JDR:sap
Attachment

Dspl

BWR6 MARK III CONTAINMENT
HYDROGEN CONTROL OWNERS' GROUP (HCOG)
RESEARCH PROGRAM STATUS
December 1982

The research program planned by the HCOG was outlined during a presentation (Attachment I) to NRC and Sandia personnel on September 10, 1982. Based on that presentation, Sandia has documented comments on the program to HCOG. The purpose of this report is to provide an update on the status of the HCOG research program and to respond to Sandia's comments.

H_2 Upper Flammability Limit Testing

Testing to define the upper flammability limits for the GM glow plug and the Tayco igniter has been initiated in the 17-liter vessel at Whiteshell.

Completeness of Combustion

It should be noted that although completeness of combustion is measured during these tests, such measurements are not and should not be used to justify the completeness of combustion assumptions (i.e., 85%) made in Clasix-3. These are tests of uniformly pre-mixed constituents. In the actual plant this will not be the case and for this reason residual hydrogen will virtually always remain following a burn; i.e., somewhere hydrogen will exist at a concentration below the lower flammability limit.

Condensation Effects

HCOG is currently assessing the feasibility of performing tests in the 17-liter vessel to define steam condensation effects on glow plug ignition limits. Plans call for performance of such tests if a testing approach can be developed which will provide meaningful results under conditions representative of those expected in a Mark III drywell during a LOCA initiated degraded core event. HCOG will complete its evaluation and reach a decision regarding the performance of such tests in February 1983.

The results of the Whiteshell testing will be submitted upon completion of the final report for these tests (planned for April 1983).

Inverted Flame Testing

HCOG has discussed the possibility of performing such tests. Currently, both Whiteshell and Nevada are being considered as potential test sites. If such testing is performed, it will further address the issue of steam condensation effects on ignition limits as well as defining heat fluxes from the inverted flame. HCOG will continue its evaluation of the need for such tests and provide the results of that evaluation during the first quarter of 1983.

1/20th Scale Combustion Visualization Tests

Construction of the 1/20th scale test facility is complete and shakedown testing is in-progress. Formal testing is scheduled to begin January 1983.

A facility description report has been prepared and is enclosed (Attachment II). This report includes a detailed drawing and description of the global venting system employed.

The objective of the global venting system is to maintain the pressure well within the facility's structural capability while maintaining the appropriate spatial distribution of gaseous constituents. In addition, this system will simulate the primary physical phenomena driving O_2 down to the wetwell; i.e., displacement of O_2 in the upper containment by hot combustion products.

Sandia expressed concern that the relatively high thermal output of the glow plugs at 1/20th scale may tend to drive mixing in the facility. To address this concern, the glow plug igniters in the test facility have been replaced by spark igniters. These devices will also be tested at Whiteshell to confirm that their ignition limits are representative of those for the glow plugs and that their thermal output is acceptably low.

Table 1 summarizes the planned test series. All tests shown will be performed at essentially constant H_2 injection rates simulating the latter (maximum H_2 flowrate) portion of the March H_2 evolution transient. This is appropriate for a test with the objective of determining the existence and character of bouyant diffusion flames above the suppression pool as higher H_2 injection rates are considered more likely to support such flames.

Shakedown tests have shown that initiation of tests with an H_2 flowrate simulating the maximum March value (1 lbm/sec full scale) results in a very low "light off" pressure (<0.2 psig) and that a diffusion flame is established above the suppression pool. Since the pressure capability of the facility is low (<5 psig), test procedures call for the initiation of all tests with this H_2 flowrate. A range of H_2 flowrates above and below this value will then be explored within the range found to support diffusive flame behavior.

The majority of planned tests will be performed with a "cold pool". This is done to maximize the O_2 available for combustion consistant with that available in the actual plant. Some hot pool tests will also be performed to investigate the thermal mixing and steam vapor effects of a hot pool.

The test matrices call for single sparger releases both individually and in addition to the ADS spargers. The locations of these spargers were chosen using engineering judgment such that the O_2 flow to the resulting flames would be maximized.

It is important to note that although single sparger release tests will be performed for information, such releases will not occur in the plant. If ADS has not been activated, Emergency Procedure Guidelines call for a minimum of seven (7) symmetrically spaced spargers to be active at the point in a degraded core event when significant H_2 production may occur. This case is similar to ADS activation (8 symmetrically spaced spargers) and will be simulated by tests performed with the ADS spargers active.

All tests will be performed without sprays. This is conservative from a mixing and temperature standpoint and will reduce the potential for thermally shocking the pyrex outer shell of the facility.

The test matrix presented in Table 1 is preliminary and will be finalized following the completion of shakedown testing.

1/4 Scale Hydrogen Combustion Test

Factory Mutual Research Corporation has been selected as the prime contractor to perform the 1/4 scale test. The design phase of this effort was initiated on December 17, 1982 and will be completed by April 1, 1983. The decision whether to proceed with construction will be made at that time based on review of 1/20th scale test results.

The test program is essentially as presented in September 1982 except that the facility will have a 40 psig pressure capability and will not be vented during testing. It is believed that heat flux data from a vented facility would be valid but would require supplementary analysis to extrapolate the results to full scale in-plant conditions. A cost benefit analysis indicates that it would be most advantageous to perform the tests in an unvented facility.

It should be noted, however, that for the purpose of defining the qualitative combustion behavior in the containment, the globally vented 1/20th scale facility is considered fully adequate.

Sandia suggests that perhaps a simpler facility could be utilized to study flame behavior, i.e., an oblong structure 20' x 40' x 50-100' high. HCOG and EPRI have thoroughly evaluated such an approach as well as several others.

An advantage of such a facility is that it simulates the full scale geometry obviating the need for development and justification of scaling relationships. However, simulation of the effects of the asymmetric flow blockage present in the wetwell annulus on O_2 supply would be difficult in such a facility. In addition, since such a facility would have an open top, an important driving force acting to push O_2 down to the wetwell would not be simulated, i.e, mass displacement by hot combustion products.

Current plans call for full scale igniters to be used in the 1/4 scale test. Before a final decision is made, an analysis will be completed to assess relative effect (test vs. plant) that these igniters will have on thermally driven mixing.

A final test matrix has not been established but will be submitted early enough to allow NRC review prior to testing.

Scaling

As part of the design effort for the 1/4 scale test, FMRC will prepare a detailed report justifying the modeling approach selected. This report will be submitted for NRC review by March 1, 1983.

TABLE 1

1/20th SCALE TEST MATRIX (1)(2)

STEADY STATE H_2 INJECTION TESTS

Test No.	H_2 Flow / Max. March: Vents	H_2 Flow / Max. March: Spargers	Number of Active Spargers	Blockage Level	Pool Temp °F	Notes
1	0	1.0	9(ADS + 152° Sparger)	Low	50- 70	
2		2.0				(3)
3		4.0				(3)
4		<1.0				(4)
5		1.0			160-190	
6		4.0				(3)
7	1.0	1.0	8 (ADS)		50- 70	(5)
8	2.0	2.0				(5)
9	0	1.0	1(136° Sparger)			
10		4.0				(3)
11		1.0	9(ADS + 152° Sparger)	High		
12		2.0				(3)
13		4.0				(3)
14		<1.0				(4)
15		1.0			160-190	
16		4.0				(3)
17	1.0	1.0	8 (ADS)		50- 70	(5)
18	2.0	2.0				(5)

TABLE 1 (Con't)

Notes for Table 1:

(1) No sprays during any tests.

(2) H_2 injection will continue until combustion is O_2 limited in the entire facility (except tests 4 and 14, see note 4 below).

(3) Test initiated with 1 x MARCH flowrate. Once flame is established, flowrate will be increased to value shown.

(4) Test initiated with 1 X MARCH flowrate. Once flame is established, flowrate is reduced until diffusion flames can no longer be maintained.

(5) Test initiated with 1 x MARCH flowrate through spargers only. Once flame is established, the sparger and vent flowrates will be adjusted to values shown.

ATTACHMENT I

VIEWGRAPHS PRESENTED TO NRC
ON SEPTEMBER 10, 1982

REVIEW OF EPRI/HCOG TEST PROGRAM

HCOG/NRC MEETING

BETHESDA, MARYLAND

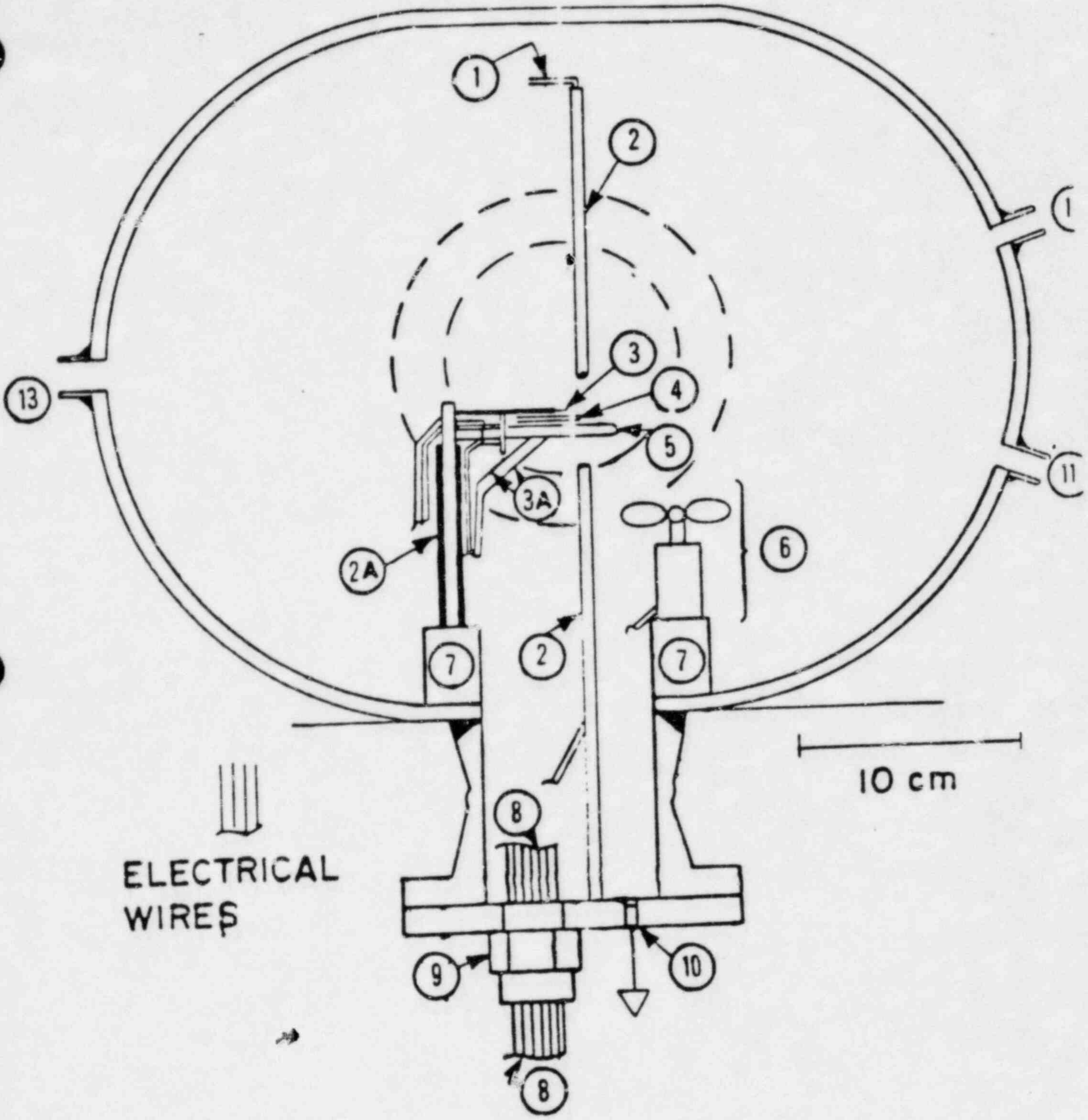
9/10/82

JH 9/10/82

CONTENTS

UPPER FLAMMABILITY LIMIT TESTING

- CONTRACTOR - ATOMIC ENERGY OF CANADA LIMITED
- OBJECTIVE - DEFINE FLAMMABILITY LIMITS FOR H_2 RICH, STEAM-AIR MIXTURES UTILIZING THE GM AC-G7 GLOW PLUG (12 VOLT) AS AN IGNITION SOURCE
- SCOPE - APPROXIMATELY 50 EXPERIMENTS WILL BE PERFORMED WITH H_2-AIR-STEAM MIXTURES RANGING FROM ~ 75% H_2-0% STEAM TO ≈ 30% H_2-45% STEAM.
- SCHEDULE - TEST INITIATION SEPTEMBER 1, 1982
  TEST COMPLETION JANUARY 31, 1983



INSTRUMENTATION FOR GLOW PLUG EFFECTIVENESS TESTS
(17-LITRE VESSEL)

MEASUREMENTS

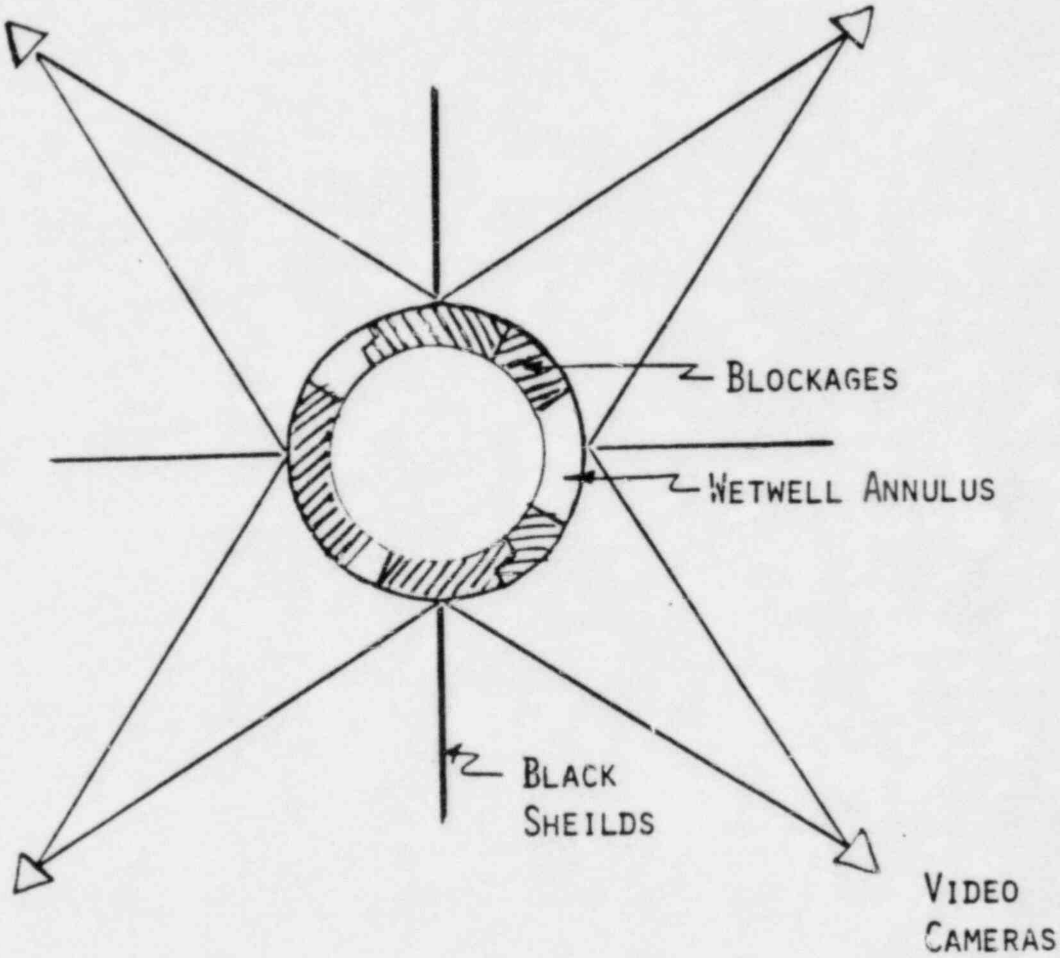
INITIAL CONDITIONS	- TEMPERATURE
	- PRESSURE
	- CONCENTRATION → PARTIAL PRESS. / → MASS SPEC.
TRANSIENT CONDITIONS	- IONIZATION → COMBUSTION
	- PRESSURE → PEAK
	- TEMPERATURE OF GAS → PEAK
	- GLOW PLUG TEMP. → IGNITION TEMP.
FINAL CONDITIONS	- PRESSURE
	- CONCENTRATION (MASS SPEC.)

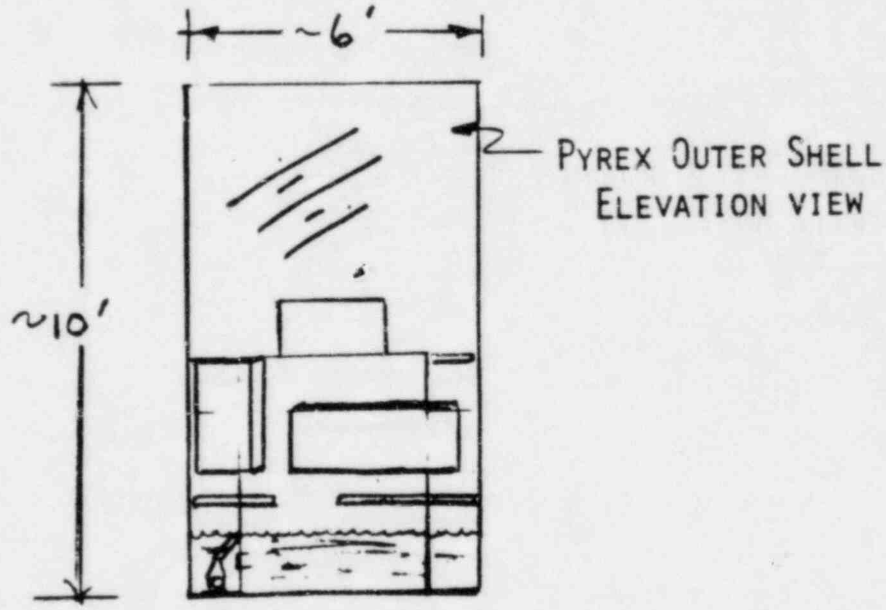
1/20TH SCALE 360° SECTOR COMBUSTION VISUALIZATION TEST

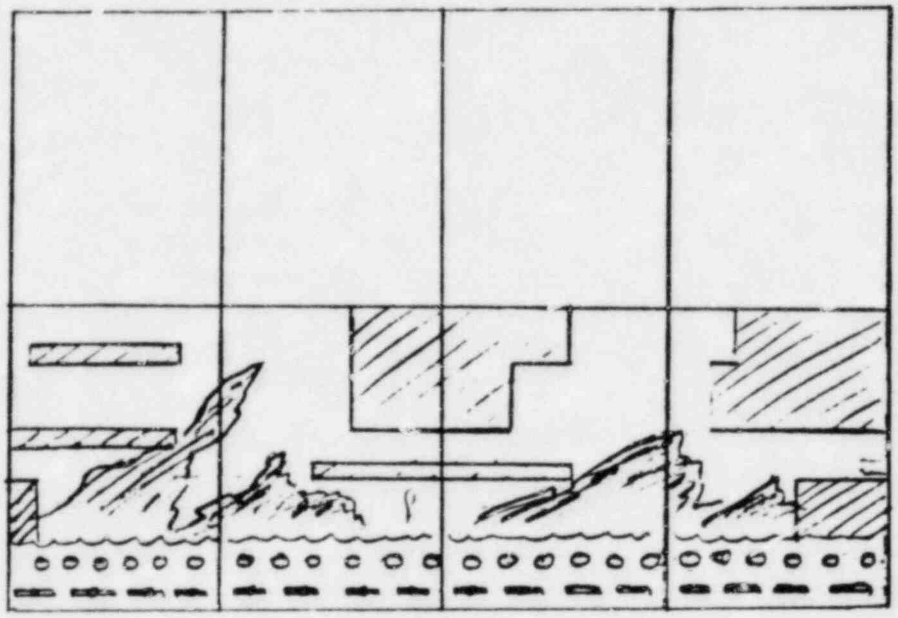
- CONTRACTOR - ACUREX CORPORATION
- OBJECTIVE - PROVIDE A VISUAL RECORD (BY SEEDING H_2 WITH C_2H_2) OF GLOBAL H_2 COMBUSTION BEHAVIOR IN A FULL 360° MODEL OF A MK III CONTAINMENT
- SCOPE - APPROXIMATELY 40 TESTS WILL BE PERFORMED INCLUDING TESTS TO QUALITATIVELY ASSESS THE EFFECTS OF VARIATIONS IN:
  - H_2 RELEASE RATE
  - BLOCKAGES/HEAT SINKS IN WETWELL
  - SPARGER VS. VENT RELEASE
  - NUMBER/LOCATION OF ACTIVE SPARGERS
  - IGNITOR LOCATION (ABOVE POOL)
- SCHEDULE

	COMPLETION DATE
DESIGN	9/1/82
CONST/SHAKEDOWN	12/1/82
TESTING	12/31/82

PLAN VIEW OF 1/20TH
SCALE VISUALIZATION FACILITY







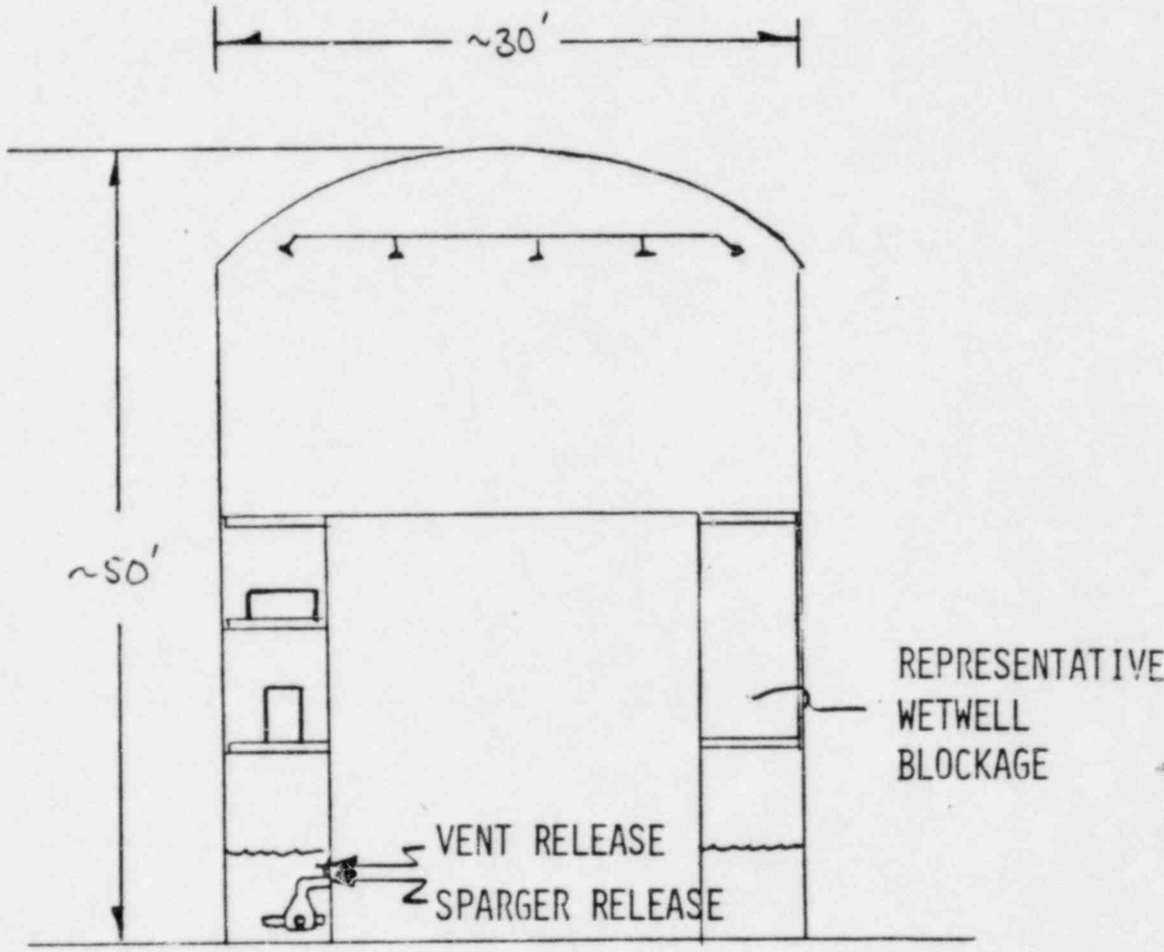
- MIXING OF VIDEO FROM EACH OF THE 4 CAMERAS ON A SINGLE TAPE WILL ALLOW CONTINUOUS VIEWING OF THE FULL 360^{o} SIMULTANEOUSLY

1/4 SCALE 360° SECTOR TEST

- CONTRACTOR -- TO BE SELECTED

- OBJECTIVE -- PROVIDE GENERIC (TO HCOG PLANTS) DIRECTLY SCALABLE HEAT FLUX, GAS FLOW, TEMPERATURE AND CONCENTRATION HISTORIES THROUGHOUT THE WETWELL AND UPPER CONTAINMENT

- SCOPE -- APPROXIMATELY 35 TESTS WOULD BE PERFORMED. TEST WOULD INCLUDE:
  - VARIATIONS IN LEVEL AND NATURE OF BLOCKAGES/HEAT SINKS
  - SPARGER AND/OR VENT RELEASE
  - POOL HEATING
  - CONT. SPRAYS
  - FULL COMPLEMENT OF IGNITERS
  - PROTOTYPICAL MODELING OF FULL CONTAINMENT RESULTING IN APPROPRIATE REPRODUCTION OF GLOBAL EFFECTS
    - PROTOTYPICAL AIR FLOWS WOULD BE DEVELOPED TO FEED FLAMES
  - HE RATHER THAN H_2 FOR MOST MIXING TESTS



- WETWELL GEOMETRY VARIATIONS SUFFICIENT TO REPRESENT ALL HCOG PLANT DESIGNS
- WALLS/BLOCKAGES SCALED TO REPRODUCE FULL SCALE TEMPERATURE RESPONSE
- ~5 PSIG PRESSURE CAPABILITY
  - ALLOWS MIXING TESTS WITH NO LOSS OF INVENTORY PRIOR TO FIRST BURN
- SYSTEM VENTED AT SEVERAL LOCATIONS DURING COMBUSTION TRANSIENT TO MAINTAIN PRESSURE WITHIN FACILITY LIMITS

1/4 SCALE TEST INSTRUMENTATION

MEASUREMENT	NUMBER	RANGE	ACCURACY
FLAME FRONT	64	N/A	N/A
GAS TEMP	25	70-2200°F	±20°F
SURFACE TEMP	15	70-2200°F	±20°F
H_2/HE CONC	8 (CONTINUOUS)	0-20%	±1% FS
	12 (MULTIPLEX	0-20%	±1% FS
O_2 CONC	12 (MULTIPLEX)	0-25%	±1% FS
H_2O VAPOR CONC	12 (MULTIPLEX)	0-50%	±1% FS
GAS VELOCITY	6 (CONTINUOUS)	-LATER-	-LATER-
	12 (MULTIPLEX)	-LATER-	-LATER-
HEAT FLUX			
TOTAL	26	-LATER-	-LATER-
RADIATIVE	5	-LATER-	-LATER-
POOL TEMP	2	70-212°F	±2°F
CONT. PRESS	2	0-10 PSIG	± .1PSI
FUEL FLOW	1	-LATER-	-LATER-

TABLE 1

TENTATIVE TEST MATRIX

(TEST 1-13 MIXING ONLY - NO COMBUSTION)

TEST NO	GAS RELEASE RATE VENTS	SPARGERS	GAS RELEASED	NO OF ACTIVE SPARGERS	BLOCKAGE LEVEL	CONT. SPRAY	NO OF IGNITER BANKS ACTIVE
1	LOW	0	HE	0	HIGH	OFF	0
2	MED	0	HE	0	HIGH	OFF	0
3	HIGH	0	HE	0	HIGH	OFF	0
4	LOW	0	H_2	0	HIGH	OFF	0
5	HIGH	0	H_2	0	HIGH	OFF	0
6	0	LOW	HE	8	HIGH	OFF	0
7	0	MED	HE	8	HIGH	OFF	0
8	0	HIGH	HE	8	HIGH	OFF	0
9	LOW	LOW	HE	8	HIGH	OFF	0
10	MED	MED	HE	8	HIGH	OFF	0
11	HIGH	HIGH	HE	8	HIGH	OFF	0
12	HIGH	HIGH	HE	8	HIGH	ON	0
13	HIGH	HIGH	HE	8	HIGH	ON	0

NOTES (TEST (1-13)

1. ALL MIXING TESTS PERFORMED WITH HEATED POOL.
2. CONTAINMENT SEALED FOR ABOVE TESTS (NO VENTING OR PRESSURE RELIEF)
3. GAS RELEASED AT CONSTANT RATE FOR ALL TESTS (1-13)
4. REPRESENTS MAXIMUM MATRIX. INTENT WOULD BE TO MINIMIZE MATRIX BASED AS KNOWLEDGE GAINED AS TESTING PROCEEDS.

TABLE 1 (CON'T)

TENTATIVE TEST MATRIX

(TEST 13 - 35 COMBUSTION TESTS)

TEST NO	GAS RELEASE RATE		GAS RELEASED	NO OF ACTIVE SPARGERS	BLOCKAGE LEVEL	CONT. SPRAY	NO OF IGNITER BANKS ACTIVE
	VENTS	SPARGERS					
14	LMT	0	H_2	0	HIGH	ON	2
15	NMT	0	H_2	0	HIGH	ON	2
16	HMT	0	H_2	0	HIGH	ON	2
17	NMT	0	H_2	0	HIGH	OFF	2
18	HMT	0	H_2	0	HIGH	OFF	2
19	REPEAT OF LIMITING TEST (14-18)			0	HIGH		2
20	0	LMT	H_2	8	HIGH	ON	2
21	0	NMT	H_2	8	HIGH	ON	2
22	0	HMT	H_2	8	HIGH	ON	2
23	REPEAT OF LIMITING TEST (22-24)			8	HIGH	OFF	2
24	LMT	LMT	H_2	8	HIGH	ON	2
25	NMT	NMT	H_2	8	HIGH	ON	2
26	HMT	HMT	H_2	8	HIGH	ON	2
27	NMT	NMT	H_2	8	HIGH	OFF	2
28	HMT	HMT	H_2	8	HIGH	OFF	2
29	REPEAT OF LIMITING TEST (24-29)						2

TABLE 1 (CON'T)
TENTATIVE TEST MATRIX
(TEST 13 - 35 COMBUSTION TESTS)

TEST NO	GAS RELEASE RATE VENTS	SPARGERS	GAS RELEASED	NO OF ACTIVE SPARGERS	BLOCKAGE LEVEL	CONT. SPRAY	NO OF IGNITER BANKS ACTIVE
30	REPEAT OF LIMITING TEST (14-29)				LOW	ON	2
31	REPEAT OF TEST 30					OFF	2
32	REPEAT OF TEST 30 WITH:						
33	REPEAT OF TEST 32					ON	1
34	REPEAT OF LIMITING TEST (14-29) WITH:						
35	REPEAT OF TEST 34						

NOTES (TEST 14-35)

1. POOL HEATED FOR ALL TESTS.
2. IGNITERS ON PRIOR TO EACH TEST.
3. PRESSURE RELIEF (WETWELL TO DRYWELL AND UPPER CONTAINMENT TO ATMOSPHERE) ABOVE .6-1 PSIG.
4. DEFINITIONS:
   - LMT - LOW MARCH TRANSIENT
   - NMT - NOMINAL MARCH TRANSIENT
   - HMT - HIGH MARCH TRANSIENT
   - LIMITING TEST - TEST RESULTING IN HIGHEST SUSTAINED HEAT FLUX
5. REPRESENTS MAXIMUM MATRIX. INTENT WOULD BE TO MINIMIZE MATRIX AS KNOWLEDGE IS GAINED AS TESTING PROCEEDS.

1/4 SCALE TEST PROGRAM

SCHEDULE

TASK	COMPLETION DATE
FACILITY DESIGN	2/1/83
CONSTRUCTION/SHAKEDOWN	8/1/83
TESTING	12/1/83
ANALYSIS/REPORTING	2/1/84

REDUCED SCALE MODELING OF BUOYANCY–CONTROLLED, TURBULENT DIFFUSION FLAMES IN ENCLOSURES

by

Francesco Tamanini
Factory Mutual Research Corp.

HCOG/NRC Meeting on "EPRI–HCOG Research Program on Hydrogen Combustion in the Mark III Containment". Bethesda, Maryland, September 10, 1982.

Factory Mutual System

NRC01

OUTLINE

1. Theoretical Basis of Froude Modeling.
2. Scaling Relations.
3. Experimental Verification:
   - Free Flows.
   - Enclosure Flows.
4. Heat and Mass Transfer Modeling.
5. Limitations of Modeling Approach.
6. Conclusions.

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THEORETICAL BASIS OF FROUDE MODELING

- The normalized versions of the momentum, species and energy equations contain the following dimensionless parameters:

  1. Froude No. $Fr = U^2/gD$
  2. Reynolds No. $Re = \rho DU/\mu$
  3. Prandtl No. $Pr = c_p\mu/\lambda$
  4. Schmidt No. $Sc = \mu/\rho\mathcal{D}$

- In turbulent convective flows, effects due to Re, Pr and Sc can be neglected (at least away from walls).

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Theoretical Basis of Froude Modeling (cont)

- Preserving Fr insures flow similarity in buoyancy–controlled flows.
- Non–premixed flames are also modeled if the chemical rates are fast (reaction rates determined by diffusion and mixing and not by kinetics).
- Flame propagation in premixed volumes may not be modeled in detail.

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SCALING RELATIONS

– Constant Froude number implies the following scaling relations (s is the scale factor):

Length	s
Velocity	$s^{1/2}$
Time	$s^{1/2}$
Temperature	s^{0}
Concentration	s^{0}
Convective flow	$s^{5/2}$

– In particular:

Fuel flow rate	$s^{5/2}$
Heat transfer coeff.	$s^{1/2}$

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Experimental Verification (cont)

- Free Flows: Pool Fires.

Centerline velocity and temperature rise data correlate as:

$$V_x/\dot{Q}^{1/5} = f_1(x/\dot{Q}^{2/5})$$
$$\Delta T = f_2(x/\dot{Q}^{2/5})$$

where the heat release rate $\dot{Q}$ scales as:

$$(\dot{Q}) \rightarrow (L^2 U) \rightarrow L^{5/2}$$

- Therefore:

$$V_x \propto L^{1/2} f_1(x/L)$$
$$\Delta T \propto f_2(x/L)$$

Factory Mutual System

McCaffrey, B. J., "Purely Buoyant Diffusion Flames: Some Experimental Results", U.S. Bu. Strds. Tech. Rept. NBSIR 79-1910, Oct. 1979.

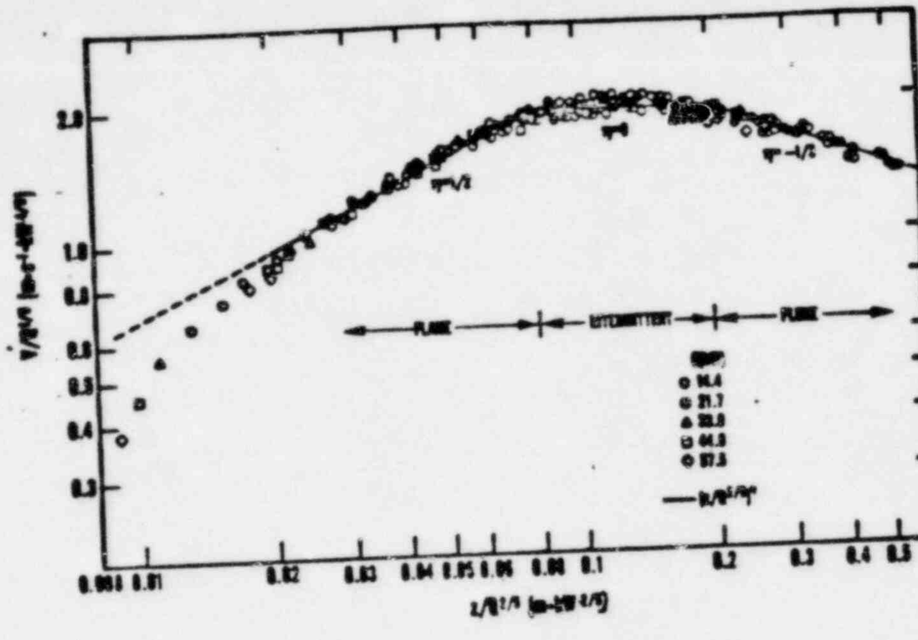

Figure 1. Center line velocity vs height

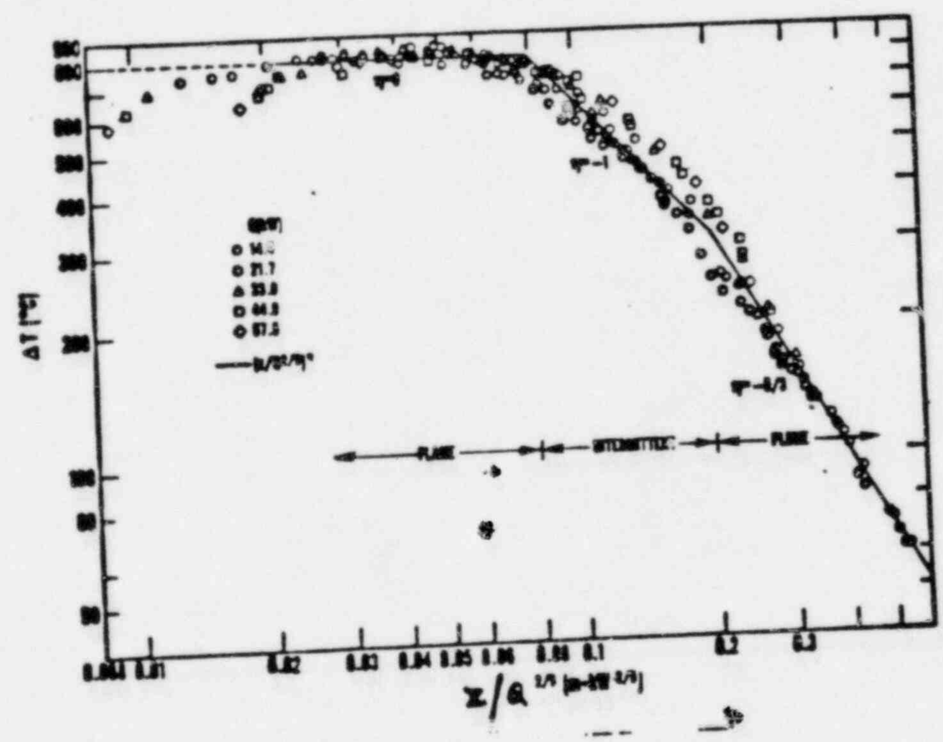

Figure 2. Center line temperature rise vs height

Factory Mutual System

McCaffrey, B. J., "Purely Buoyant Diffusion Flames: Some Experimental Results", U.S. Bu. Stds. Tech. Rept. NBSIR 79-1910, Oct. 1979.

Experimental Verification (cont)

– Enclosure Flows: Flow Rates through Openings.

The flow rate through an opening can be explained by a simple hydrostatic model based on temperature distribution:

$$\dot{m}_g = W_o \rho_\infty T_\infty C \int_N^{H_o} \sqrt{(2g/T_r) \int_N^z (1/T_a - 1/T_r)\,dz'}\;dz$$

or, by assuming the temperature in the hot layer to be constant:

$$\dot{m}_g = 2/3\sqrt{2g}\, C\rho_a A_o \sqrt{H_o} \sqrt{(T_a/T_r)(1 - T_a/T_r)}\,(1 - N/H_o)^{3/2}$$

These experimentally verified equations show that the flow rate is proportional to the 5/2 power of scale, as required by Froude modeling.

Factory Mutual System

Steckler, K. D., Quintiere, J. G. and Rinkinen, W. J., "Flow Induced by Fire in a Compartment", 18th Symposium (International) on Combustion, (to appear).

Experimental Verification (cont)

– Enclosure Flows: Feedback–controlled Fires.

Room fires (heat feedback–controlled burning) modeled successfully at 1/4 scale: Rate of burning, gas and wall temperatures, CO and CO_2 production.

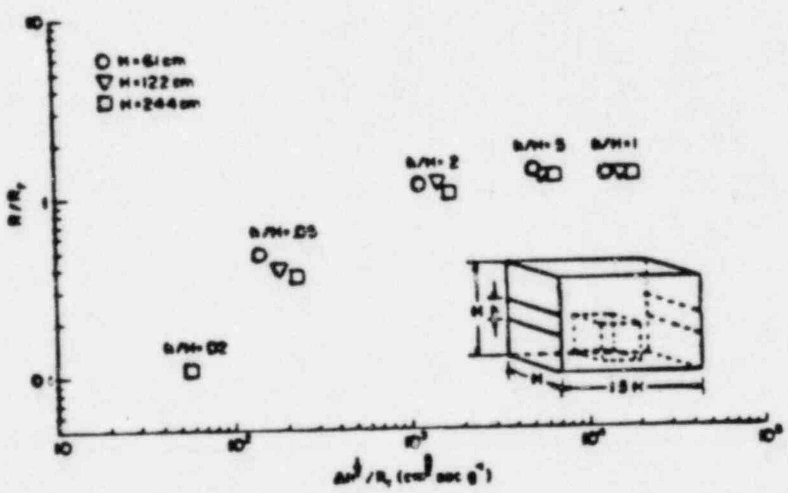

Figure 3. Burning rate factor as function of ventilation factor for various enclosure scales and geometries; P (porosity of wood crib) = 0.08 cm.

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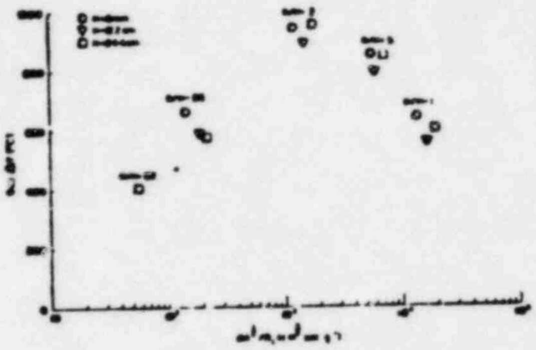

Figure 4. Gas temperature increase associated with data in Figure 3 (loc. of thermocouples positioned H/4 from end walls, H/10 from ceiling level and midway between side walls).

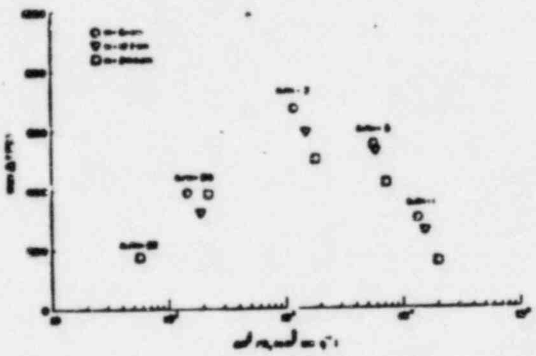

Figure 5. Wall temperature increase associated with data in Figure 3 (loc. of thermocouples positioned H/4 from end walls and H/4 from ceiling level on one of the side walls).

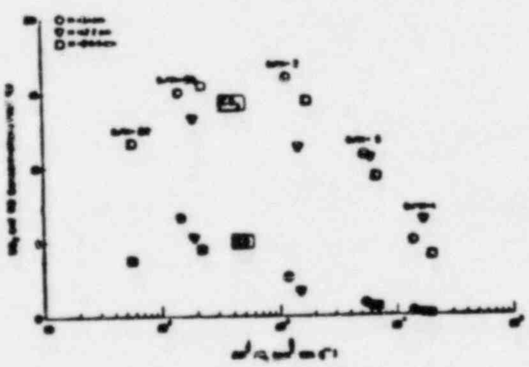

Figure 6. Concentrations of carbon monoxide and carbon dioxide associated with data in Figure 3 (at sampling point positioned H/4 from one end wall, H/10 from ceiling level and midway between side walls).

Factory Mutual System

Heskestad, G., "Physical Modeling of Fire", J. Fire & Flammability, Vol 6 (July 1975), p.253.

Experimental Verification (cont)

– Enclosure Flows: Complex Interactions.

FMRC fire test building (200x250x30–60 ft high) modeled at 1/12.5 scale. Model used to simulate ventilation induced by sprinklered fires.

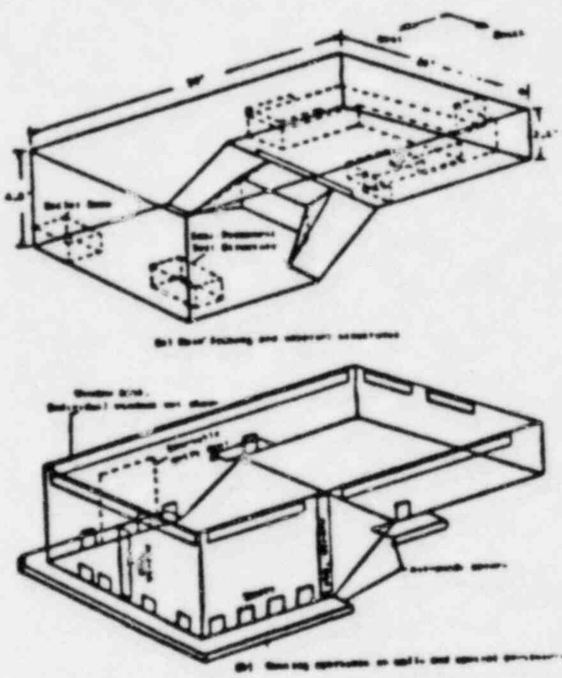

Figure 7. Schematic views of model of FMRC's fire test building

Factory Mutual System

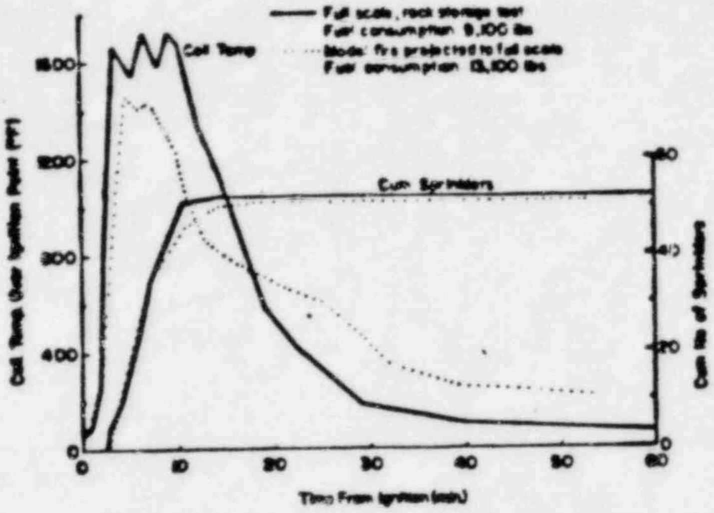

Figure 8. Comparison of results in FMRC's fire test building and scale model (212° F sprinklers, 10' X 10' spr. spacing, 0.3 gpm/ft² water density).

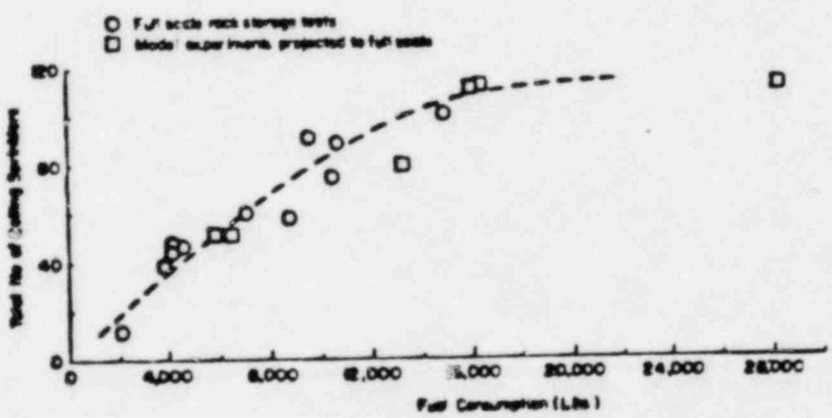

Figure 9. Total number of sprinklers related to mass of cellulosic fuel consumed in FMRC's fire test building and scale model (165°F sprinklers, 10' X 10' spr. spacing 0.3 gpm/ft² water density).

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Heskestad, G., "Physical Modeling of Fire", J. Fire & Flammability, Vol 6 (July 1975), p.253.

HEAT AND MASS TRANSFER MODELING

– Convection versus Radiation.

1. Convective heat transfer to ceilings and submerged objects has been found to be a weak function of scale (power of s in the range $-1/4$ to $1/5$).

2. Radiative heat transfer scales as s^0 if flames are optically thick, as s if flames are optically thin.

3. In flames from hydrogen/steam mixtures, radiation is a secondary contributor to overall heat transfer.

Factory Mutual System

Heat and Mass Transfer Modeling (cont)

– Thermal Response of Objects.

Assuming that heat fluxes scale as $s^{1/2}$, the surface temperatures are preserved if:
1. $(\lambda \rho c_p) \rightarrow s^{3/2}$ for thermally thick objects
2. $(t) \longrightarrow s$ for thermally thin objects

For case 1, the material used to simulate the object in the model is different from that of full scale; for case 2, the material is the same.

Factory Mutual System

Heat and Mass Transfer Modeling (cont)

– Flow/Spray Interactions.

Droplet trajectories and evaporation rates are modeled if:

1. Droplet diameter;
2. Drop flux density; and
3. Initial velocities

all scale as $s^{1/2}$.

Correct scaling of the above parameters can be obtained through appropriate selection of nozzle type and water supply pressure.

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LIMITATIONS OF MODELING APPROACH

- It is the absolute size of the model, and not the scale factor, which defines the limit in the minimum allowable model size.
- The minimum acceptable size depends on the nature of the phenomenon under study.
- For confined flames, the minimum length scale should be of the order of 1–2 feet.

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CONCLUSIONS

- Froude modeling offers a very attractive approach for the simulation of large-scale, buoyancy-controlled, non-premixed combustion phenomena.
- Its validity has been experimentally verified in several studies.
- The approach appears ideally suited for the modeling of the hydrogen diffusion flames in the Mark III containment.
- Based on the analysis of the scaling of convective heat transfer, for a 1/4 scale model, heat fluxes near the hydrogen release points can be assumed to be equal to those expected at full scale.

A multiplying factor in the range 1 to 2 should be applied to extrapolate fluxes at higher locations.

ATTACHMENT II

1/20th SCALE TEST FACILITY
DESCRIPTION REPORT

1/20TH-SCALE MARK III COMBUSTION VISUALIZATION TEST FACILITY
FACILITY DESCRIPTION REPORT

EPRI Project Number RP 1932-32

Acurex Corporation
Energy & Environmental Division
485 Clyde Avenue
Mountain View, California 94042

Principal Investigators
William S. Kennedy
Ken Wolfe

EPRI Project Manager
John Hosler
Nuclear Power Division

SECTION 1

1/20TH-SCALE MARK III HYDROGEN BURN TEST FACILITY

A 1/20th-scale model of a Mark III BWR containment is currently being assembled at Acurex Corporation, Mountain View, California and will be used for a series of hydrogen flame visualization tests. The facility accurately simulates the Mark III containment including drywell/wetwell configuration, suppression pool, and peripheral blockages in the annular region between the drywell and outer containment walls. Hydrogen is admitted through x-quenchers and/or vents in the suppression pool and is ignited by a number of distributed ignitors. The entire outer wall of the facility is fabricated from rolled Pyrex glass to allow visualization of the hydrogen flames.

The following sections of this report describe the details of the system. However, it should be recognized that minor changes may be made during shakedown testing.

1.1 TEST VESSEL

The test facility is shown in Figures 1-1 and 1-2. The drywell is fabricated from a 1/8-in. thick rolled steel plate and welded to an integral steel support skirt. Cutouts in the skirt allow access to the drywell interior. The upper part of the support skirt also serves as the outer wall of the wetwell pool. Four vertical members support the steel roof. The sides of the vessel are enclosed by eight panels of 7/32-in. thick rolled pyrex plate. The glass is held in place by circumferential steel bands which compress its edges against gasketed seats.

The vessel is a true 1/20th-scale version of the Grand Gulf nuclear units with two exceptions. The spherical dome at Grand Gulf was replaced by a flat top in the test facility; however, the containment volume is accurately scaled. Details of the plant configuration at the top of the drywell (the "cruciform" structure) were modified. Both changes were made to facilitate fabrication and are not expected to affect test results.

The thermal modeling of the facility was performed according to the criteria of Appendix A, which states that in a proper 1/20th-scale test, the walls which

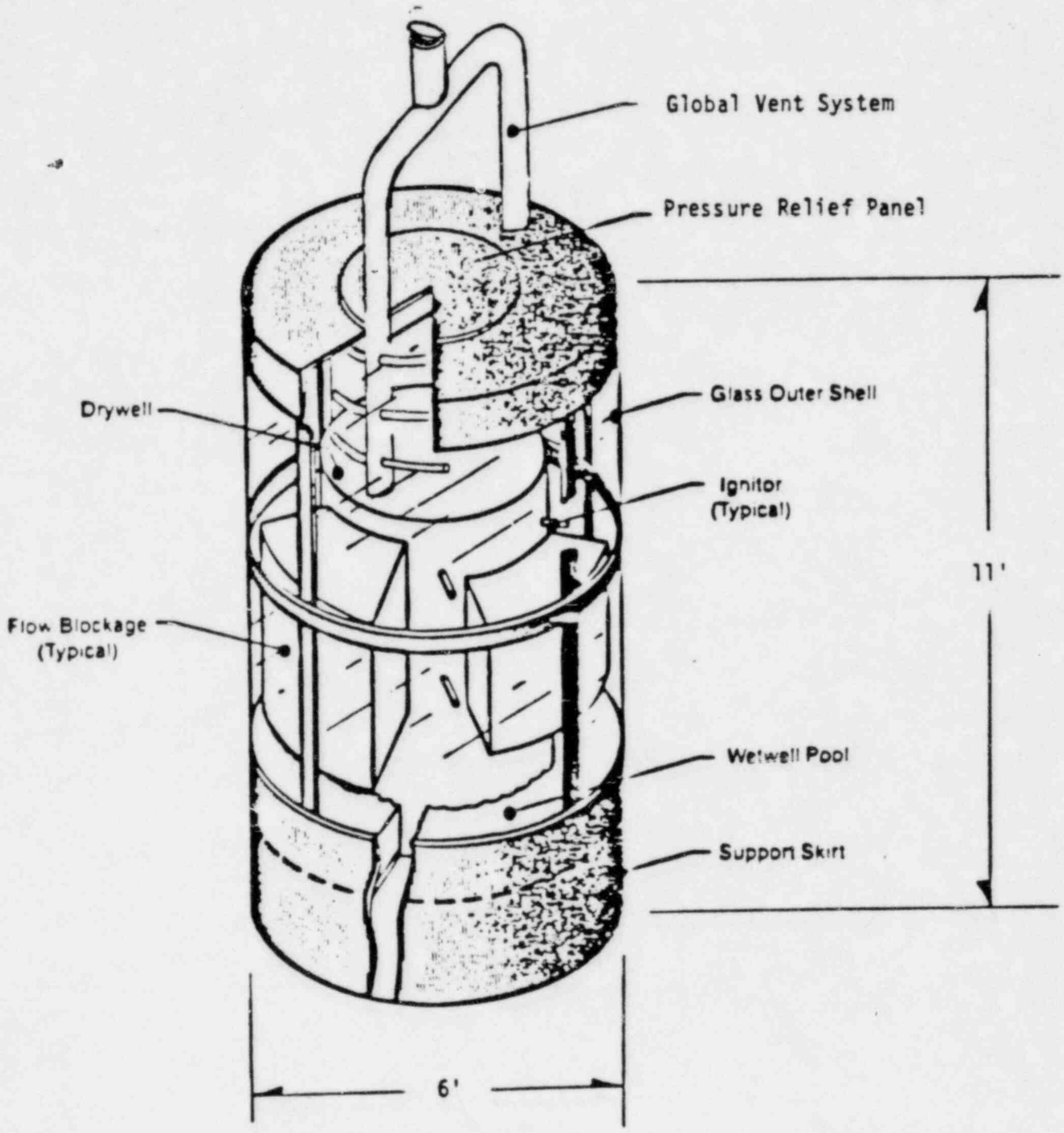


FIGURE 1-1 1/20TH SCALE MK III CONTAINMENT COMBUSTION VISUALIZATION TEST FACILITY

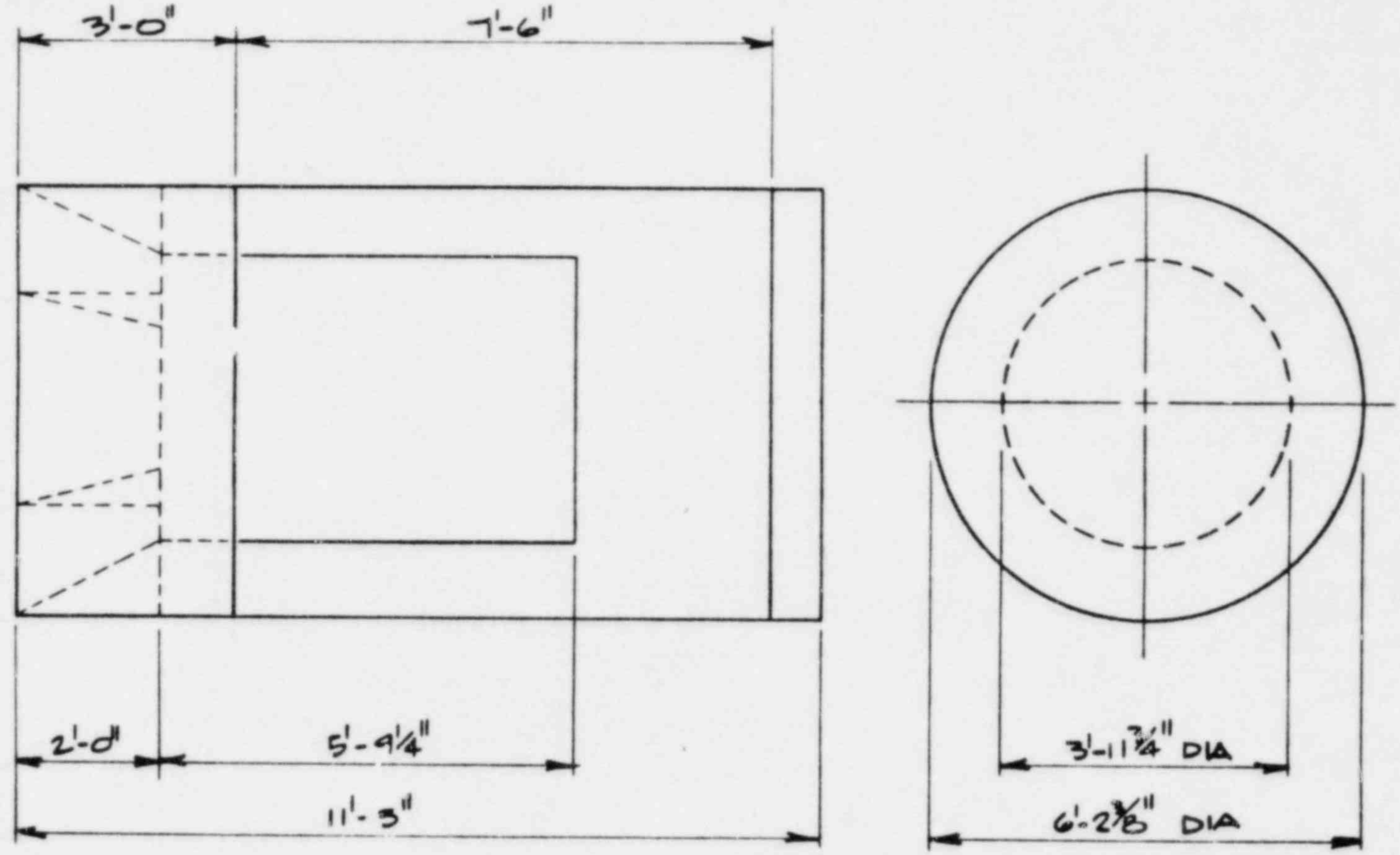


Figure 1-2. Test Facility Dimension

simulate concrete should have a $k \rho C_p$ product of approximately 2×10^4 $WJ/m^4{}^\circ C^2$. The value of this parameter for the glass is greater than desired but cannot be changed. However, the drywell wall properties could be altered by selection of a suitable insulation. "Thermo-12," a Johns-Manville material was selected. Although its $k \rho C_p$ product is between 10^4 and 2.4×10^4 $WJ/m4^\circ C^2$ depending on temperature, it has desirable mechanical and moisture-resistant properties. The drywell wall is covered with a 1-in. thick layer of this insulation. Blockages between the drywell wall and outer containment wall (e.g., HCU floor) are also simulated with structures cut from this insulation. Details of the blockages are given in section 2 of this report.

Although the facility would ideally be operated as a closed volume (i.e., no venting during a test), this is impossible due to the structural limitations of the plate glass walls. Consequently, two pressure relief systems were incorporated in the design. The first system (figure 1-3) consists of a network of 24 1/2-in. diameter tubes which draw air from a set of locations uniformly distributed throughout the containment. These tubes are manifolded into two 3-in pipes which exit the facility and are manifolded to a 4-in pipe on which a flapper valve is mounted. This valve is adjusted to open when the internal pressure exceeds ambient pressure by 0.1 psi. This distributed-source system has the advantage of venting an effective "mixed-mean" fluid as opposed to a single-point vent which would release fluid with properties specific to a region near the vent. Thus the natural global distribution of fluid properties is approximately preserved.

The second pressure relief system is a spring-loaded lid on top of the wetwell which can be adjusted to lift at pressures on the order of 1 to 2 psi. This large relief area provides protection against extremely severe burns.

The facility has been designed for a maximum internal pressure of 5 psig. However, it is anticipated that it will be run at pressures below 1 psig.

The wetwell pool is nominally 11.3-in. deep and can be heated with four 10-kW heaters to a maximum temperature of approximately 185°F. The heaters are controlled manually with on/off switches.

1.2 GAS FLOW SYSTEM

Hydrogen gas is metered into the facility mixed with 1 to 2 volume percent acetylene. The acetylene causes the otherwise colorless hydrogen flame to burn with a yellowish tint which is easily photographed.

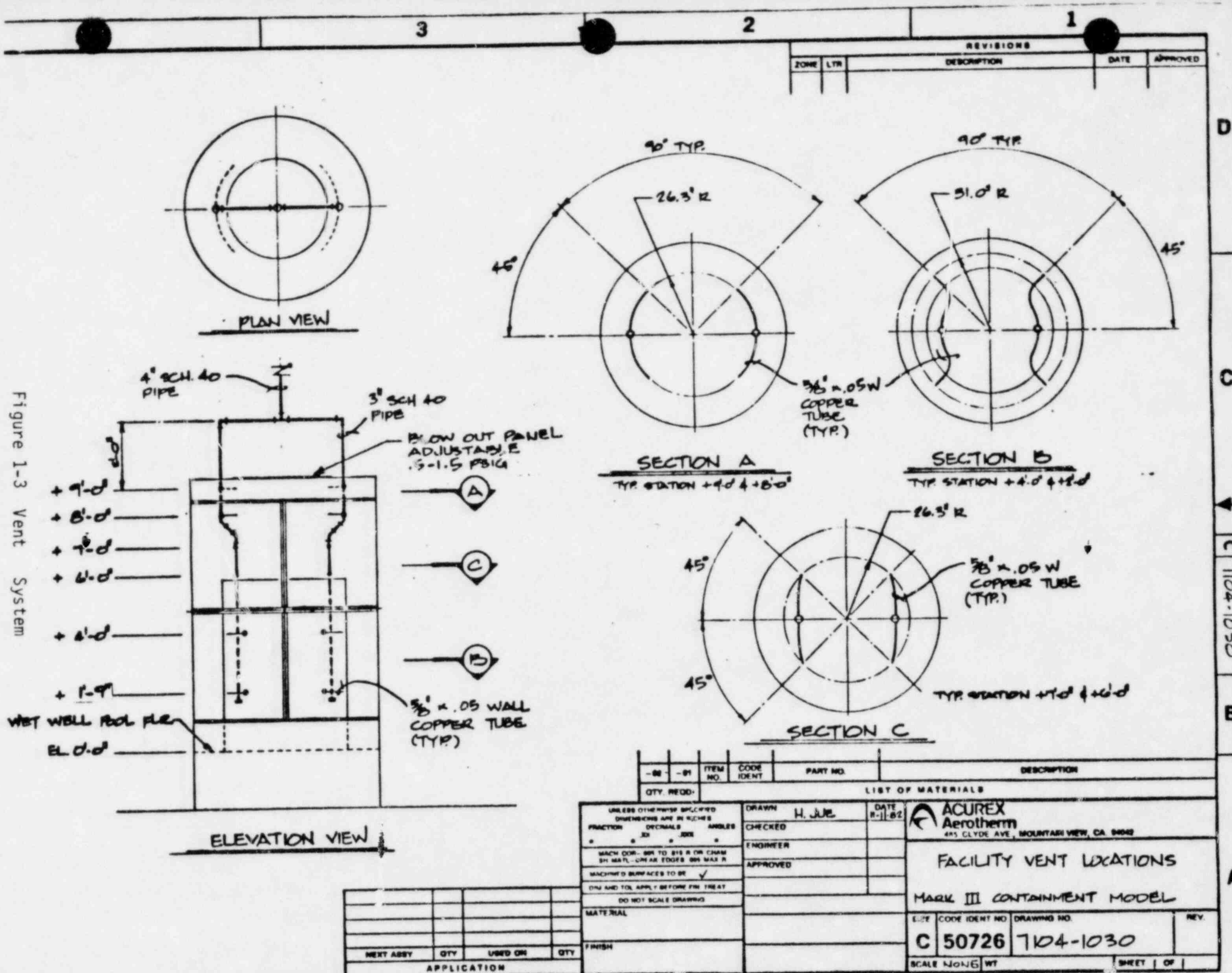


Figure 1-3 Vent System

As shown in Figure 1-4, two independent flow systems provide hydrogen to the spargers and vents respectively. Flow is regulated manually and is measured with rotameters. Two rotameters are required to cover the entire range of flow which has a maximum of 0.00224 lbm/sec. Vent flow runs through a 1/2-in. copper tube from the flow metering station to a distribution manifold located inside the drywell. The manifo[illegible] tributes the flow to each of the 40 vents through small orifices, which provide a high enough differential pressure between the manifold and each vent to ensure uniform flow to all vents.

The sparger flow system is essentially identical to the vent system except that the manifold has only eight outlets. While all 45 vents will operate simultaneously, any number of spargers (from one to eight) at any of 20 locations in the pool can be operated at total flowrates up to 0.00224 lbm/sec.

The location of vents and spargers is shown in Figure 1-5. Details of each installation are presented in Figure 1-6.

1.3 IGNITOR SYSTEM

Spark ignition devices (spark plugs) were selected as ignitors. These devices are individually powered by = 4700 volt ac transformers.

The spark plugs either screw into the wetwell region from the drywell wall or into the upper containment from the roof of the facility. The ignitors are located in the same positions as the Grand Gulf ignitors. Full scale dimensions of these locations are given in Table 1-1. The ignitors can be operated in two or more banks if required.

1.4 WETWELL FLOW BLOCKAGES

Concrete obstructions in the annular area between the drywell and outer containment walls are fabricated from the same material which insulates the wall of the drywell (Johns-Manville Thermo-12). While the obstructions can be easily changed to represent various generic or plant-specific configurations, the baseline configuration is based on Grand Gulf as shown in Figure 1-7.

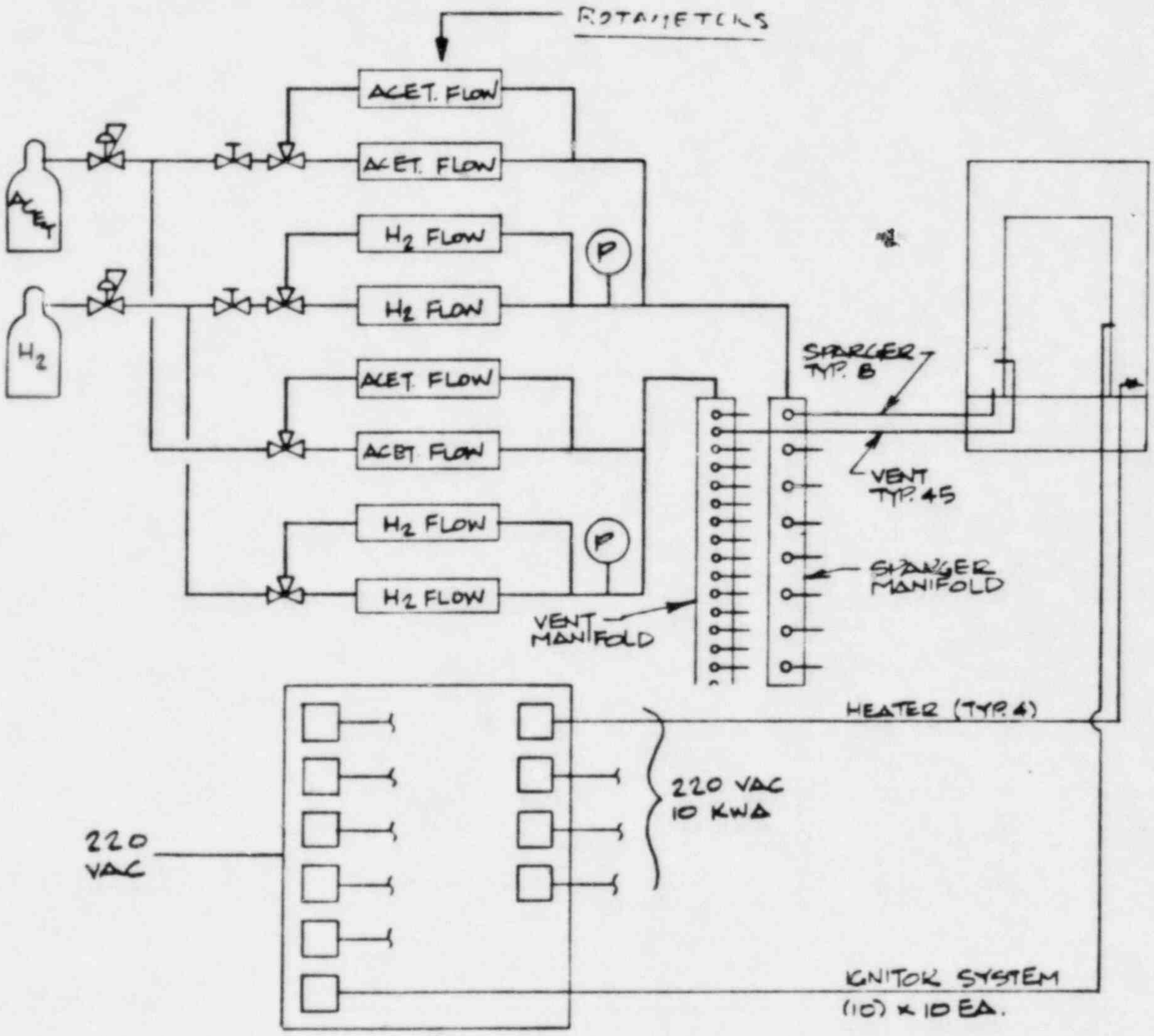
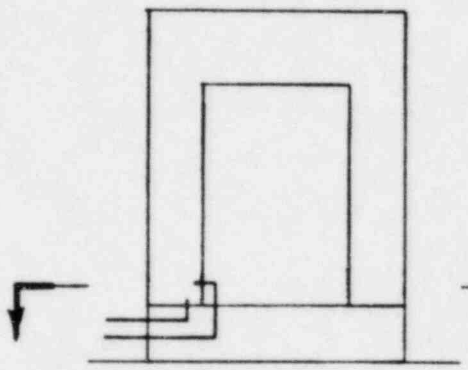


Figure 1-4. P&ID



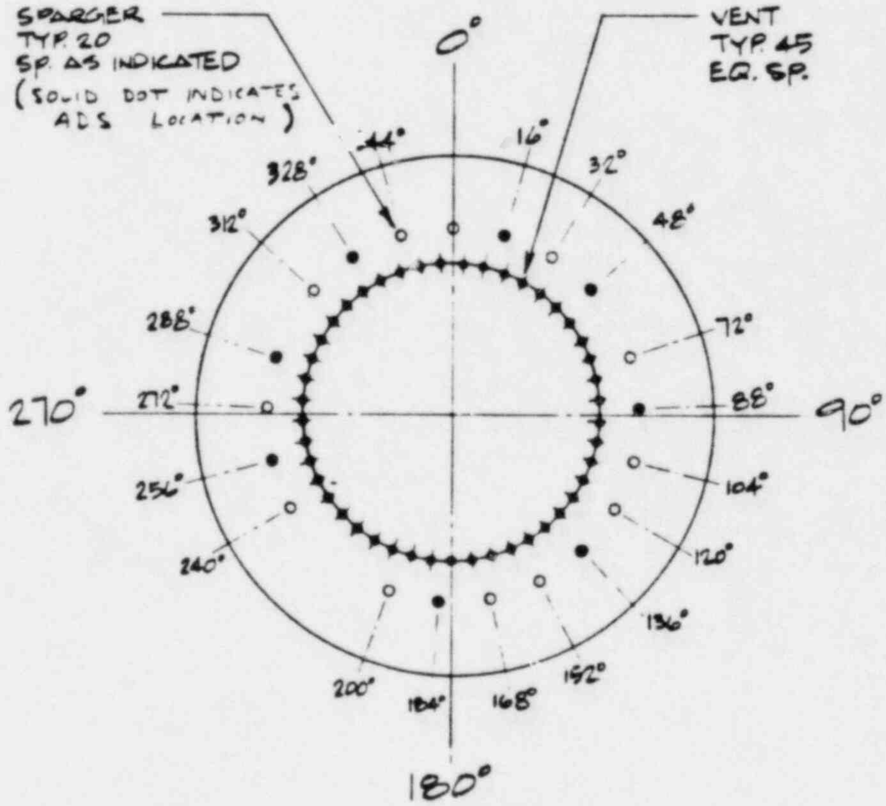
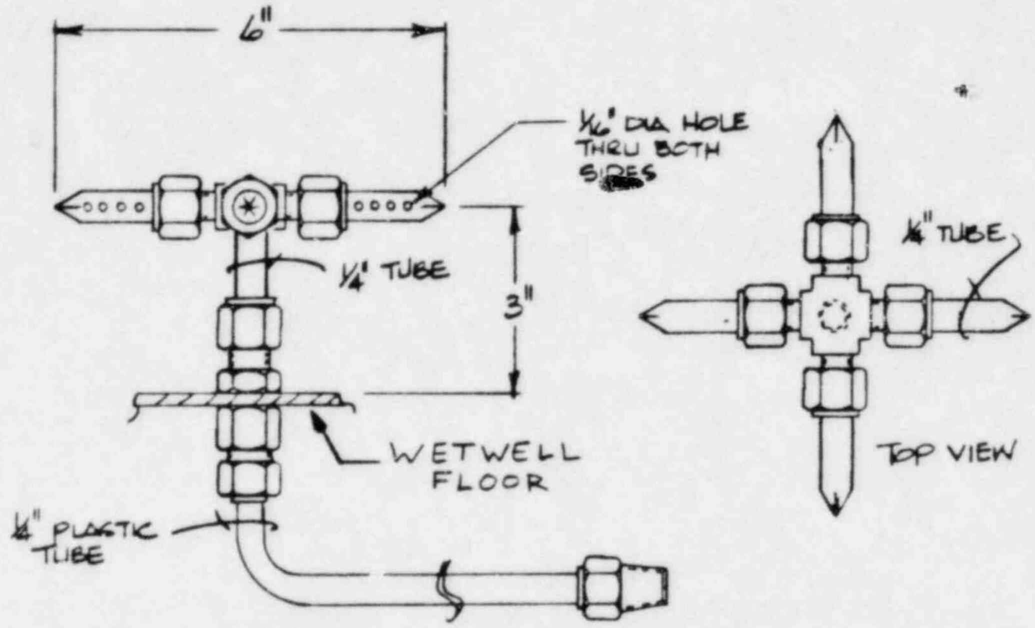
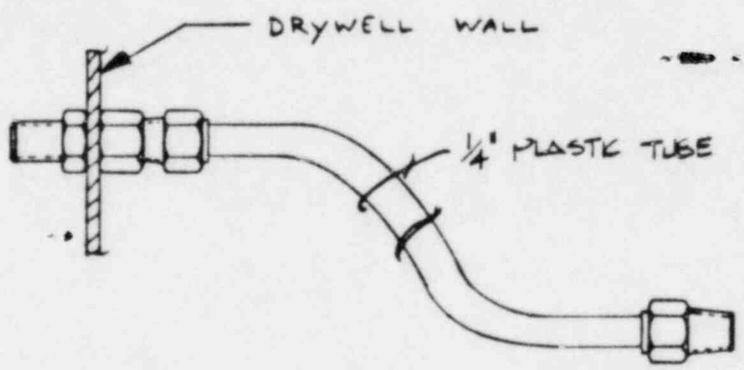


Figure 1-5. Sparger and Vent Locations



SPARGER DETAIL



VENT DETAIL

Figure 1-6. Sparger/Vent Detail

Table 1-1

FULL-SCALE IGNITOR LOCATIONS

Elevation[a] ft	Elevation[a] in.	Azimuth	Radius ft	Radius in.
136		20	51	9
132	10	47	53	0
132	10	75	51	9
132	10	107	51	9
132	10	135	51	9
132	10	165	51	9
132	10	195	51	9
145	7	220	60	
134	4	253	51	9
134	4	285	51	9
134	4	317	52	8
136		349	51	9
166		16	51	9
160	4	36	53	6
157	10	70	51	9
157	10	100	51	9
160	4	135	51	2
155	10	164	51	9
155	10	196	61	9
165		226	61	4
160	4	260	54	2
159	4	285	51	5
159	4	321	51	5
166		344	51	9
182	9	30	61	
167	8	41	49	
168	10	70	46	2
168	10	109	51	5
178	10	70	51	9
178	10	109	51	5
182	4	136	51	9
182	4	254	55	9
183	4	278	47	7
182	4	293	58	11
183	4	320	53	2
202		90	45	
202		92	48	
202		106	55	8
207	7	135	55	8
208	4	210	49	6
204	4	256	53	8
204	11	284	53	8
207	9	310	56	6
202		341	55	

[a]For reference, elevation of wetwell bottom is 93 ft

Table 1-1 (Concluded)

Elevation[a] ft	in.	Azimuth	Radius ft	in.
202		21	50	4
202		32	42	
207	9	59	44	
202		74	55	8
202		88	48	
202		90	37	
202		90	34	
202		90	22	
204	11	242	26	8
207	9	298	26	8
262		6	55	5
262		48	55	5
262		91	55	5
262		140	55	5
262		183	55	5
262	9	225	55	5
262		268	55	5
262		333	55	5
283	10	349	39	8
283	10	34	39	8
283	10	81	39	8
283	10	127	39	8
283	10	152	39	8
283	10	199	39	8
283	10	242	39	8
283	10	286	39	8
295	10	349	15	3
295		158	15	3

[a]For reference, elevation of wetwell bottom pool is 93 ft

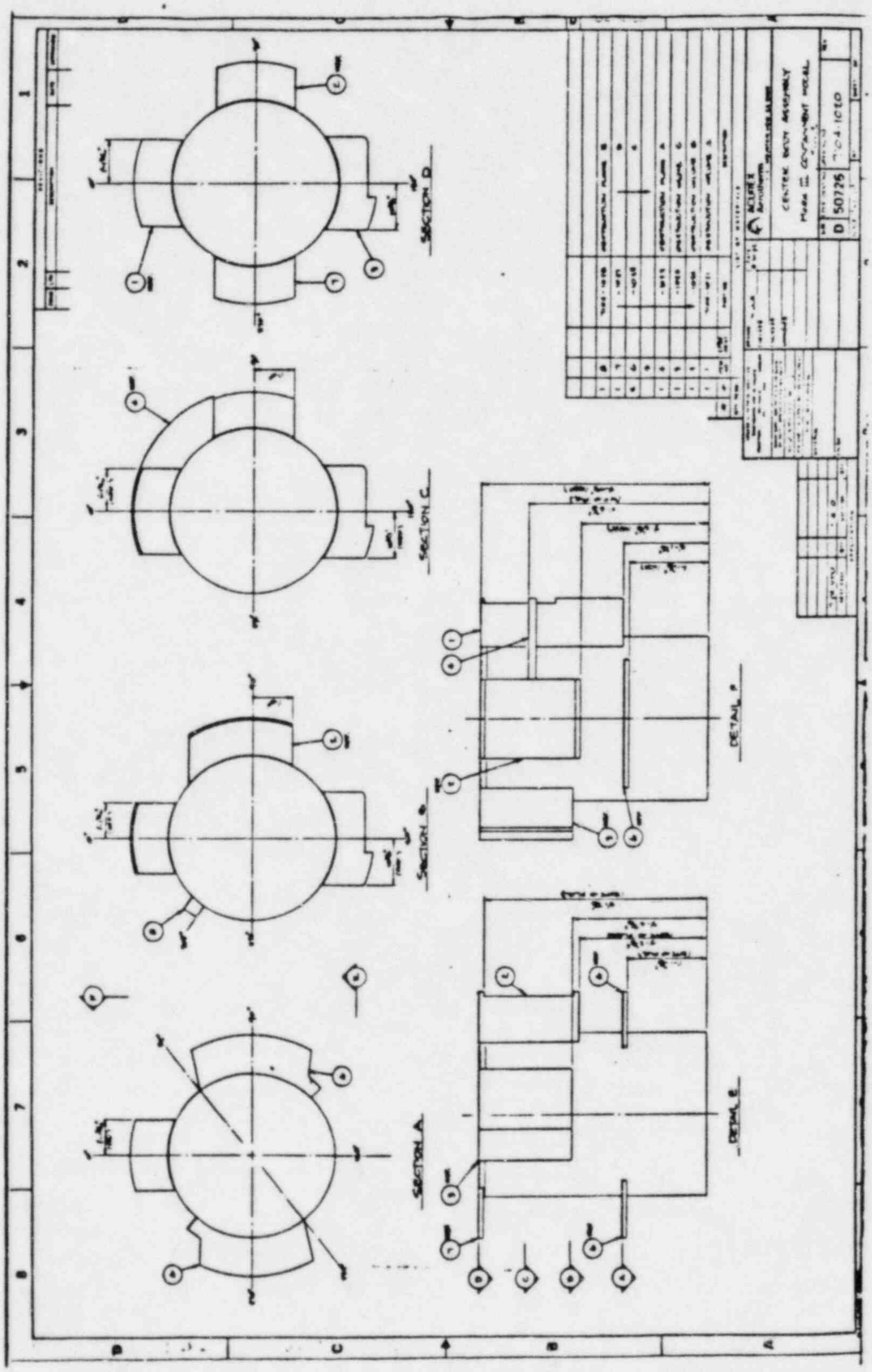


Figure 1-7. Blockages

1.5 WATER SPRAY SYSTEM

Containment water spray is simulated in the test facility by six spray nozzles located 1 ft below the top of the wetwell on a common header. The scaled flowrate of 6.3 gpm (11,300 gpm full scale) is supplied by a multistage centrifugal pump which draws water from the wetwell inventory.

1.6 FACILITY INSTRUMENTATION

Facility instrumentation is listed in Table 1-2. The primary test data is the record obtained by four video cameras which provide complete coverage of the facility. The four video records are mixed in real time onto a single videoframe such that the entire facility can be viewed at once on a single monitor.

Other instruments from which data are recorded include six type K thermocouples and a pressure transducer. These data are recorded on a Brush (Gould) strip chart recorder.

O_2 concentration is monitored in the global vent system outlet.

Table 1-2

INSTRUMENTATION

Measurement	Number	Instrument	Range	Response Time (sec)	Accuracy
Containment temperature	6[a]	Type K thermocouple	--	~0.3	5°F
Containment pressure	1[a]	Strain-gauge XDCR	0-5 psig	0.002	0.05 psi
Water temperature	1	Type K thermocouple	--	1	5°F
Spray water flowrate	1	Rotameter	1-10 gpm	--	0.3 gpm
Hydrogen flowrate	2	Rotameter	20-1,800 SCFM	--	1 percent
Acetylene flowrate	2	Rotameter	0.5-50 SCFM	--	1 percent
Oxygen concentration in vent system outlet	1	Galvanic	0-25 percent	2 min	0.1 percent

[a]Recorded on strip chart

Appendix A

MODELING CONSIDERATIONS

The primary purpose of the tests planned for this experimental facility is to reproduce the flow and combustion dynamics subsequent to hydrogen ignition. Even within the confines of this limited perspective, it appears desirable to simulate the response of the containment walls to the flame heat fluxes. By including this feature, the uncertainty of the data would not only be reduced, but the possibility that the test results might be quantitatively accurate would also be left open. Therefore, the material and thicknesses of the walls in the test structure will be chosen based on the scaling of heat fluxes as required by Froude modeling except for the pyrex windows. In practice this would make the exposed surfaces in the model follow the temperature-versus-time history of those in the actual containment.

The scaling relations which apply to flow properties if the Froude number of the model is maintained at the same value as that of the flow to be modeled can be summarized as follows. If s indicates the scale reduction (in our case s = 1/20), then the following properties scale as:

lengths	s
velocities	$s^{1/2}$
time	$s^{1/2}$
total fuel flow	$s^{5/2}$
heat fluxes	$s^{1/2}$

In particular, the full-scale accident duration of 7,800 s postulated by the MARCH predictions would be scaled in the model by a test lasting $7{,}800/\sqrt{20} = 1{,}744$ s. Similarly, the large-scale flow of hydrogen of 4 lb/s and the total release of 2,600 lb would be modeled by a hydrogen flow of $4/(20)^{5/2} = 0.00224$ lb/s and a total release of $(1/20)^{5/2} \times (1/20)^{1/2} \times 2{,}600 = 0.33$ lb.

With regard to the thermal response of walls, the temperature of two different surfaces exposed to the same environment will be the same if the heat transfer is dominated by convection and if the wall materials have the same value for the parameter:

$$h^2\tau/(k\ \rho\ c_p)$$

where

h = heat transfer coefficient

τ = time scale

k = thermal conductivity

ρ = material density

c_p = specific heat.

This result applies to the case of thermally thick walls, in which negligible heat escapes from the unexposed surface. This is definitely the case for concrete walls and floors in the Mark III containment. In practice, to have the model reproduce wall temperatures of the actual containment, the wall material must be such that:

$$\frac{k_M(\rho c_p)_M}{k_F(\rho c_p)_F} = \frac{h_m{}^2\tau_M}{h_F{}^2\tau_F}$$

where subscripts M and F refer to model and full scale respectively. Since both h and τ must scale as $s^{1/2}$, it follows that:

$$k_M(\rho c_p)_M = s^{3/2} \times k_F(\rho c_p)_F \quad .$$

For the case of concrete:

$$k_F = 0.93 \text{ W/m °C}$$
$$(\rho c_p)_F = 1.93 \times 10^6 \frac{\text{J}}{\text{m}^3\text{°C}}$$

The 20 to 1 scale reduction of the model then implies:

$$\lambda_M (\rho c_p)_M = 2 \times 10^4 \ \mathrm{WJ/m^4\ {}^\circ C^2} \quad .$$

Simulating the response of thermally thin bodies such as grating and small metallic pieces of equipment can also be done easily. By inspection of the equation governing the temperature rise of an isothermal body, it can be deduced that the parameter to be preserved is:

$$\frac{h\tau}{b\rho c_p}$$

where b is the length scale of the object, which is assumed to be geometrically similar to the actual full-scale item. If the same material is used in the model as at full scale, then:

$$b_M = b_F \frac{h_M \tau_M}{h_F \tau_F} = b_F \ s$$