NUREG/CR-5079
SAND87-3139

Experimental Results Pertaining to the Performance of Thermal Igniters

Prepared by Michael K. Carmel

Sandia National Laboratories

Prepared for
U.S. Nuclear Regulatory Commission

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 2120 L Street, NW, Lower Level, Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Office of Information Resources Management, Distribution Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-5079
SAND87-3139

Experimental Results Pertaining to the Performance of Thermal Igniters

Manuscript Completed: September 1989
Date Published: October 1989

Prepared by
Michael K. Carmel

Sandia National Laboratories
Albuquerque, NM 87185

Prepared for
Division of Engineering and Systems Technology
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN A1301

ABSTRACT

This report summarizes the results of various experimental programs regarding the performance of thermal igniters for the deliberate ignition of hydrogen in light water reactors. Experiments involving both premixed combustion and combustion with continuous hydrogen injection are reviewed. Combustion characteristics examined include flammability limits of hydrogen:air and hydrogen:air:steam mixtures, combustion pressure rises, combustion completeness, flame speeds, and heat transfer aspects. Comparisons of igniter type and igniter reliability under simulated reactor accident conditions are included. The results of the research programs provide a broad data base covering nearly all aspects of hydrogen combustion related to the performance of deliberate ignition systems.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

This work was supported by the U.S. Nuclear Regulatory Commission under the direction of A. Notafrancesco. I would like to express my appreciation to S.E. Dingman, A. Notafrancesco, R.E. Hogan, L.S. Nelson, J.E. Kelly, T.D. Brown, and F.E. Haskin, who reviewed the original draft of this document and who provided constructive changes and suggestions, which have been incorporated in this work.

1. INTRODUCTION

The combustion of hydrogen during postulated core uncovery accidents in light water reactors can be a threat to the integrity of the containment system and safety equipment of these plants. One of the methods used to mitigate the effects of hydrogen combustion is deliberate ignition of the hydrogen by igniters in containment. The systems are designed to burn hydrogen at low concentration rather than allowing it to accumulate to more threatening levels. Many experimental programs have been conducted to address the performance of igniters under varying conditions. This report serves to summarize the conclusions of those programs regarding the effectiveness of deliberate ignition systems.

1.1 Deliberate Ignition Systems

Deliberate ignition systems are currently utilized in BWR Mark III and PWR ice condenser plants. The medium-volume (i.e. 3-4×10^4 m^3) containments that these plants employ have design pressures of about 100 kPa, or 15 psig (although detailed analyses predict much higher ultimate failure pressures). The integrity of these containments could be threatened by the pressure transient resulting from the deflagration (subsonic flame burn) or detonation (supersonic combustion wave) of rich mixtures of hydrogen. They could, however, survive combustion of lean mixtures, which produce lower pressure rises. The deliberate ignition systems are designed to promote burning of lean rather than rich hydrogen mixtures.

The effectiveness of igniters as ignition sources in these systems can be evaluated by the characteristics of the combustion processes they initiate. Measurements of the peak pressure of combustion, resultant flame speed, and completeness of combustion are useful in determining igniter performance. Also relevant to effectiveness under severe accident conditions are qualities such as performance in the presence of water vapor or microfog and operability during station blackout scenarios [1].

1.2 Igniters

Devices most widely used as ignition sources in current deliberate ignition systems are thermal (hot surface) igniters. Thermal igniters provide a transfer of thermal energy to provide ignition, and require electrical input for operation. Other ignition sources that have been considered include spark plugs, pilot flames, plasma jet igniters [2,3], and catalytic igniters [4]. This report will only address the performance characteristics of thermal igniters.

Figures 1.1 and 1.2 show the two types of thermal igniters currently installed in deliberate ignition systems [5]. These figures also show the igniter assemblies, which may vary among plants. Figure 1.1 shows the General Motors AC Model 7G glow plug, a cylindrical igniter with a design operating voltage of 12 Vac and a power requirement of about 95 watts. Figure 1.2 shows the Tayco Model 193-3442-4 helical igniter, with a design operating voltage of 120 Vac and a power requirement of about 525 watts. The assemblies include sheet metal shields to prevent direct impingement of containment spray droplets. These assemblies are distributed throughout the containment in strategic locations. The igniters are to be energized immediately following the start of an accident and to remain on as long as emergency operating procedures prescribe (usually until safe shutdown of the unit).

1.3 Experimental Research Programs

Numerous research programs conducted since 1980 have provided data on hydrogen combustion and the performance of igniters to determine the effectiveness of deliberate ignition systems. These include studies of the combustion characteristics of hydrogen burns initiated by igniters, flammability limits of hydrogen:air and hydrogen:air:steam mixtures, and hydrogen mixing processes. Several programs have investigated the effect of water sprays on igniter performance. Others have studied the effect of steam condensation on igniter effectiveness. Most research programs reported heat transfer characteristics of hydrogen combustion and resultant flame speed data.

This report summarizes findings relevant to the performance of thermal igniters from eight major hydrogen combustion research facilities. These are:

(1) The Fully Instrumented Test Site (FITS)
(2) The Variable Geometry Experimental System (VGES)
(3) The Nevada Test Site (NTS)
(4) The Hydrogen Igniter Experimental Program at Lawrence Livermore National Laboratory (LLNL)
(5) The Whiteshell Nuclear Research Establishment (WNRE)
(6) Tests conducted by the Acurex Corporation
(7) Tests conducted by Fenwal Incorporated
(8) The 1/4-Scale Mark III Containment Hydrogen Combustion Program

Chapters 2 through 9 of this report review each test program individually, and Chapter 10 serves to summarize the important conclusions regarding deliberate ignition obtained from these test programs.

Table 1.1 outlines the general scope of the research programs reviewed here. All but two of the test programs involved small-scale testing, performed in experimental vessels with less than 20 m^3 free volume. The two large-scale programs were the NTS tests performed in a 2000 m^3 spherical vessel, and the 1/4-Scale tests performed in a 1/4-scale model of a Mark III containment. All but one of the programs (the 1/4-Scale tests) examined pre-mixed combustion of hydrogen:air or hydrogen:air:steam mixtures, and four of the programs investigated combustion with the continuous injection of hydrogen and steam into the test volume. In general, all the experimental research programs reviewed here provide fairly comprehensive studies of hydrogen combustion phenomena and yield results that are relevant to the design of deliberate ignition systems.

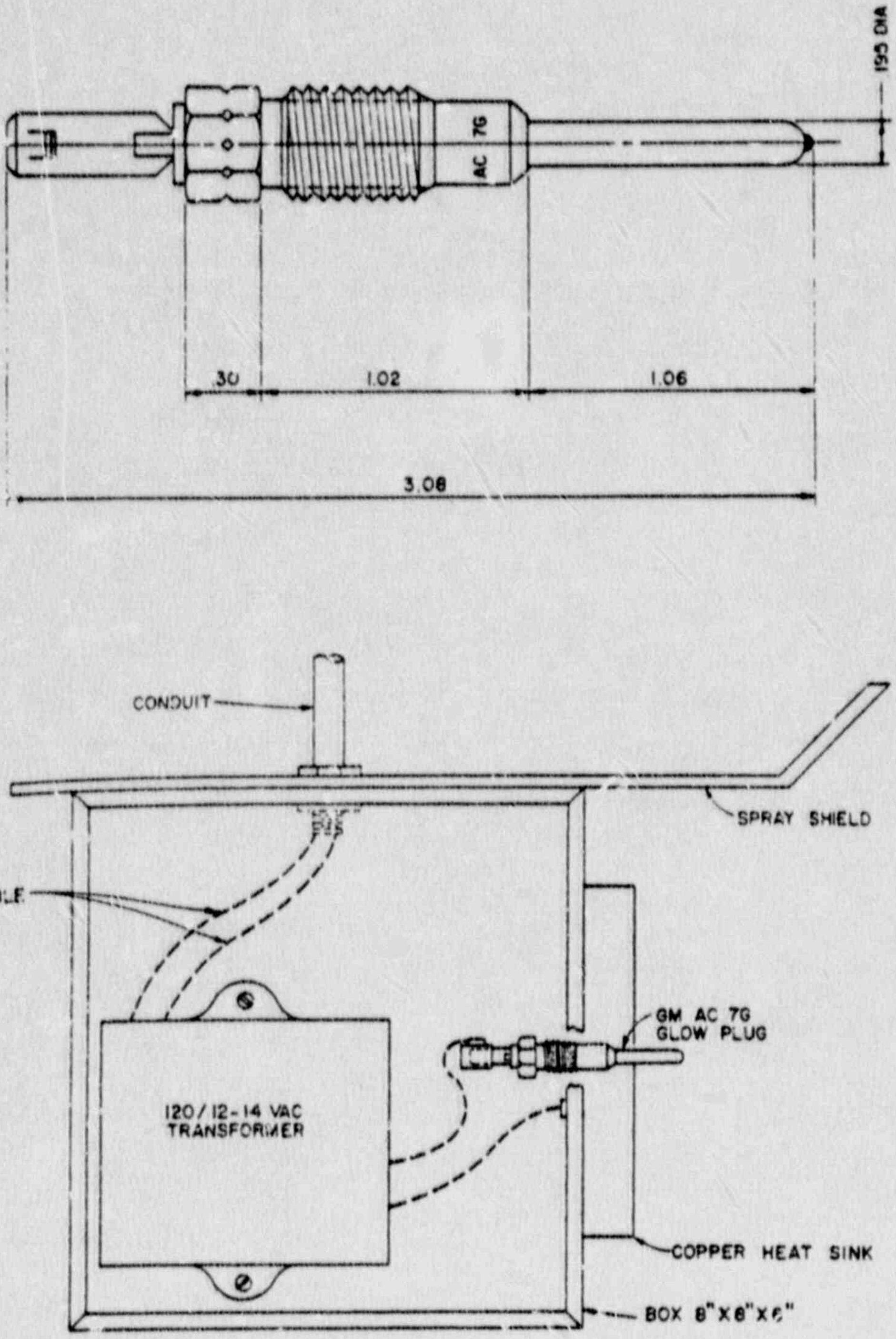


Figure 1.1 Schematic of General Motors AC 7G glow plug and assembly (taken from Reference 5).

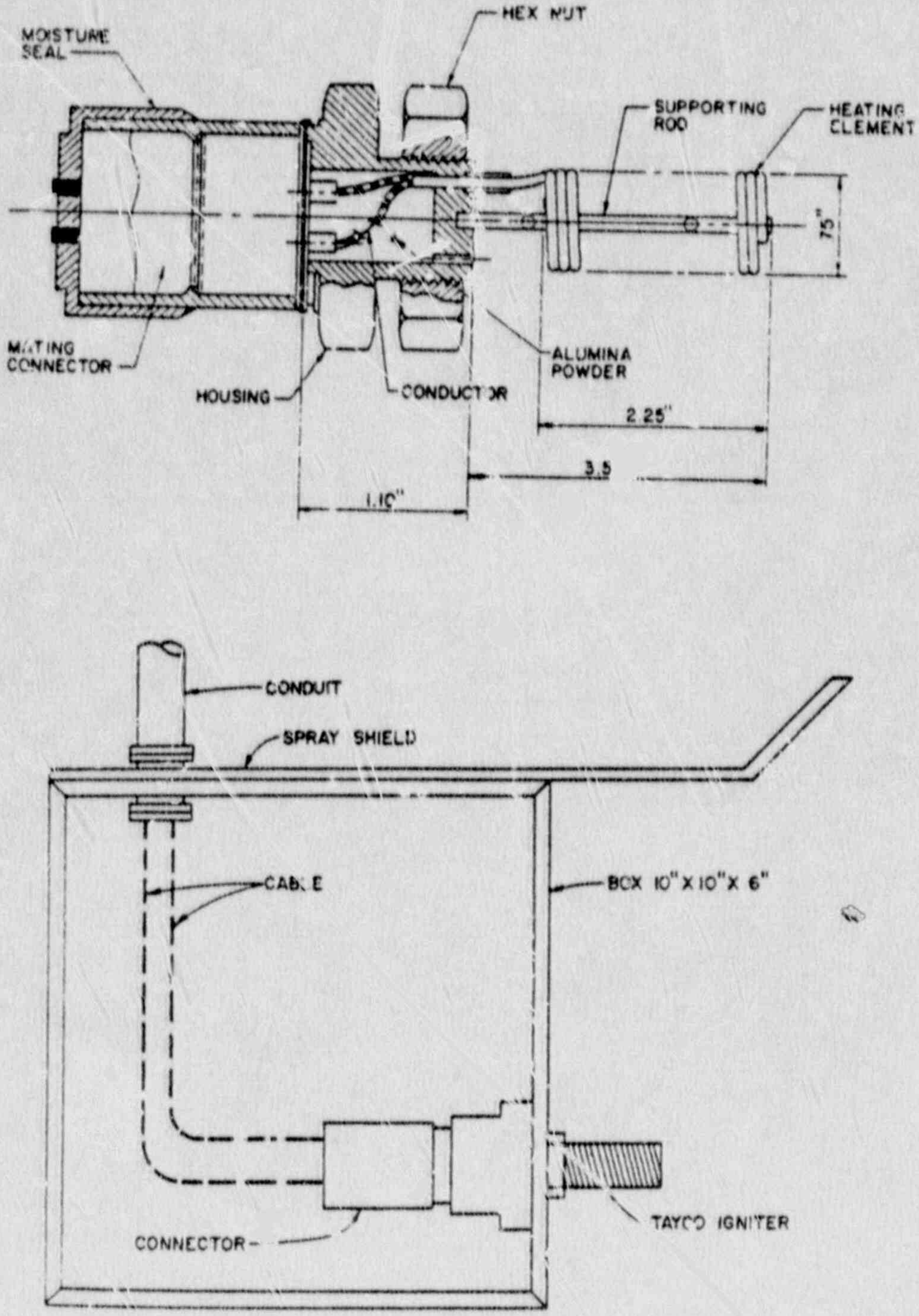


Figure 1.2 Schematic of Tayco Model 193-3442-4 thermal igniter and assembly (taken from Reference 5).

TABLE 1.1 - Scope of Thermal Igniter Exerimental Programs

	FITS	VGES	NTS	LLNL	WNRE	Acurex	Fenwal	1/4-Scale
Small-scale	•	•		•	•	•	•	
Large-scale			•					•
Pre-mixed	•	•	•	•	•	•	•	
Dynamic (Continuous Injection)			•			•	•	•
Igniter Type		•			•			
Igniter Location		•	•	•		•		•
Steam	•		•	•	•	•	•	•
Diluent Gases		•						
Flammability Limits	•			•	•			
Varied Initial Temperature	•	•				•	•	•
Sprays		•	•			•	•	•
Condensation				•	•			
Fans	•	•	•	•	•	•	•	
Aqueous Foam		•						

2. SNL FITS TESTS

A series of 239 hydrogen:air:steam combustion experiments sponsored by the NRC in 1983 was performed in the 5.6 m^3 Fully Instrumented Test Site (FITS) vessel located at Sandia National Laboratories in Albuquerque, New Mexico [6]. These experiments addressed combustion characteristics and flammability limits of combustible atmospheres that might occur inside containment during a severe accident. The data obtained in these premixed combustion tests is useful in benchmarking computer code simulations of hydrogen:air:steam combustion and containment response modeling.

2.1 Facility Description

Figure 2.1 shows a schematic of the FITS facility. As shown, the facility is a cylindrical vessel 3.4 m (11.2 ft) tall and 1.5 m (4.9 ft) in diameter, with a design working pressure of 2.38 MPa (345 psia) and 2.86 cm (1.13 in) thick steel walls. The upper head of the vessel is removable and there are twenty-five port penetrations used for instrumentation and gas feedthroughs. Burns were initiated with both spark plug and glow plug igniters located in the lower portion of the vessel. Two pneumatic fans were used to ensure proper mixing before every experiment and during the turbulent mixing tests.

2.2 Flammability Limits

The hydrogen:air:steam flammability results are shown in Figures 2.2 and 2.3 with air partial pressures of ~83 kPa (12 psia) and an initial temperature of ~110°C. Figure 2.2 shows results for the quiescent (fans off) tests, while Figure 2.3 shows results for the turbulent (fans on) environment. In these figures, an observation is classified as "no burn" if no appreciable pressure rise was detected (generally << 6 kPa). An observation is classified as a "marginal burn" if the measured overpressure was less than 10% of the Adiabatic Isochoric Complete Combustion (AICC) calculated overpressure for the same initial conditions, while those measuring more than 10% of the AICC overpressure are classified "burns". These figures indicate that any combustible hydrogen:air mixture is inerted in the FITS vessel with ~52% steam.

A correlation of this data was developed to describe the three-component flammability limit over the entire range of flammability [6]:

$$\%Steam = 100 - \%H_2 - 37.3\,exp(-0.007\%H_2) - 518.0\,exp(-0.488\%H_2) \qquad (2.1)$$

where %Steam is the volume percent of steam that will inert a hydrogen:air:steam mixture containing $\%H_2$ volume percent hydrogen and $(100-\%Steam-\%H_2)$ volume percent air.

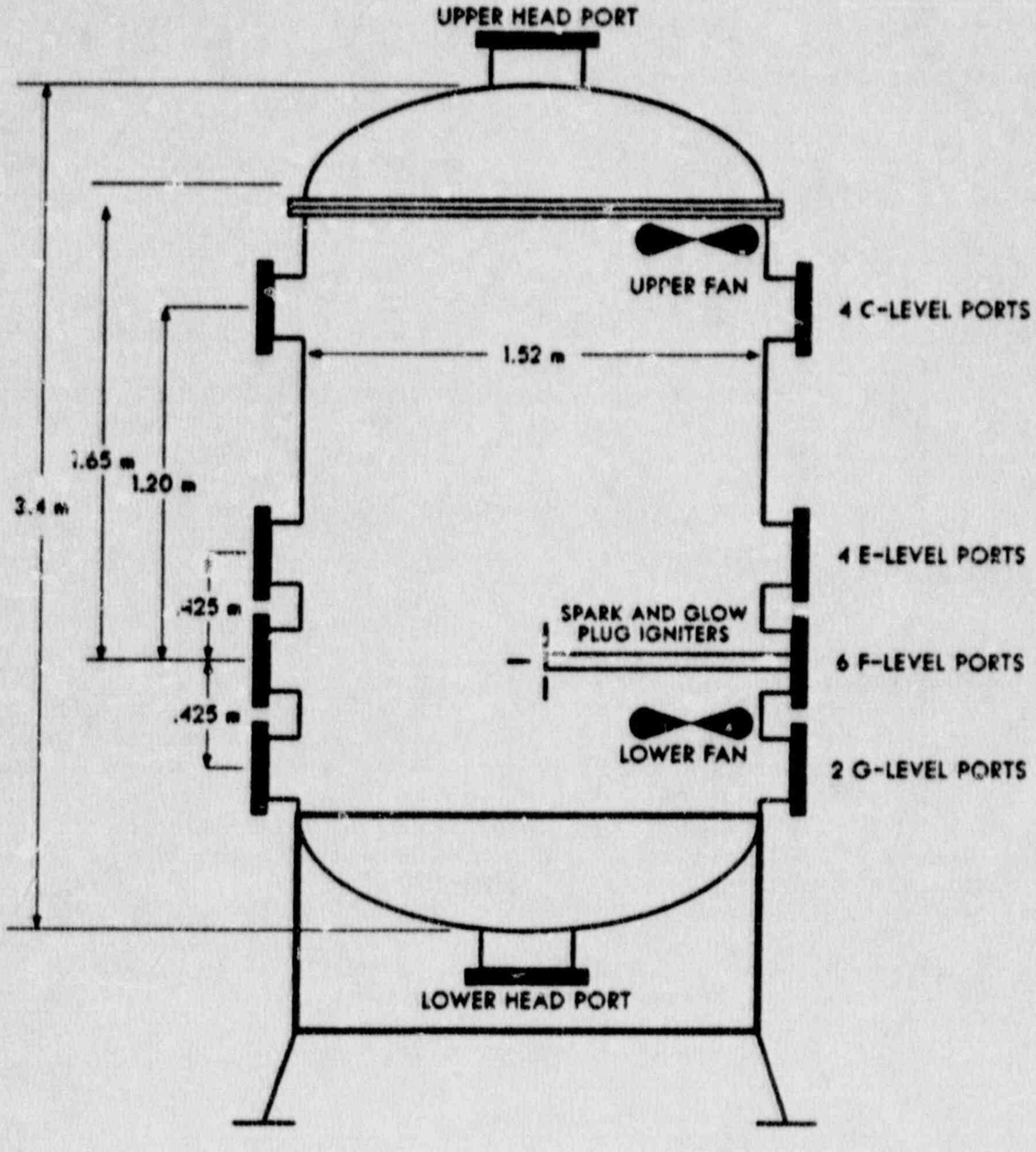


Figure 2.1 Schematic of the FITS vessel (taken from Reference 6).

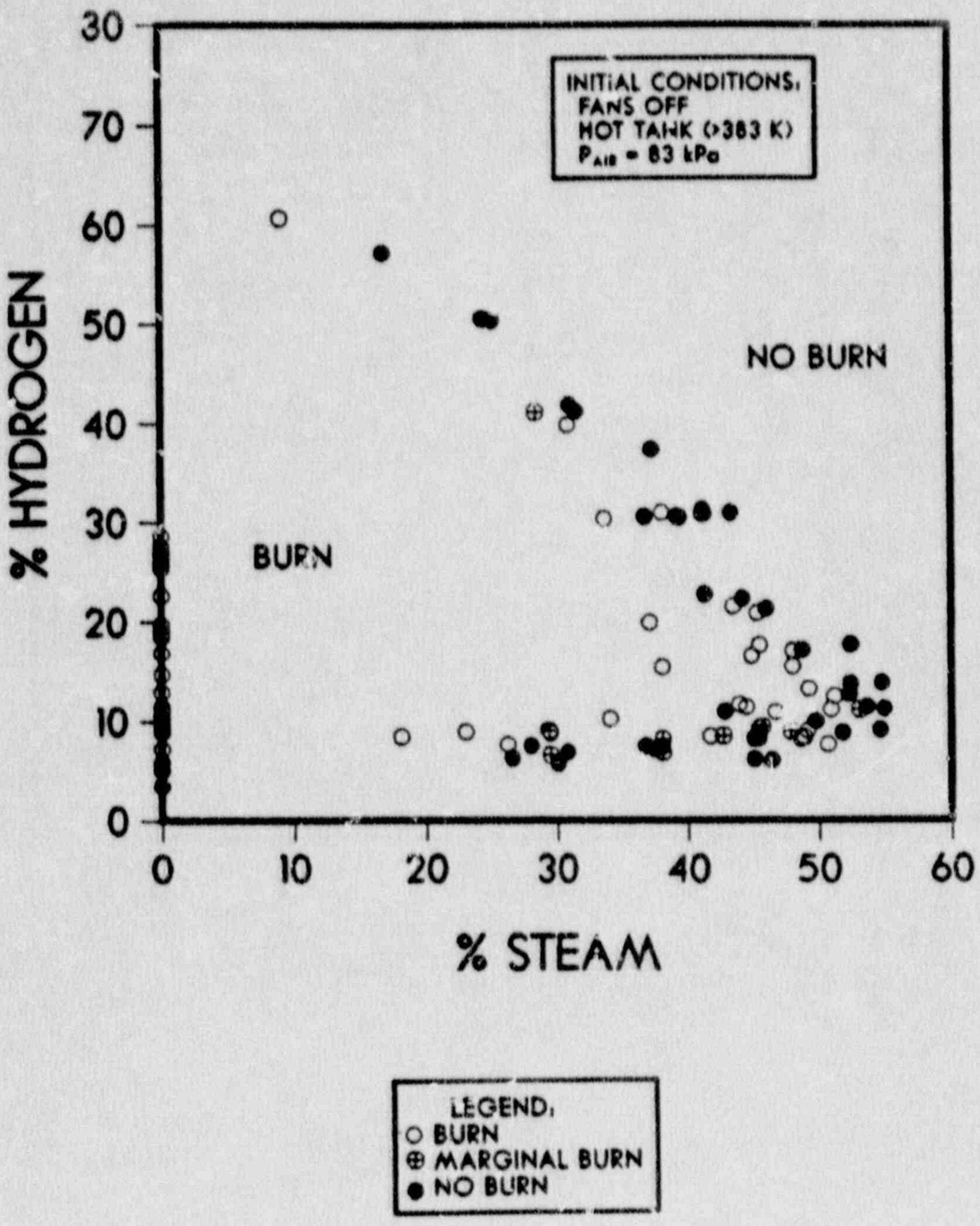
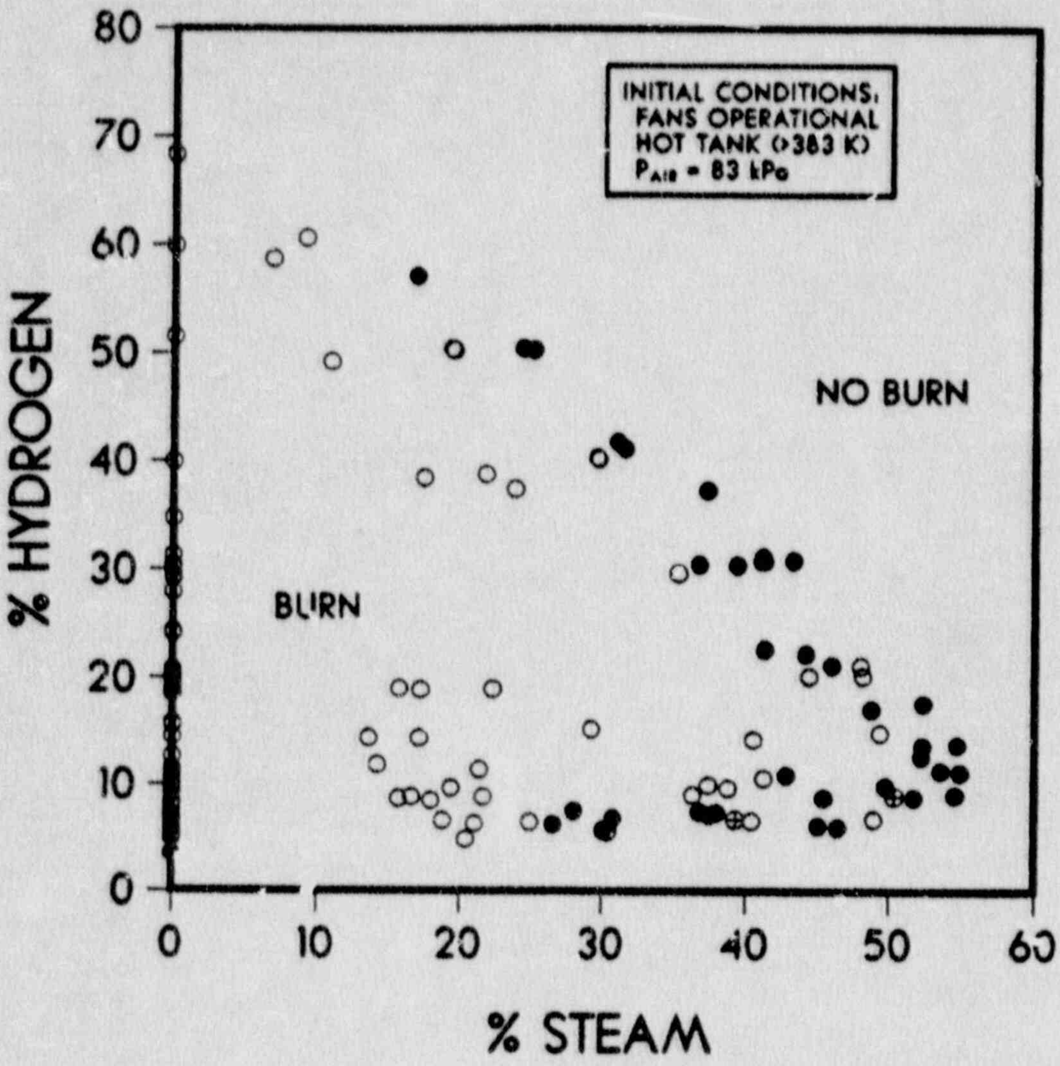


Figure 2.2 FITS hydrogen:air:steam flammability data with fans off (taken from Reference 6).



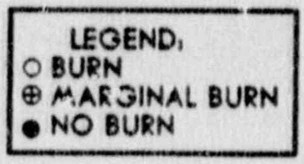


Figure 2.3 FITS hydrogen:air:steam flammability data with fans operational (taken from Reference 6).

2.3 Combustion Pressure Rises

The combustion peak pressure was measured for each of the hydrogen:air and hydrogen:air:steam burns. Figure 2.4 shows the normalized peak pressure (ratio of peak-to-initial pressure) as a function of the initial hydrogen concentration for both the quiescent and turbulent hydrogen:air burns in cold-wall and hot-wall tests. Figure 2.5 shows the same data for the hydrogen:air:steam burns as a function of hydrogen concentration in hydrogen:air only. Cold-wall burns are those hydrogen:air tests performed at ambient preignition temperature (~300 K), while hot-wall burns refer to those performed at elevated temperatures (~385 K)

The normalized peak combustion pressure was observed to increase with increasing hydrogen concentrations of up to ~30%, at which point it decreased with further increases in hydrogen concentration. The presence of steam tended to decrease the normalized peak pressure when compared to equivalent hydrogen:air burns (i.e., burns with equivalent hydrogen-to-air ratio). A comparison of the experimentally measured peak combustion pressure to the AICC calculated peak pressure indicated that relatively complete combustion (>95%) occurred for hydrogen concentrations greater than ~10%, while less complete combustion was observed for hydrogen concentrations approaching the lean flammability limit.

Figures 2.4 and 2.5 also demonstrate that turbulence increased the extent of combustion of the lean burns (where buoyancy governs flame propagation), while having less effect on the rich burns. The results show that burns initiated at ambient temperatures (cold-wall) resulted in more severe combustion environments than did burns at elevated temperature (hot-wall) with the same hydrogen-to-air ratio, since fewer moles of hydrogen and oxygen were available as the gas densities decreased.

2.4 Heat Transfer Characteristics

The experimentally measured pressure signatures were used to infer the global (spatially averaged) postcombustion heat transfer characteristics through use of the data reduction program SMOKE [7]. These results show that convection dominated the time-integrated heat transfer of the lean (<10%) hydrogen:air burns, while radiation was slightly more prevalent for the hydrogen:air burns near stoichiometry. Radiation was the dominant cooling mechanism for hydrogen:air:steam burns with moderate quantities of steam (<20% by volume), due to the increase in bulk gas emittance. For higher steam concentrations (>~30%), the total energy deposition to the vessel walls decreased slightly compared to equivalent hydrogen:air burns and radiation and convection were equally important mechanisms, due to the reduced combustion severity and lower post-combustion gas temperature. Figures 2.6 and 2.7 show the ratio of radiative to total postcombustion energy deposition for the hydrogen:air and hydrogen:air:steam burns, with the ratio for the hydrogen:air:steam burns again plotted as a function of the hydrogen concentration in hydrogen:air only.

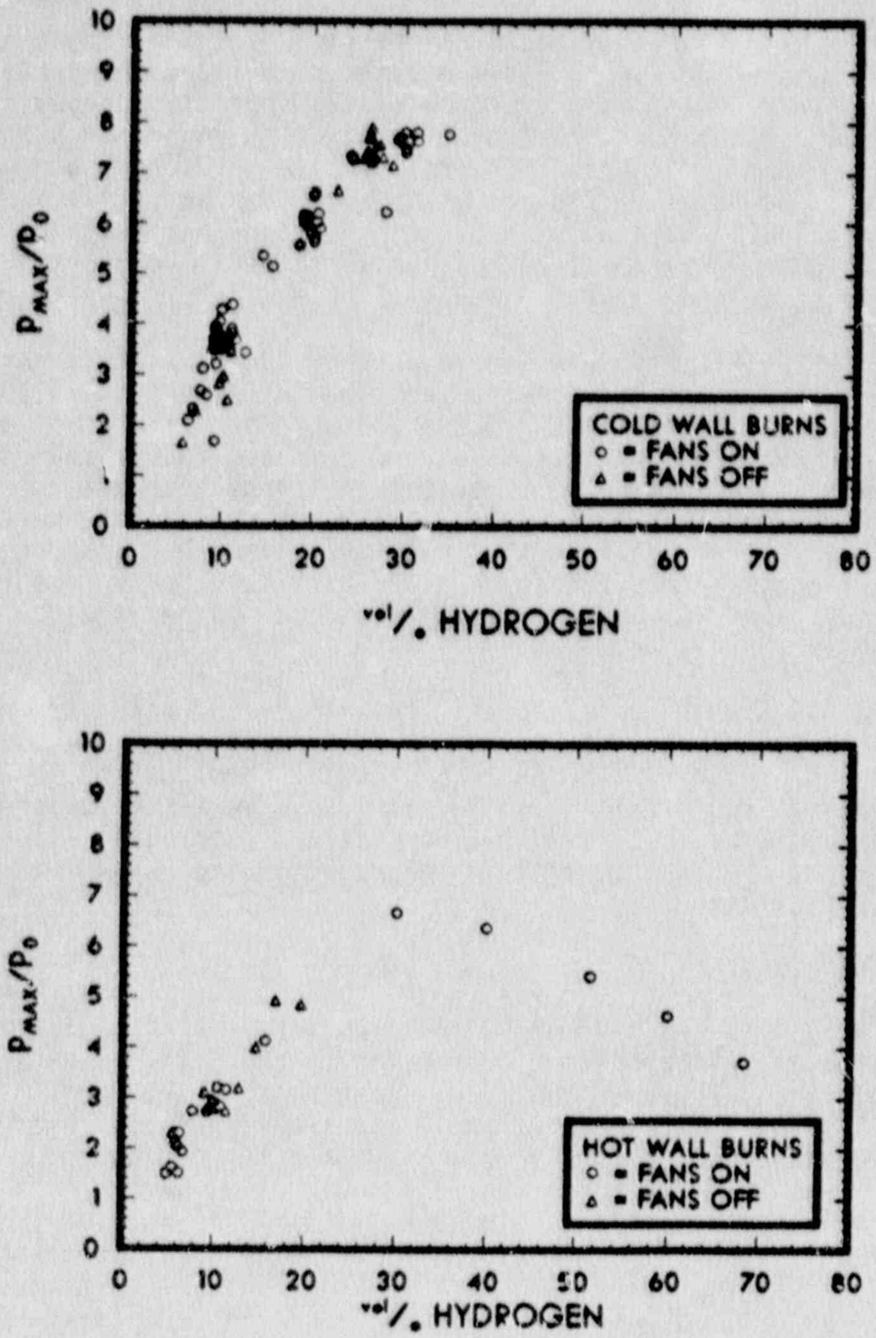


Figure 2.4 Normalized peak combustion pressure for the cold- and hot-wall hydrogen:air burns in the FITS vessel (taken from Reference 6).

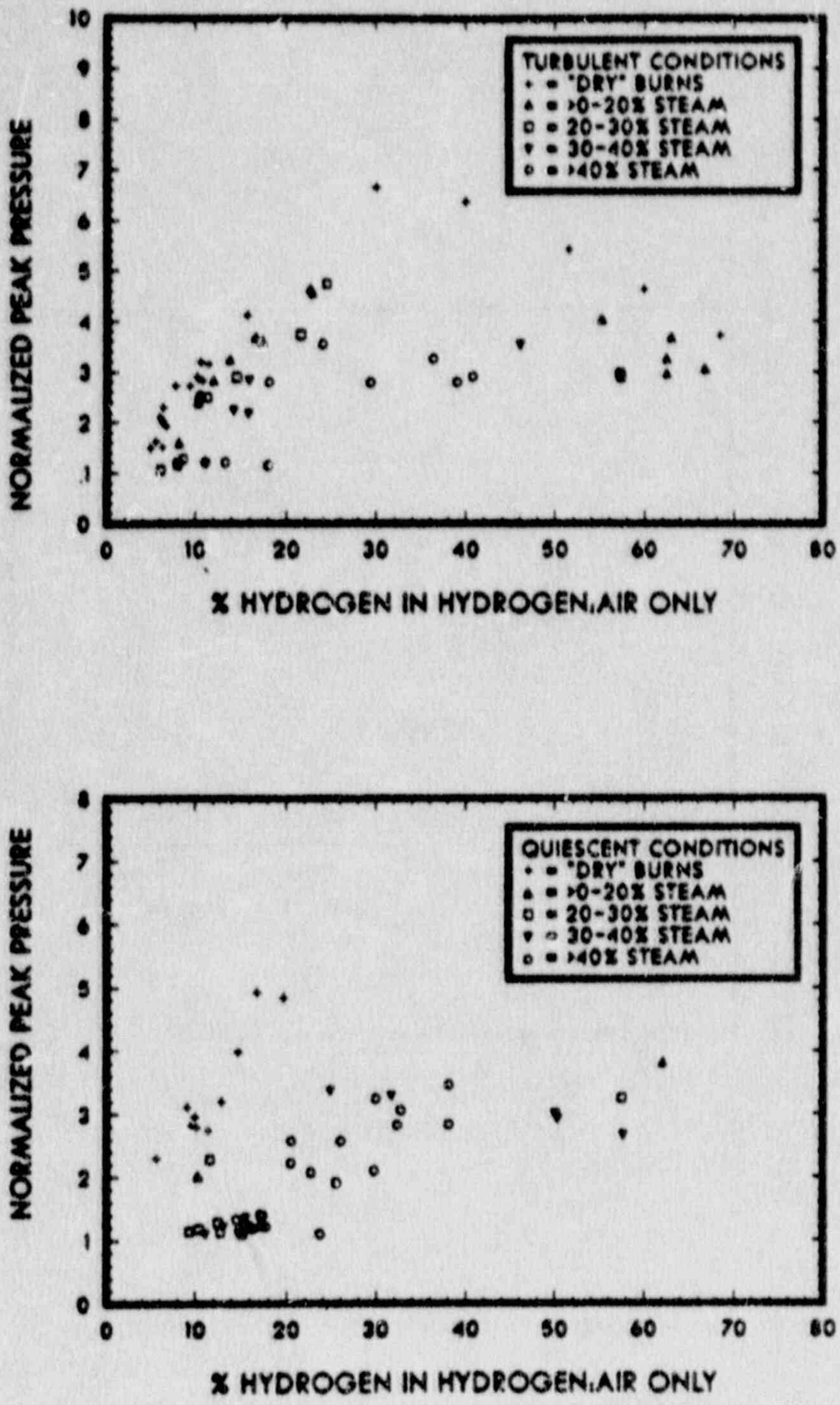


Figure 2.5 Normalized peak combustion pressure for the hydrogen:air:steam burns in the FITS vessel as a function of the hydrogen concentration in hydrogen:air only (taken from Reference 6).

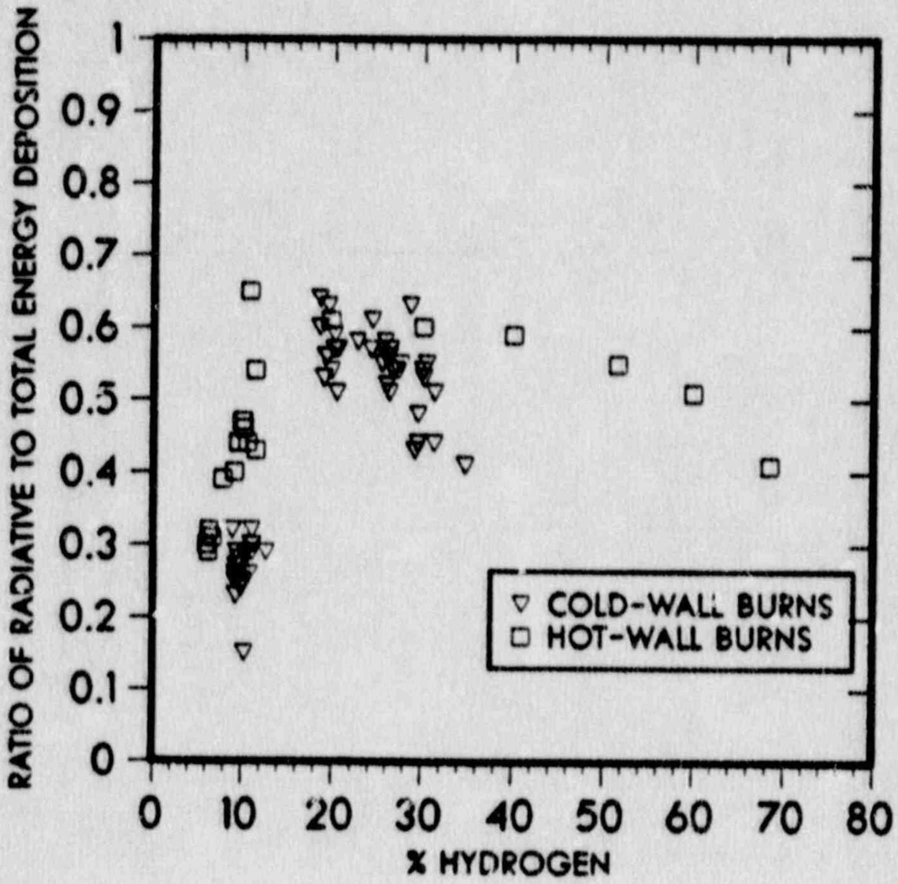
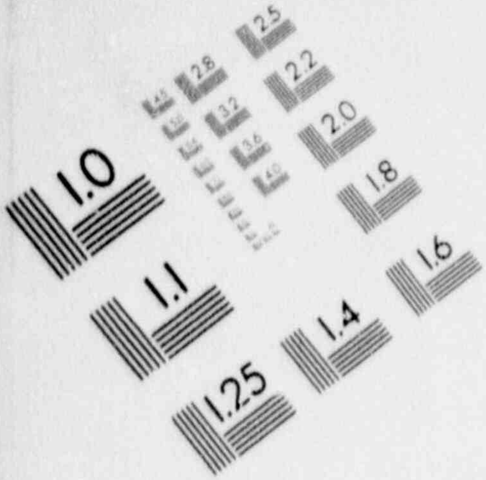
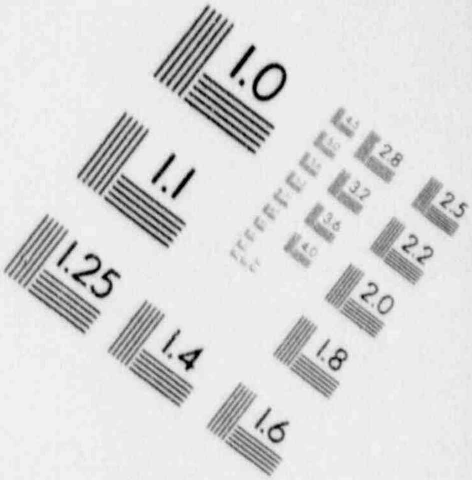


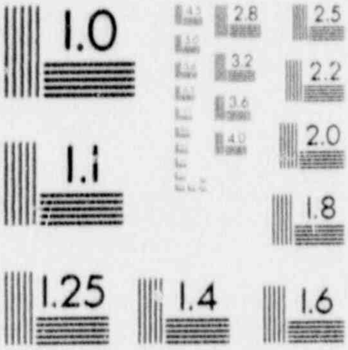
Figure 2.6 Ratio of the global radiative to total energy deposition for the hydrogen:air burns in the FITS vessel (taken from Reference 6).



1

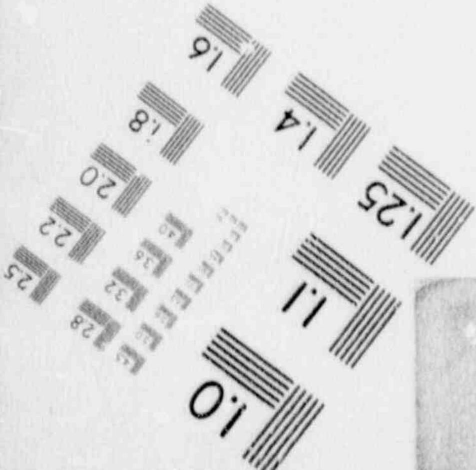
IMAGE EVALUATION
TEST TARGET (MT-3)

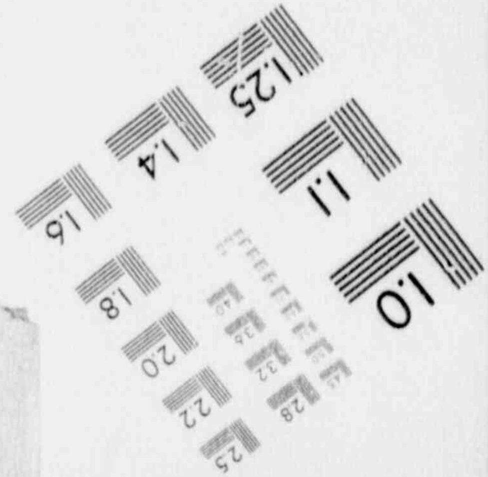




150mm

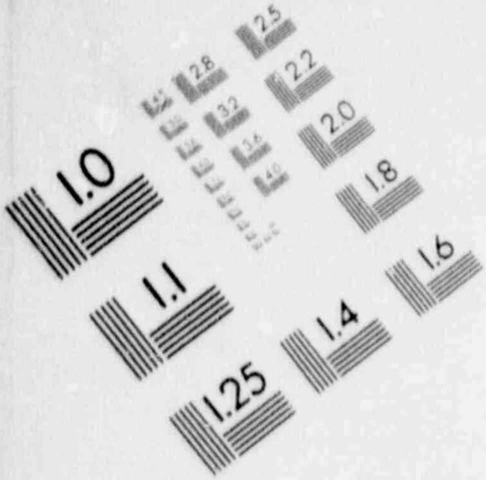
6″

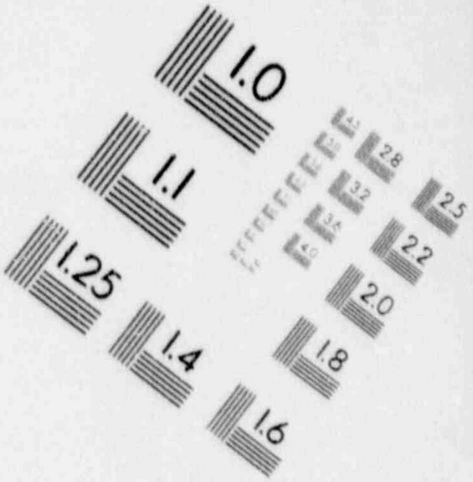


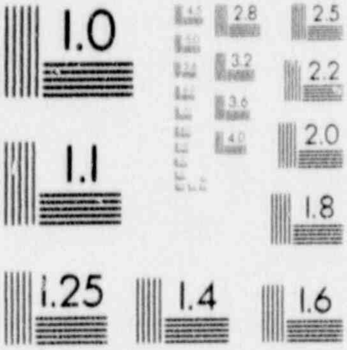


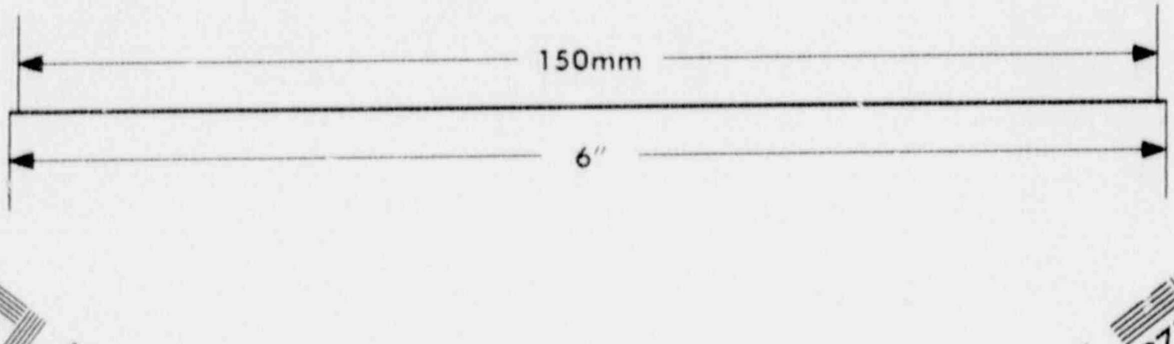
1

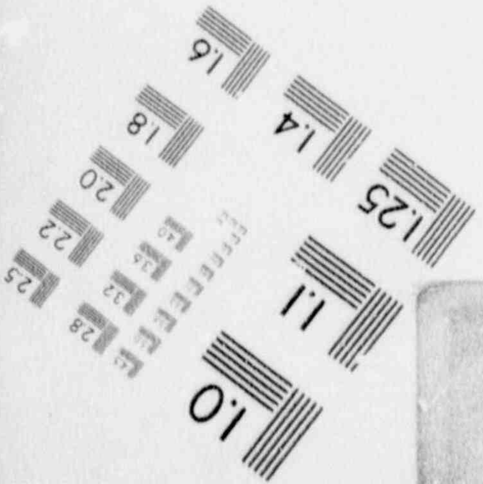
IMAGE EVALUATION
TEST TARGET (MT-3)

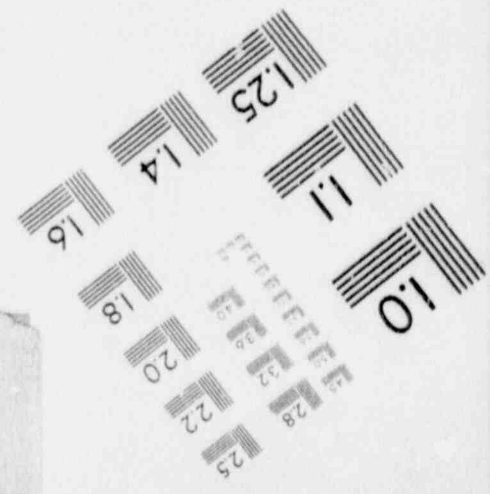






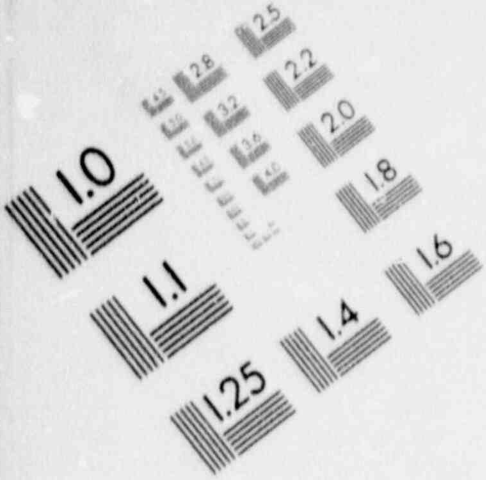


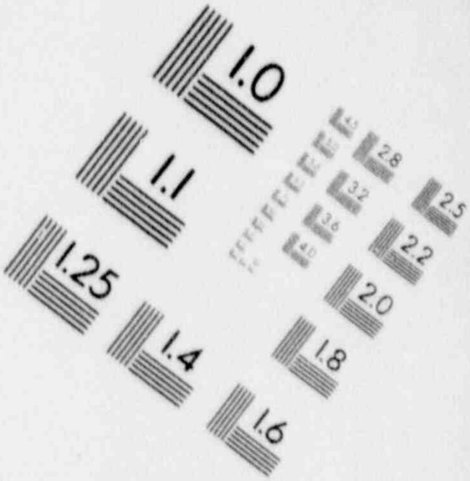


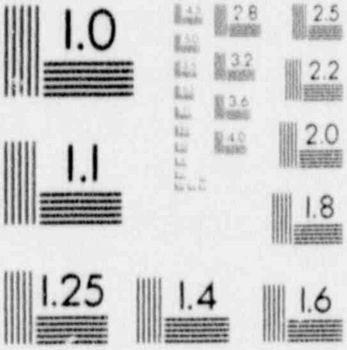


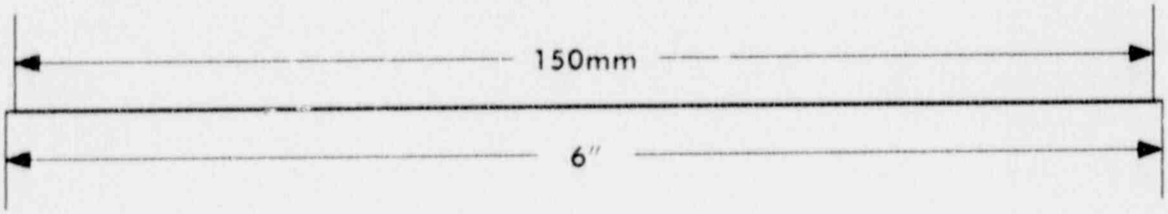
1

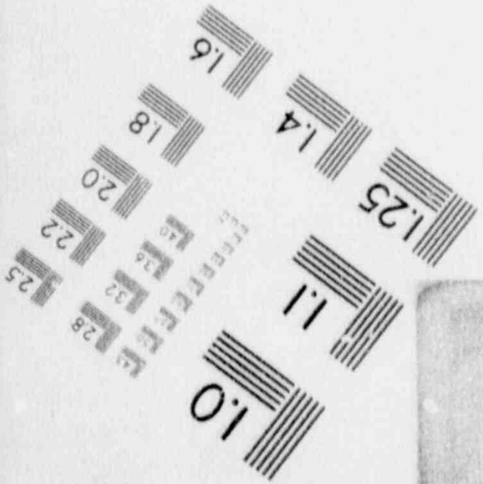
IMAGE EVALUATION
TEST TARGET (MT-3)

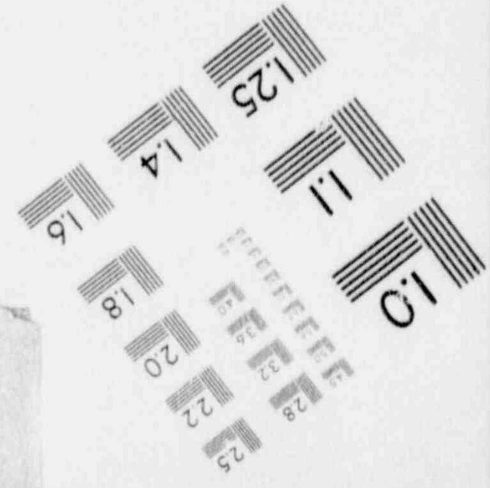






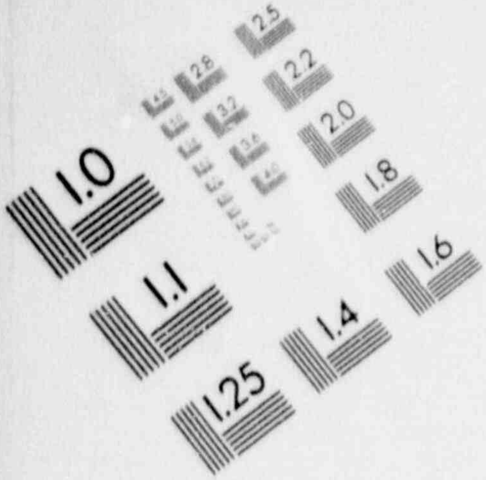


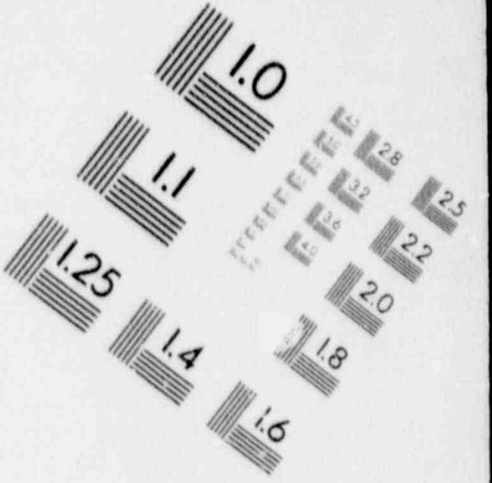


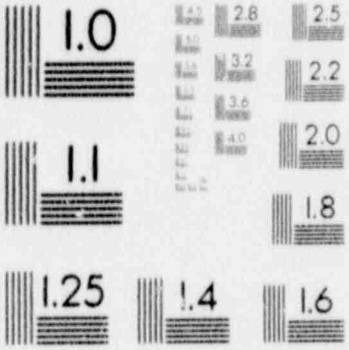


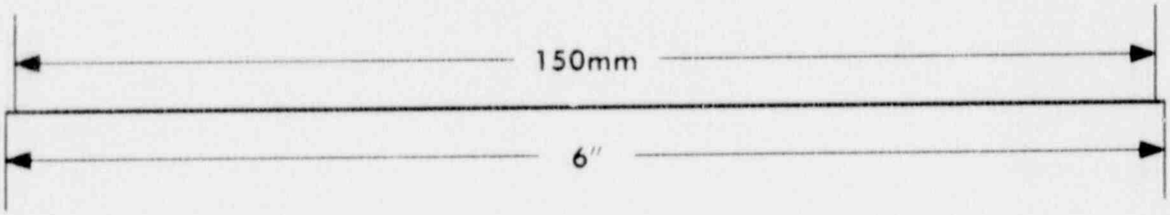
1

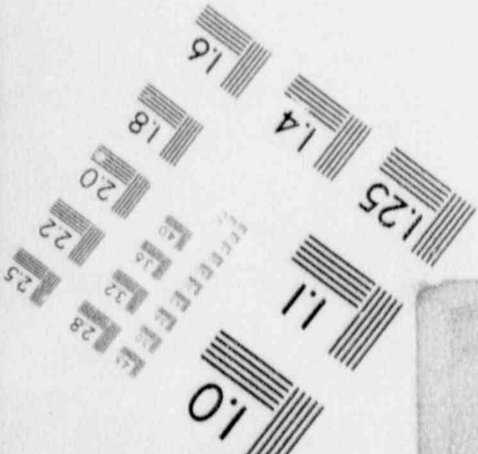
IMAGE EVALUATION
TEST TARGET (MT-3)

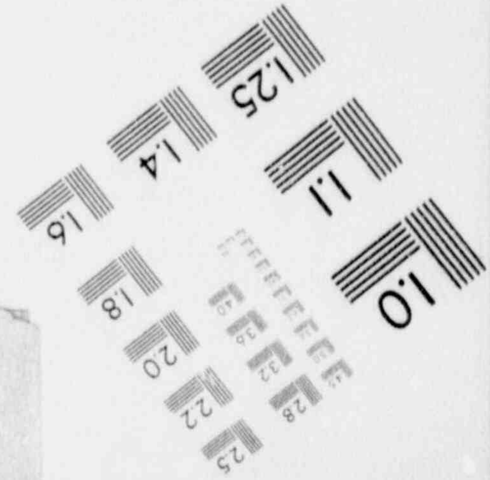












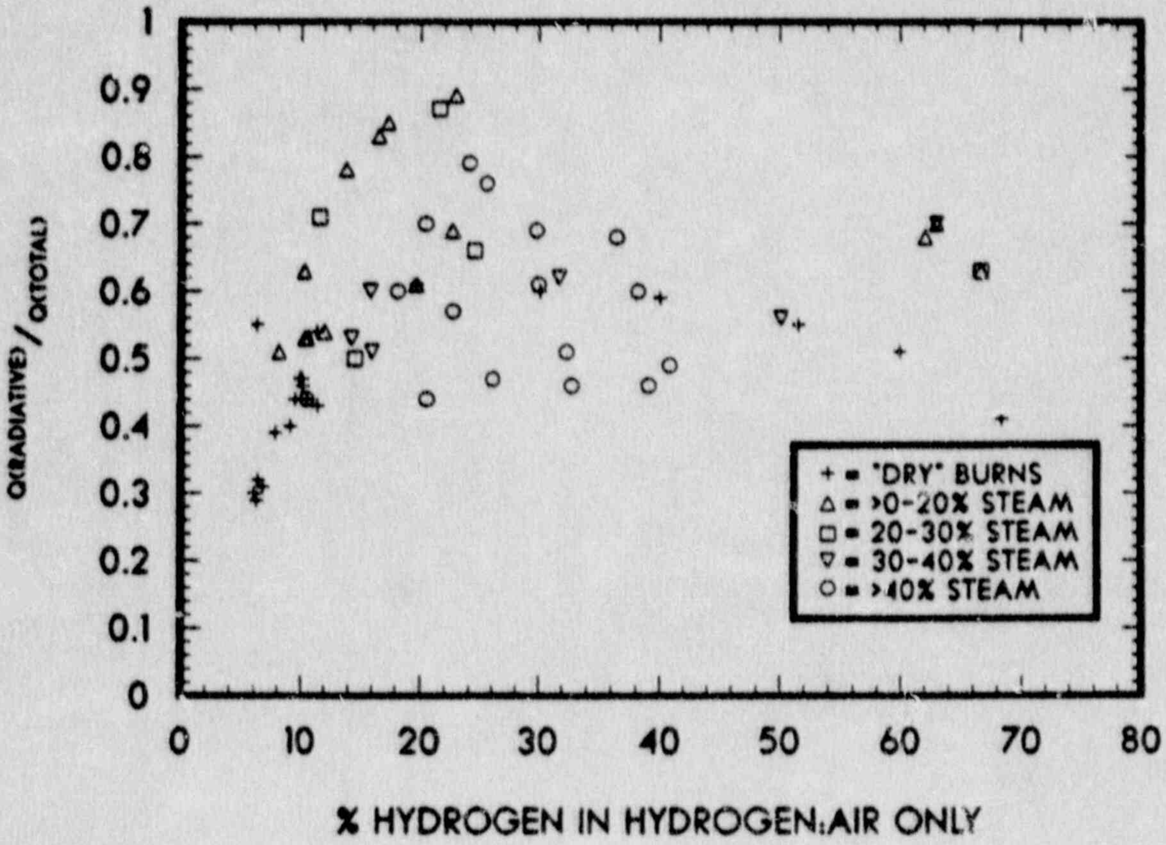


Figure 2.7 Ratio of the global radiative to total energy deposition for the hydrogen:air:steam burns in the FITS vessel as a function of the hydrogen concentration in hydrogen:air only (taken from Reference 6).

3. SNL VGES TESTS

The 5.1 m^3 Variable Geometry Experimental System (VGES) combustion chamber at Sandia National Laboratories was used extensively for studies of closed volume deflagrations in hydrogen:air mixtures in the absence of steam [8]. The NRC sponsored this experimental program in 1981 to examine the effects on hydrogen:air combustion of varying particular parameters:

- hydrogen concentration
- pre-combustion gas motion
- pre-combustion gas pressure
- igniter type
- igniter location
- concentration of additional diluent gas (N_2, CO_2)
- presence of an aqueous foam
- presence of water sprays

3.1 Facility Description

The VGES combustion chamber is a cylindrical tank 4.27 m (14 ft) in length and 1.22 m (4 ft) in diameter. The bottom end is buried in the ground with only the flanged top end exposed. The top is covered by a 0.61 m (2 ft) high removable dome. The first 11 test series and over 100 experiments utilized the VGES tank in the configuration shown in Figure 3.1. Later test series examining the effect of water sprays used the configuration shown in Figure 3.2.

The muffin-type fans in Figure 3.1 are used to mix the contents of the tank before and after hydrogen addition and also before postburn gas sampling. Figure 3.2 shows a muffin fan mounted at the same level as the igniter to produce a horizontal gas flow across the igniter. This flow is set up to simulate a containment environment, where airflows are caused by the entrainment of the containment atmosphere by downward falling drops during the operation of the water spray system.

Three types of igniters were used during the first series of VGES experiments—an exposed 300-W photoflood lamp filament, a standard GM AC 7G cylindrical glow plug, and a 30-J raised spark-gap consisting of two copper wires 2 mm (0.05 in) apart. During the water spray series, the GM AC 7G glow plug was studied along with a Tayco Model 193-3442-4 helical igniter.

3.2 Combustion Pressure Rises

Results of the dry tests show that peak combustion pressures increased rapidly with hydrogen concentration from 5% to 8%. The normalized peak pressure data (ratio of the peak-to-initial pressure) are plotted in Figure 3.3. Also shown are data for the adiabatic isochoric complete combustion calculation at ambient conditions. The figure shows that measured pressures were substantial fractions of the theoretical maximum pressures for hydrogen concentrations above 7%. The falloff of the data from the adiabatic values above 10% hydrogen was attributed to tests conducted with reduced air pressure or increased initial mixture temperature, which both cause slight reductions in peak

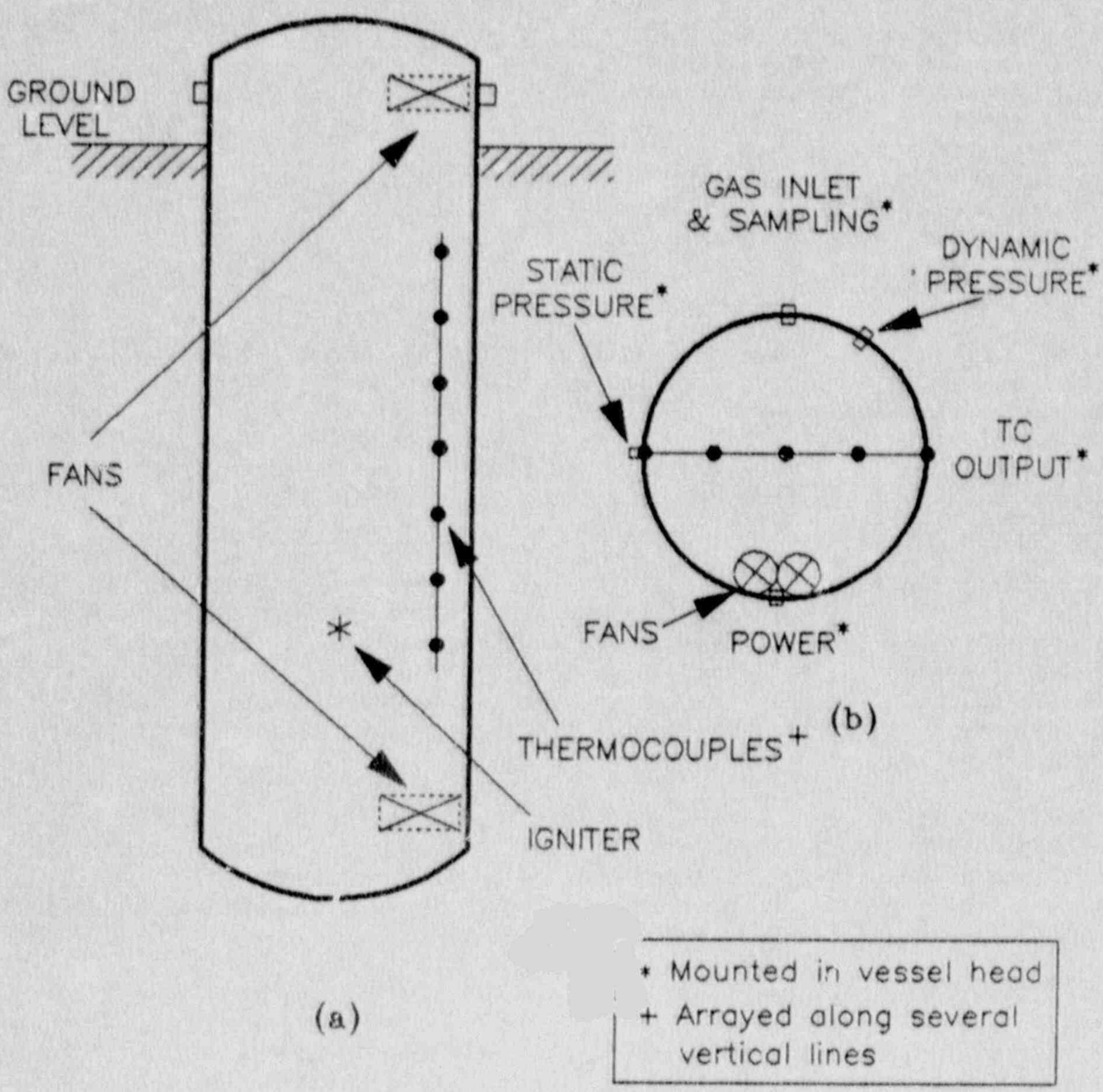


Figure 3.1 Schematic of the VGES chamber, (a) elevation view and (b) top view showing access ports.

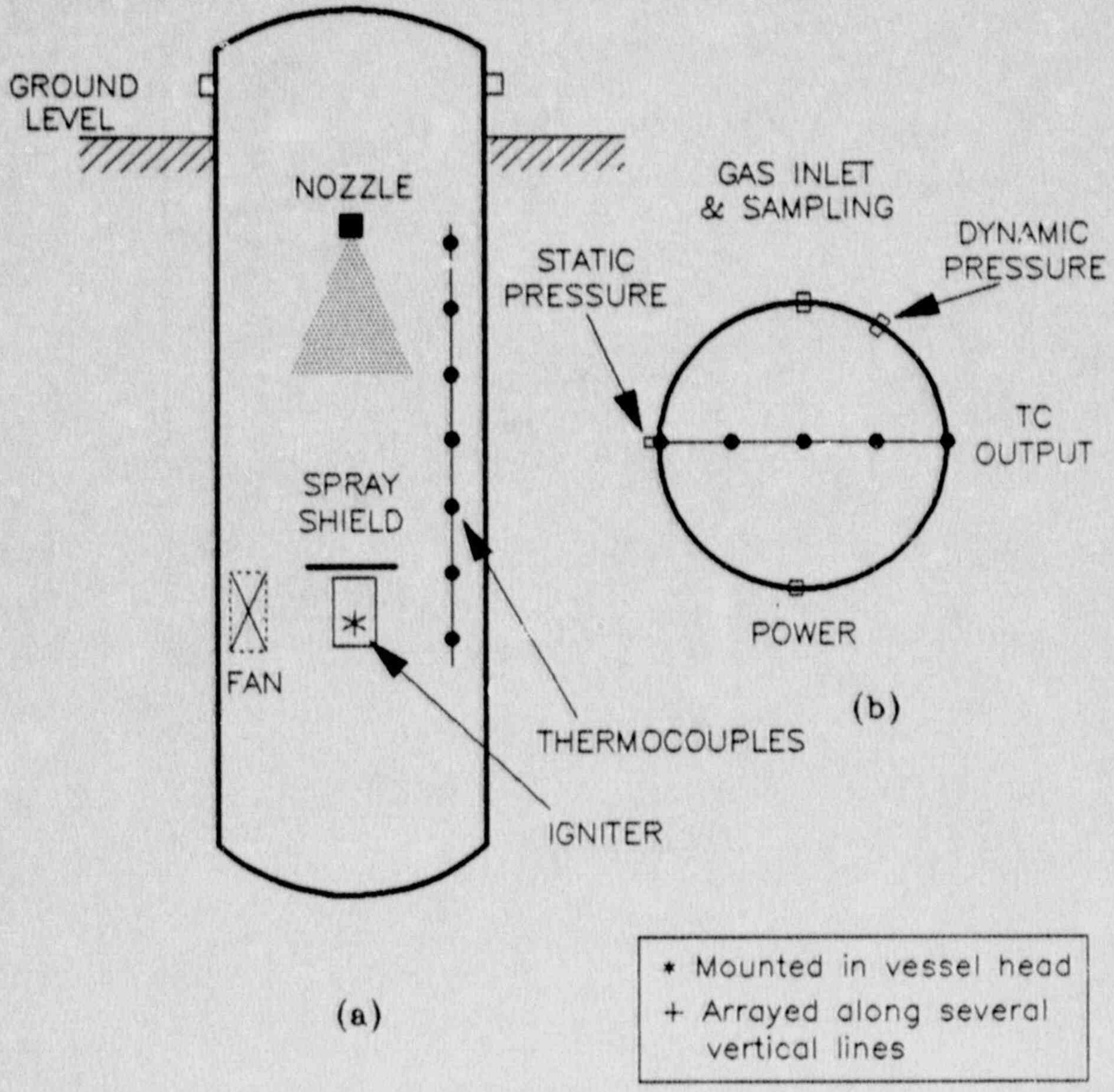


Figure 3.2 Schematic of the VGES chamber for water spray tests, (a) elevation view and (b) top view showing access ports.

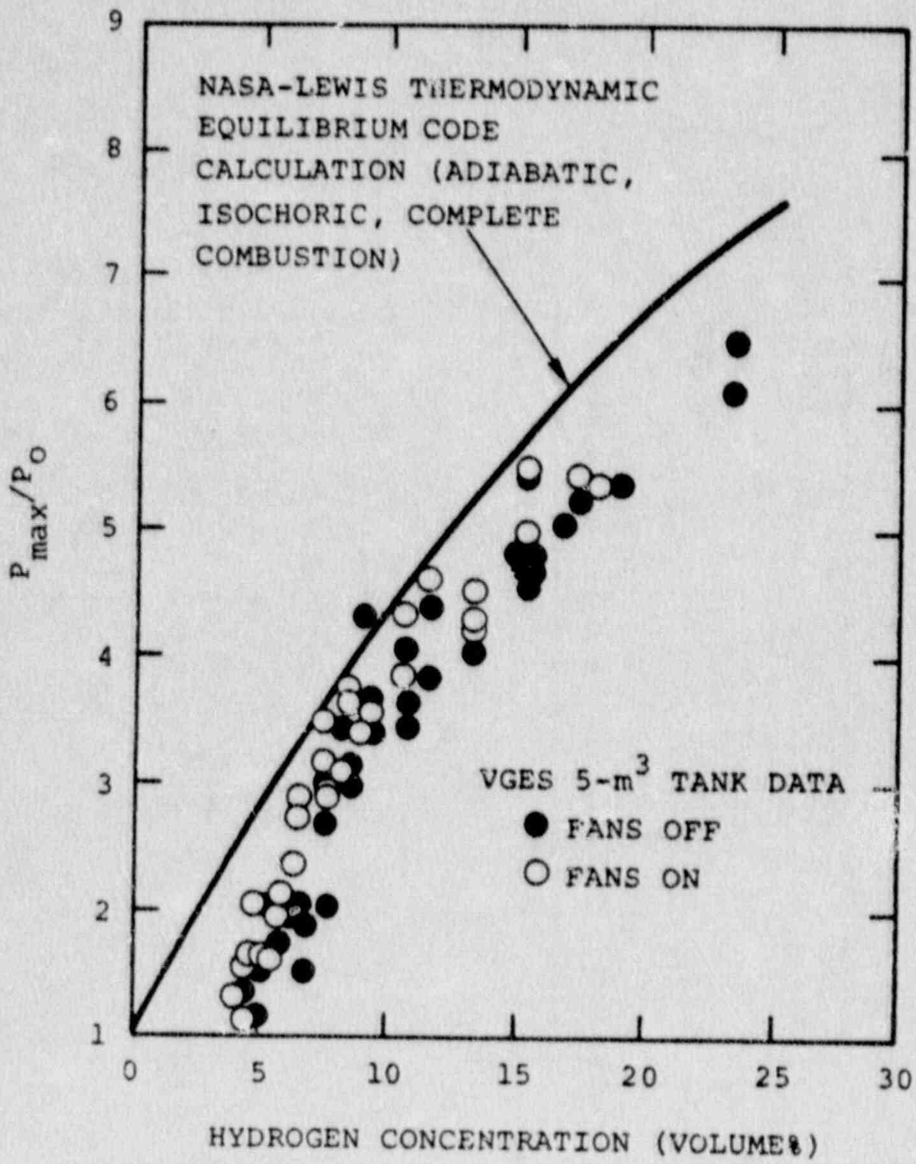


Figure 3.3 Normalized peak pressure for VGES hydrogen:air burns (taken from Reference 8).

pressure at lower hydrogen concentrations. The disparity is present because the adiabatic values were calculated assuming ambient pressure and temperature.

Pre-combustion gas motion was very important for hydrogen concentrations below 10%. In general, burns with the fans on produced higher peak pressures for hydrogen concentrations below ~8% due to an increase in combustion completeness and energy release rate. Reducing the pre-combustion gas pressure had the effect of slightly decreasing the normalized peak pressure and mean pressure derivative over the range tested. This is due to a reduction in the number of moles available for combustion and indicates a reduction in the chemical release rate and the completeness of combustion.

3.3 Effect of Igniter Type

Variations in igniter type were found to be unimportant. All three igniters used during the experiments proved reliable in igniting the hydrogen concentrations tested. Igniter location was important only for quiescent mixtures with less than 8% hydrogen. In these cases, the combustion completeness was lowered when the igniter was raised because the flame propagated only upward, leaving unburned hydrogen at the bottom of the vessel.

3.4 Flame Speeds

Flame speed values, obtained from thermocouple arrival-time data, are shown in Figures 3.4 and 3.5 for both upward and downward speeds. Higher flame speeds were attained in burns with the fans on, especially with hydrogen concentrations below ~10%. These figures also show that upward flame propagation is faster than downward propagation. Figure 3.6 shows the calculated mean pressure derivative ($\Delta P/\Delta t$) as a function of hydrogen concentration. This value increased with increasing hydrogen concentration and was larger for the "fans on" burns. The figure indicates that the chemical energy release rate did not tend to significantly increase in quiescent mixtures until hydrogen concentrations were above ~8%, while the release rate for the "fans on" burns tended to increase for hydrogen concentrations above ~6%.

3.5 Effect of Diluent Gases

Tests conducted with extra nitrogen added to hydrogen:air mixtures at ambient temperature indicated no significant differences in the burn characteristics when compared to tests performed with similar hydrogen:air molar ratios (after N_2 addition). The addition of nitrogen does, however, dilute the fraction of hydrogen in the mixture and produce burns indicative of the actual hydrogen concentration. The peak combustion pressure is reduced with the addition of nitrogen when compared to hydrogen:air mixtures with the equivalent hydrogen:air molar ratio, and a mixture can be inerted if enough nitrogen is added.

The addition of CO_2 had the same effect as N_2 on hydrogen:air combustion in reducing the peak pressure, burn velocity, and pressure derivative. The increased heat capacity of CO_2, however, made it more effective in reducing

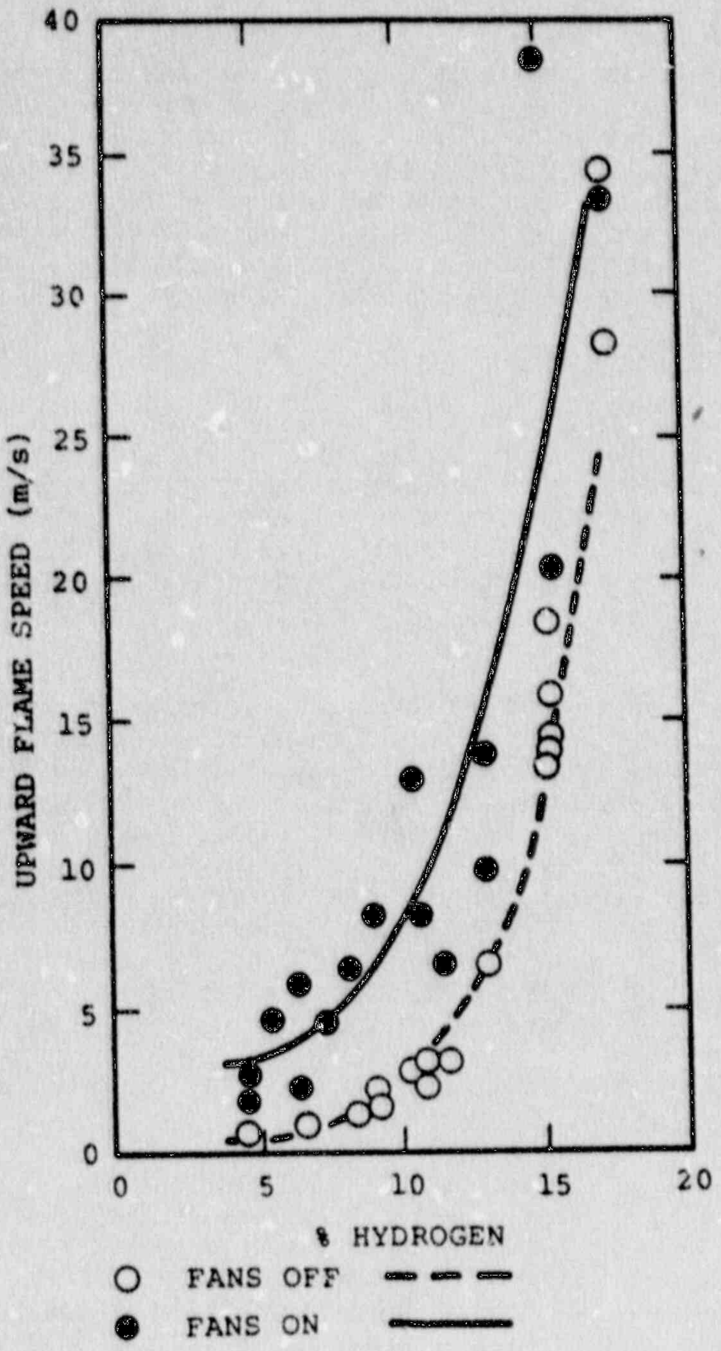


Figure 3.4 Upward flame speed values in VGES chamber (taken from Reference 8).

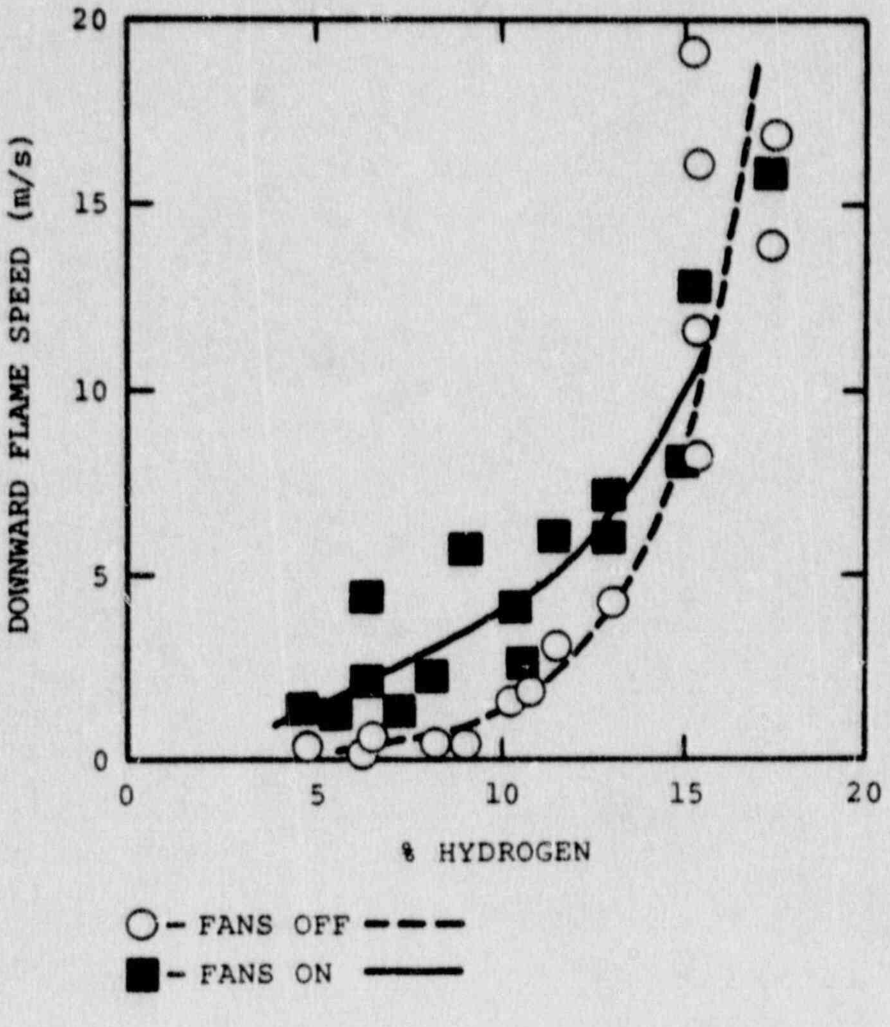


Figure 3.5 Downward flame speed values in VGES chamber (taken from Reference 8).

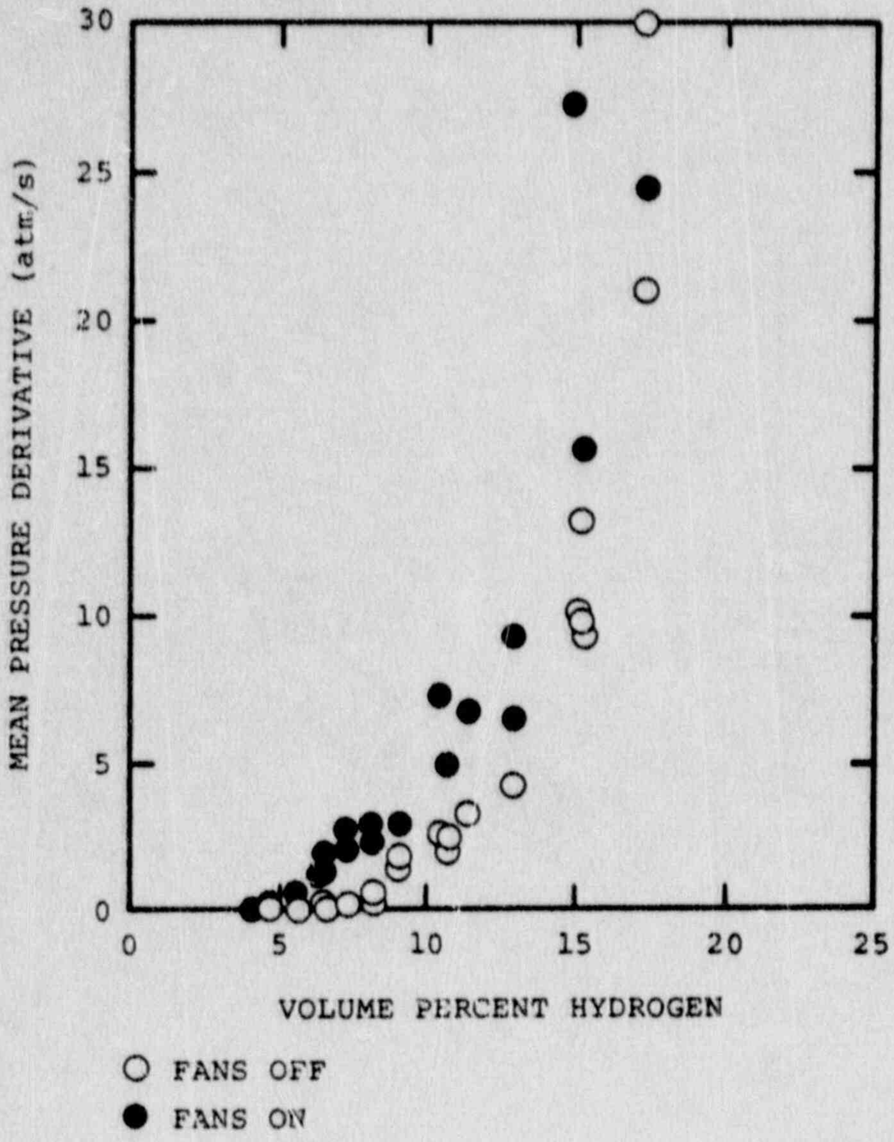


Figure 3.6 Mean pressure derivative (ΔP/Δt) for VGES tests (taken from Reference 8).

peak combustion pressure compared to N_2. Results of these tests tend to indicate that ~54% CO_2 will inert a hydrogen:air mixture. Comparisons of combustion with hydrogen:air:CO_2 mixtures and similar hydrogen:air:steam mixtures from FITS [6] and Whiteshell [15,16] tests tend to indicate that CO_2 and steam have comparable combustion mitigation effects.

3.6 Effect of Aqueous Foams

A series of VGES tests studied the effects of hydrogen combustion in aqueous foam. For hydrogen:air mixtures with less than ~15% hydrogen, filling the tank with 620:1-expansion foam caused marked reductions in the peak combustion pressures and temperatures. The pressure rise times were similar between tests with and without foam at the same hydrogen concentrations. However, with higher hydrogen concentrations (>15%), the pressure rise time was greatly reduced in tests with foam (~9 ms) compared to tests without foam (~70 ms). The pressure waves and flow generated by the accelerated flames in the foam tests caused severe damage to the foam generator and fan, even though no appreciable difference in peak pressure was observed compared to the no-foam tests.

3.7 Effect of Water Sprays

Another series of VGES experiments studied the ability of helical (Tayco) and cylindrical (GM) igniters to ignite lean hydrogen:air mixtures and to operate at elevated temperatures when subjected to water spray fluxes and/or gas flows that simulate the conditions in containment during the operation of the water spray system. The initial experiments were performed with a water spray equivalent to that anticipated in the upper compartment of a PWR ice condenser containment (37.3 $L/m^2 \cdot min$ (0.915 $gal/ft^2 \cdot min$)). It was found that the helical igniter would ignite a lean, 6.5% hydrogen:air mixture at a surface temperature of 575°C (1066°F), while the cylindrical igniter needed a surface temperature of 721°C (1330°F) to ignite the same mixture.

This test series showed that when either igniter was exposed to unshielded water spray, there was a threshold spray flux ($L/m^2 \cdot min$) above which it would not operate properly at elevated temperature. This threshold flux was substantially lower for cases where the igniter was cold when first exposed to the spray than for cases where the igniter was hot when it was first exposed. The cold igniter cases refer to tests performed with the igniter and the water spray solenoid energized simultaneously. The hot cases are those in which the igniter was turned on and allowed to heat up for at least 100 s before the water spray system was activated. This allowed the surface of the igniter to reach its plateau temperature by the time the solenoid valve was actuated. Heat transfer on the igniter surface is reduced since the surface is above the film boiling temperature, and the igniter is allowed to remain hot at a higher spray flux than for the cold cases. The threshold spray flux in both hot and cold cases was also sensitive to both the igniter geometry and operating voltage. For fluxes below the threshold, the surface temperature of the helical igniter was normally more strongly affected by impinging water sprays than was the cylindrical igniter.

Horizontal gas flows without sprays at velocities between 10 and 20 m/s cooled both igniter types to temperatures below which they would satisfactorily ignite lean (6%) hydrogen:air mixtures. Table 3.1 summarizes the spray flux and airflow threshold values for both igniters. Measurements showed that the tip of the cylindrical igniter was cooled less strongly by the airflows than were its side walls. When exposed to water spray fluxes and airflows simultaneously, the surface temperature of the helical igniter was highly sensitive to both, while the surface temperature of the cylindrical igniter was determined primarily by airflows.

A horizontal sheet metal spray shield placed above either igniter protected it against cooling by water spray fluxes equivalent to that expected in a PWR ice condenser containment, and insures satisfactory igniter operation for horizontal airflows up to 5.6 m/s.

Table 3.1 Igniter Threshold Values for VGES Tests

	Helical Igniter (120 Vac)	Cylindrical Igniter (14 Vac)	
Surface temperature required for ignition	575°C	721°C	
Threshold spray flux — cold igniter	~16 L/m^2·min	~39 L/m^2·min	
Threshold spray flux — hot igniter	~24 L/m^2·min	>~53 L/m^2·min*	
Threshold air flow (at 0.083 MPa)	~12 m/s	~13 m/s ~7 m/s (@12 Vac)	Wall
		~20 m/s ~10 m/s (@12 Vac)	Tip

* The highest spray flux tested was ~53 L/m^2·min.

4. NTS TESTS

A series of tests to investigate hydrogen combustion in a large-scale vessel was conducted by EG&G at the Nevada Test Site (NTS) in 1983. These tests, funded jointly by the Electric Power Research Institute (EPRI) and the Nuclear Regulatory Commission (NRC), studied hydrogen mixing and ignition processes as well as survivability of safety-related equipment in postulated degraded-core accident hydrogen burn environments. Both premixed and continuous injection combustion tests were performed with mixtures of hydrogen, air and steam.

4.1 Facility Description

The NTS tests were performed in a 15.85 m diameter, 2048 m^3 spherical vessel (hydrogen dewar), shown schematically with support systems in Figure 4.1. The test series consisted of forty separate experiments in two general classes. Twenty-four of the experiments were premixed hydrogen:air:steam combustion tests, with hydrogen concentrations ranging from 5 to 13% by volume and steam concentrations from 4 to 40% [9,10,11]. The second class of tests involved the continuous injection of hydrogen into air:steam mixtures to study the effects of diffusion flames [9,10,12]. Ignition was initiated by GM AC 7G glow plug igniters located in various places throughout the volume to investigate variations in igniter location. Several of the premixed and continuous injection tests also evaluated the effect of spray systems and fans on combustion rate and post-combustion gas cooling.

4.2 Combustion Completeness

Figure 4.2 shows the combustion completeness for the premixed tests as a function of initial hydrogen concentration. It shows a direct relationship between the initial concentration of hydrogen and the fraction of hydrogen burned. Deviations from the trend were primarily the result of variations in igniter location, with combustion completeness lower for tests with igniters positioned in the center and top of the vessel, where downward flame propagation is limited. Variations in steam content and the presence of sprays tended to have a lesser effect on the combustion completeness. The figure demonstrates that complete combustion occurred in the NTS vessel for nearly all burns with initial hydrogen concentrations greater than 7-8%, and the glow plug could effectively ignite lean hydrogen mixtures as low as 5.2% (provided steam concentrations were low).

4.3 Combustion Pressure Rise

Gas pressure profiles were obtained for each of the NTS tests. Figure 4.3 shows the normalized peak pressure (ratio of peak-to-initial pressure) for each of the pre-mixed burns. In the range tested, the normalized peak pressure increased with increasing hydrogen concentration, with the values for tests with steam (>10%) generally lower than those for the "standard" tests (~5% steam) at equivalent hydrogen concentrations (i.e., burns with equivalent hydrogen-to-air ratio). Steam acted as a heat sink and an inert diluent in the combustion mixture, which tended to lessen the peak gas temperatures and pressure excursions. Fans and sprays were effective in increasing the

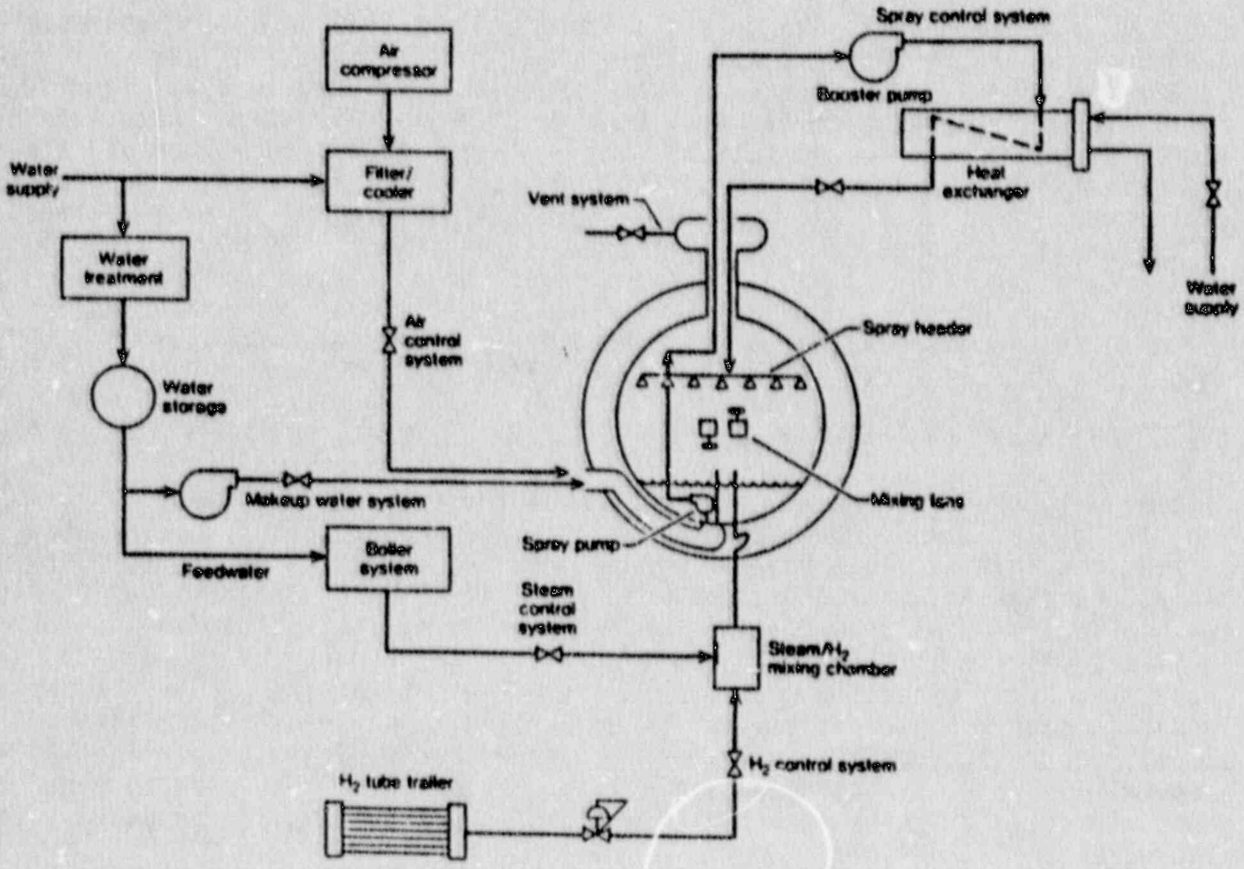


Figure 4.1 Schematic of Nevada Test Site facility (taken from Reference 12).

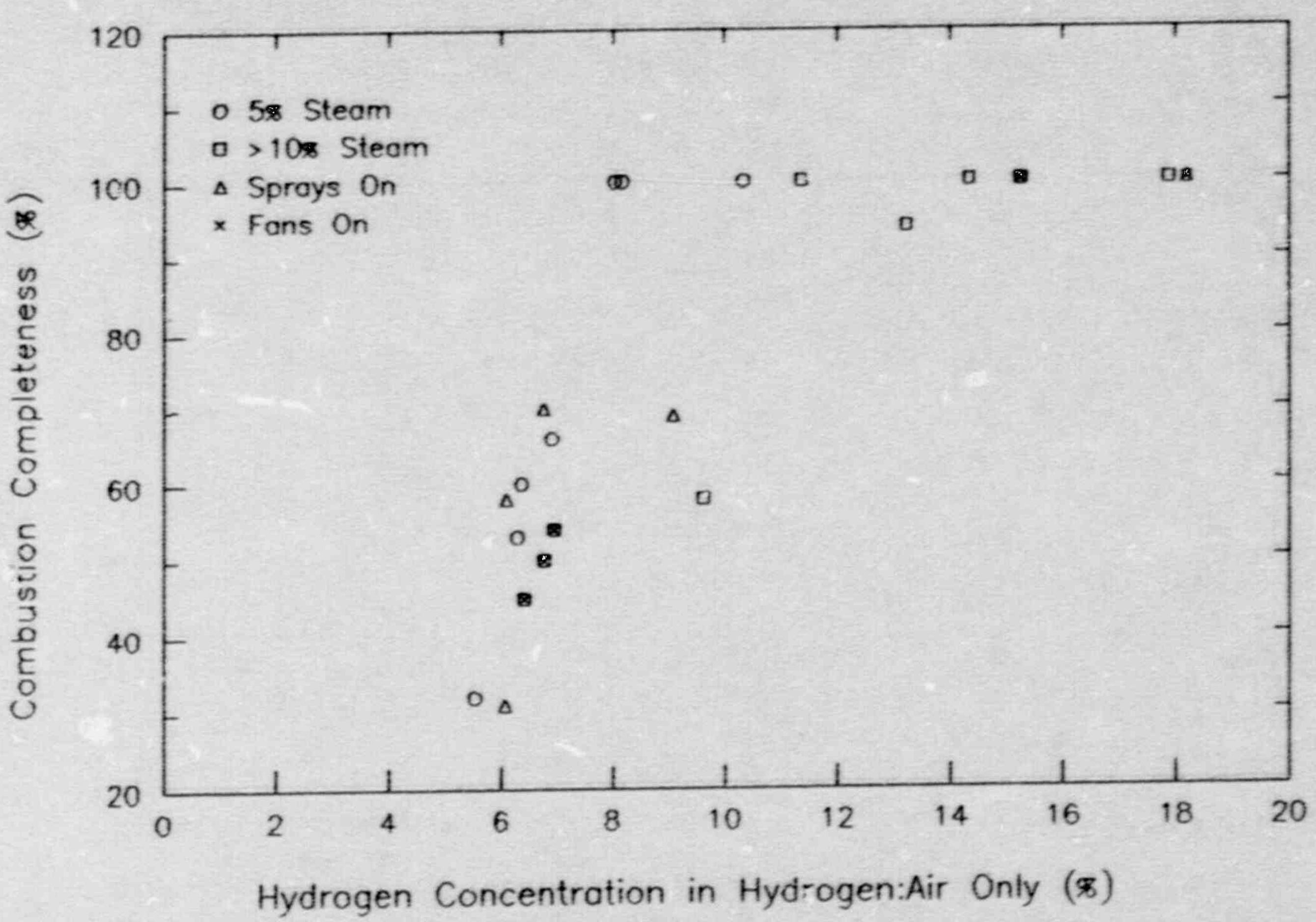


Figure 4.2 Combustion completeness for NTS premixed combustion tests.

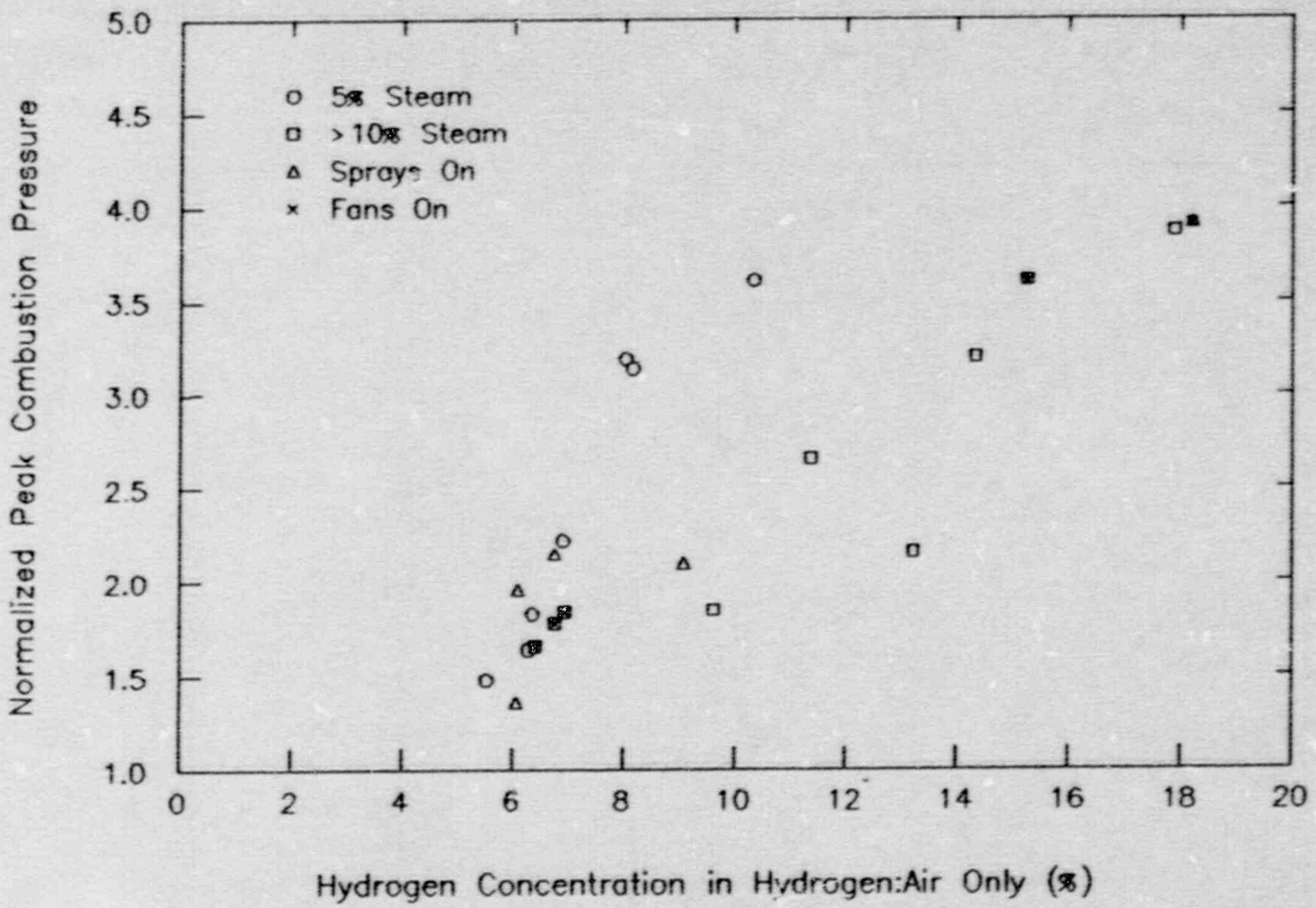


Figure 4.3 Normalized peak pressure for NTS premixed combustion tests.

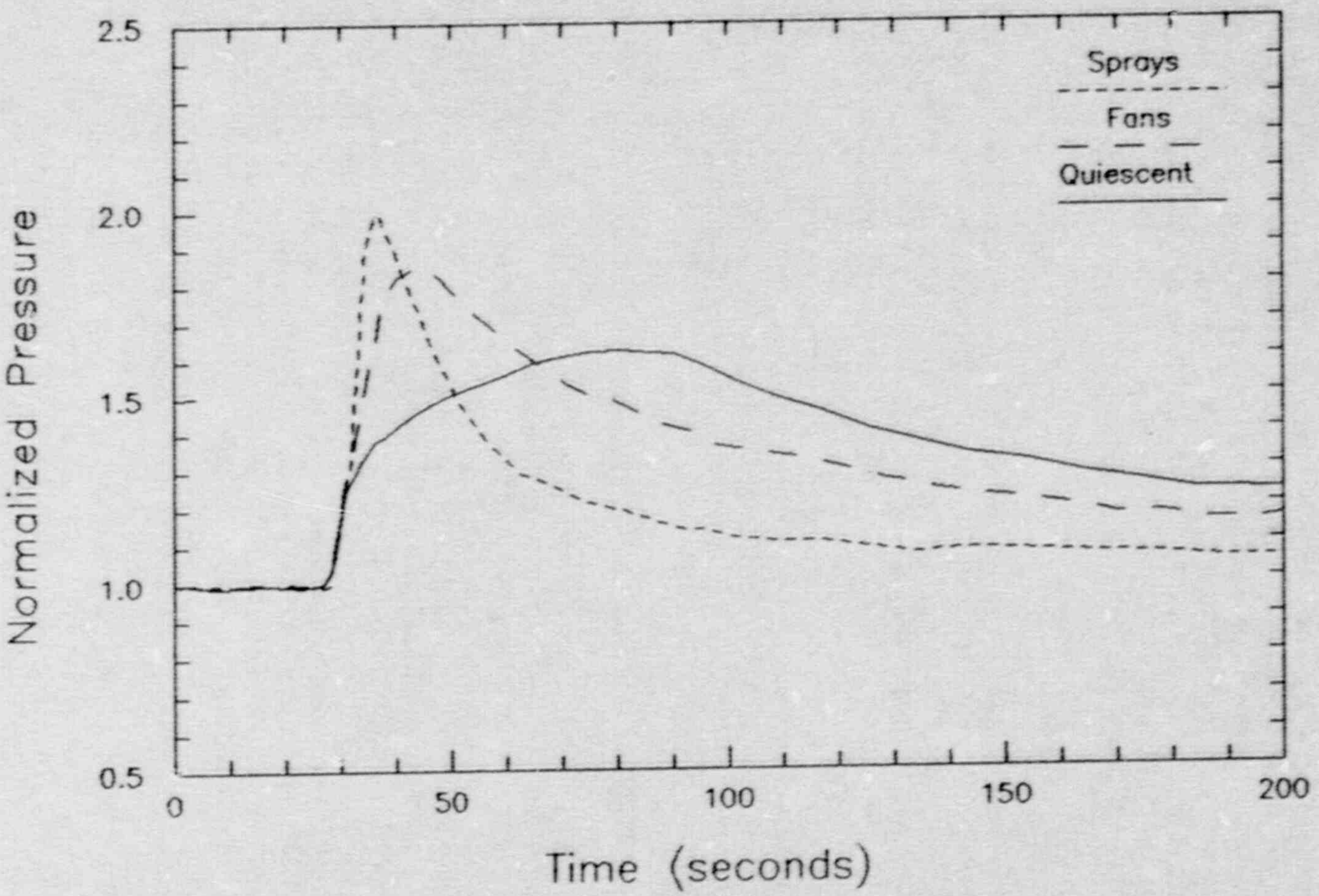


Figure 4.4 Gas pressure profiles for three NTS premixed tests comparing the effect of sprays and fans.

turbulence and enhancing the rate of combustion for lean mixtures of hydrogen. Figure 4.4 compares pressure profiles from three 6% hydrogen combustion tests. As the figure shows, sprays were found to promote more turbulence and more rapid combustion than were fans. The same trend was observed in the continuous injection tests, as Figure 4.5 demonstrates. In this figure, the pressure profiles from three tests with nearly identical source parameters are presented. These tests were conducted with a 1 m diameter diffuser source and nominal flowrates of 1.8 kg/min hydrogen and 27 kg/min steam. The figure shows that fans significantly reduce the peak gas pressure and temperature due to an increase in the heat transfer coefficient, but that sprays are clearly the most effective in enhancing the heat transfer.

4.4 Effect of Igniter Location

The NTS tests demonstrated the advantage of having more than a single igniter to initiate combustion. Igniter location was important in the combustion of lean (<~8%) hydrogen mixtures, since downward flame propagation is limited in these cases. In two premixed quiescent cases where there was a single igniter at the top of the vessel, local burning was observed around the igniter, but the flame was quenched before it could propagate downward to initiate a global vessel burn. Other cases demonstrated that igniters distributed throughout the vessel, as they would be in reactor containments, could effectively ignite combustible mixtures of hydrogen. Ignition occurred when the local concentration around the igniter reached the lean flammability limit for that mixture.

4.5 Burn Characteristics in Continuous Injection Tests

The ignition behavior observed most frequently in the continuous injection tests was slow ignition and diffusion flame burning, as opposed to fast ignition (deflagration) which occurred in the premixed tests. The ignition behavior was determined by both the fluid motion induced by the hydrogen-steam source and the location of the igniters. For slow ignition, the gas pressure and temperature rises within the vessel were produced entirely by diffusion flame. Figure 4.5 shows this behavior for the three continuous injection tests discussed previously. The slow initial rise in pressure due to gas compression by the injected mixture was followed by a more rapid pressurization around 160-300 sec. as combustion was initiated and the entire plume was ignited. The pressure decrease around 600-750 sec. occurred after the oxygen concentration dropped, extinguishing the diffusion flame.

Three continuous injection tests were carried out to determine the effect of the source nozzle size on the combustion characteristics. Three different source diameters of 1 m, 0.13 m, and 0.038 m were tested with nominal flowrates of 1.9 kg/min hydrogen and 28 kg/min steam. Figure 4.6 demonstrates that decreasing the nozzle size increased the heat transfer coefficient and reduced the peak pressure. The smaller nozzle diameter for a fixed flowrate caused an increase in the jet momentum, resulting in increased bulk gas motion and boundary layer dissipation.

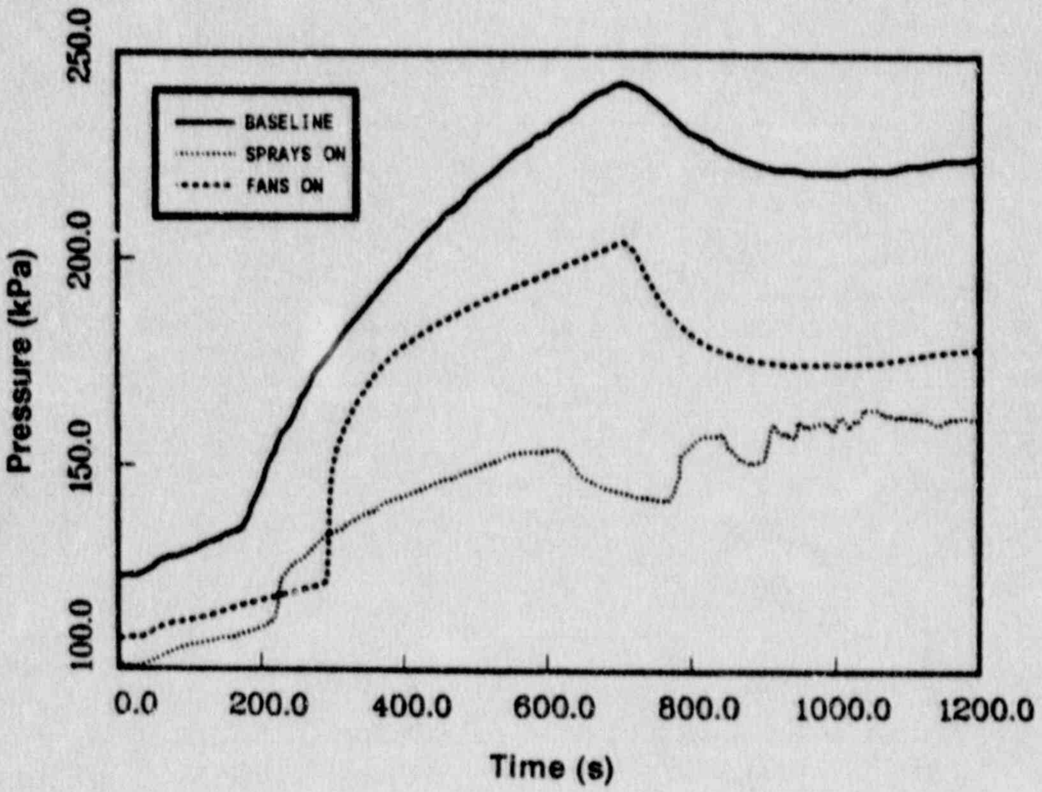


Figure 4.5 Gas pressure profiles for three NTS continuous injection tests comparing the effect of sprays and fans (taken from Reference 13).

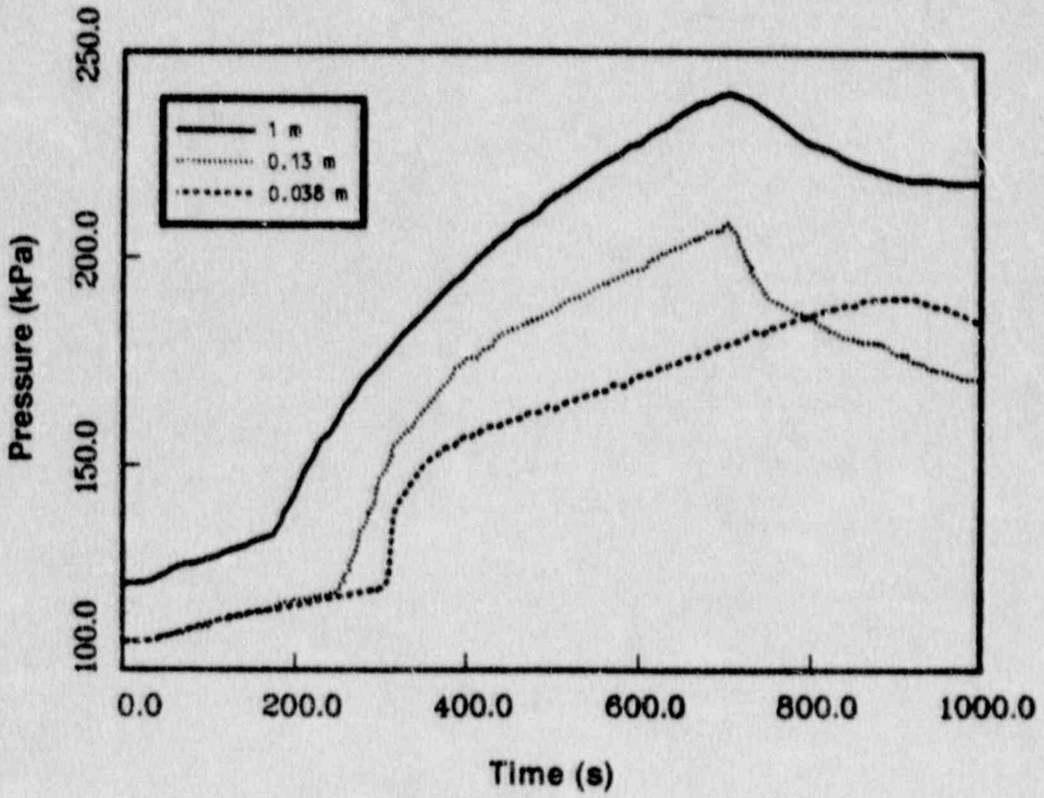


Figure 4.6 Gas pressure profiles for three NTS continuous injection tests comparing the effect of nozzle size (taken from Reference 13).

4.6 Burn Duration During Premixed Tests

The NTS tests demonstrated that flame spherical propagation speed is not meaningful for representing large volumetric burns with low hydrogen concentration (5%-8%). For burns at these low concentrations, the flame would rise through the vessel in a turbulent ball of fire, its upward motion dominated by the buoyant effect of the heated mixture. Upon reaching the top of the vessel, the flame would proceed to burn around the sphere, eventually reaching the lower regions. Due to these observed differences in vertical and horizontal flame propagation speeds in the NTS vessel, a more accurate representation of large scale combustion phenomena was the burn duration, defined as the time interval from combustion initiation to the time of peak pressure. Figure 4.7 demonstrates the effect of steam concentration, fans, and sprays on burn duration for varying initial concentrations of hydrogen. The figure shows that the burn duration decreased as the hydrogen concentration was increased. This can be attributed to the turbulence in the flames themselves, which increase as hydrogen concentration is increased. The figure also shows that, as noted before, sprays were more effective than fans in inducing turbulent mixing.

4.7 Heat Transfer Characteristics

Global estimates of the radiative and total postcombustion heat transfer were inferred from the pressure measurements. The comparative peak radiative and total heat flux results are plotted in Figures 4.8 and 4.9 for both the "standard" (~5% steam) and steam-laden (>10%) tests. These show that the relative importance of radiative heat transfer increases with initial hydrogen concentration. Radiative transfer becomes the more important energy exchange mechanism in the "standard" tests for hydrogen concentrations above 8%. This mechanism does not become dominant in the steam-laden tests until hydrogen concentrations are greater than 9-10%, since steam acts as a diluent in reducing the peak temperatures.

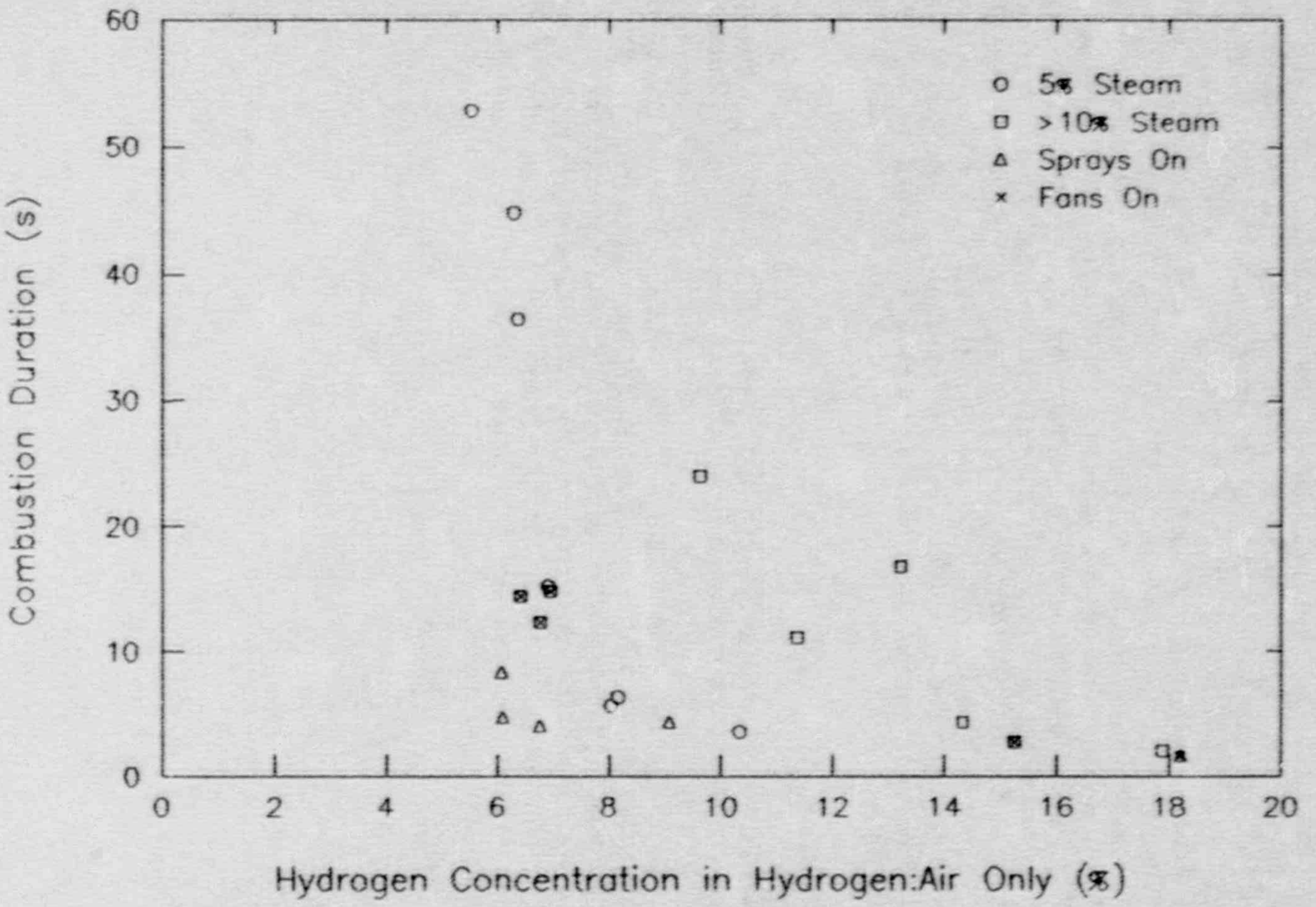


Figure 4.7 Burn duration for NTS premixed combustion tests.

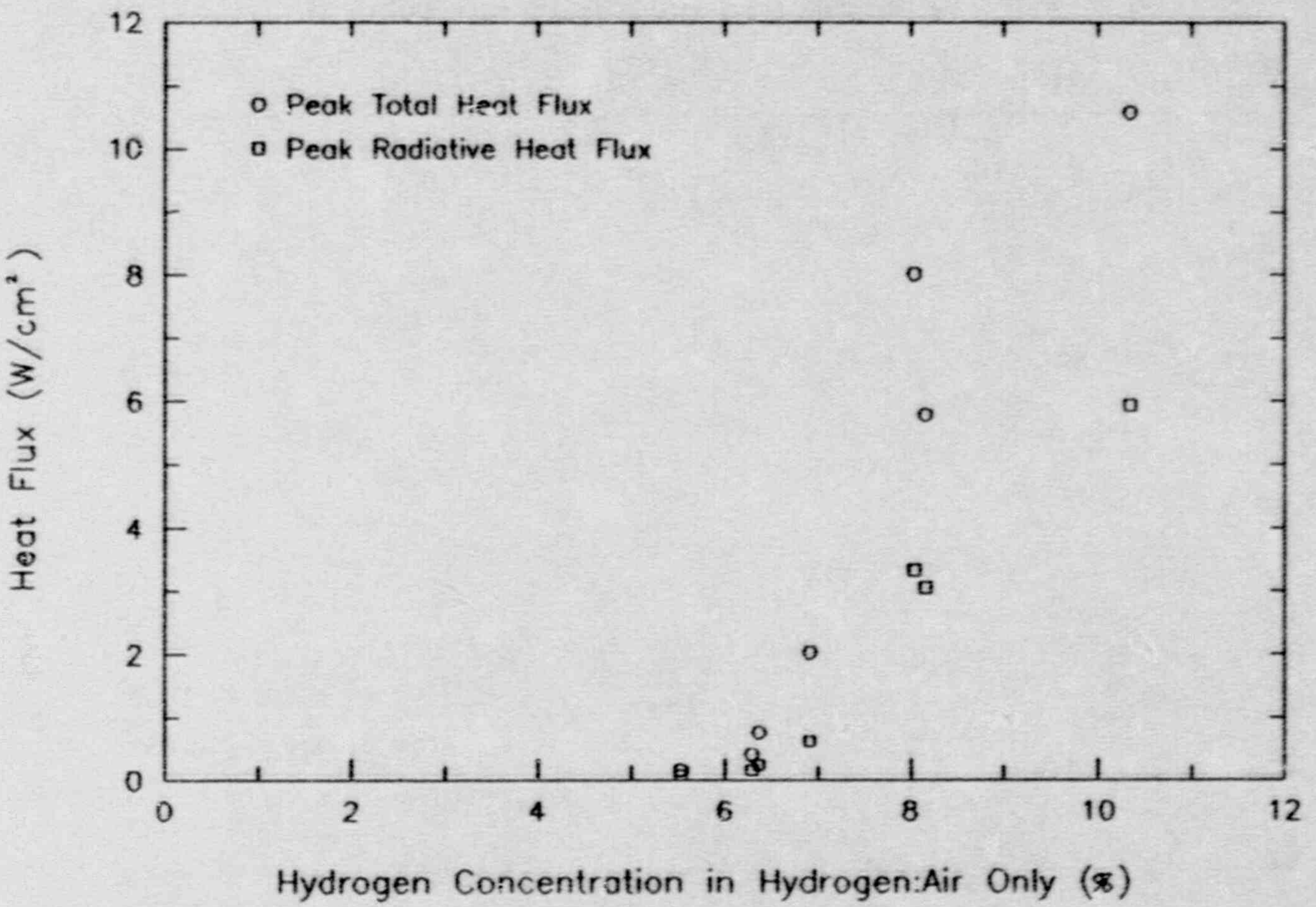


Figure 4.8 Peak radiative and total heat flux for "standard" NTS premixed combustion tests.

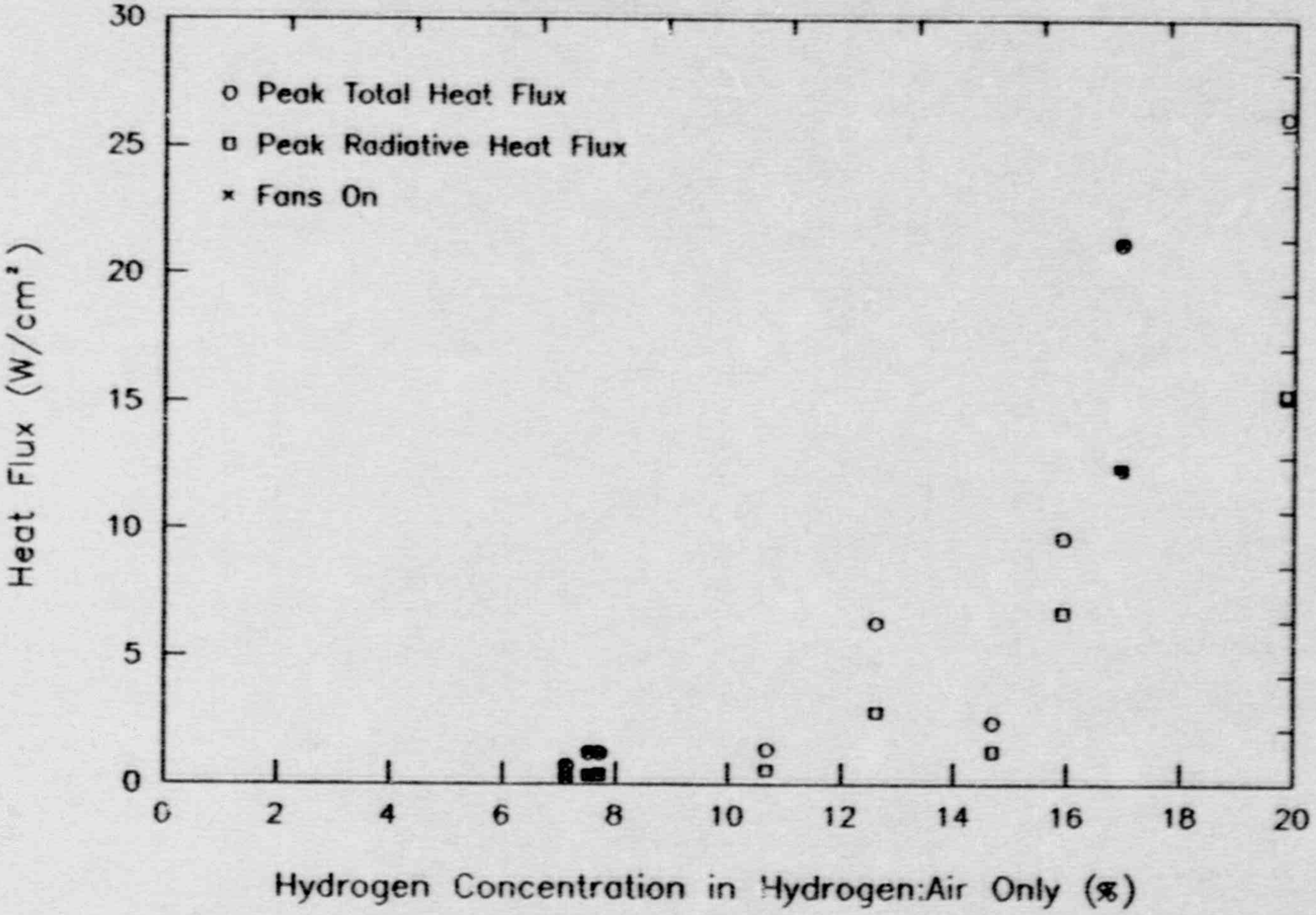


Figure 4.9 Peak radiative and total heat flux for steam-laden NTS premixed combustion tests.

5. LLNL HYDROGEN IGNITER EXPERIMENTAL PROGRAM

The NRC sponsored the Hydrogen Igniter Experimental Program at Lawrence Livermore National Laboratory (LLNL) in 1980-81 to evaluate the use of glow plugs as deliberate ignition sources in hydrogen:air:steam environments [13,14]. The purpose of the work was to better understand the influences of steam and fog on ignition and flame propagation in lean hydrogen mixtures.

5.1 Facility Description

The LLNL program consists of 100 premixed combustion tests conducted in a 0.5 m diameter by 1.5 m long compressed air storage tank. The tank has 0.5 cm thick walls, a working pressure of 1.4 MPa, and a free volume of 0.3 m^3. The test facility, shown schematically in Figure 5.1, includes a steam generator, compressed air and hydrogen supplies, and a 15 cm electric fan to study the influence of mixture circulation on burn characteristics. The ignition source for the experiments is the GM AC 7G glow plug, which can be placed at various elevations in the center of the vessel. The primary data recorded from the tests includes temperature, pressure and gas concentration measurements.

5.2 Flammability Limits and Combustion Completeness

Dry (hydrogen:air) combustion tests were conducted with hydrogen concentrations from 4% to 16% by volume. Additional tests were performed with stoichiometric (29%) mixtures. The results show that burns could be achieved for hydrogen concentrations as low as 6%, with the transition to complete combustion occurring at concentrations between 8% and 9%. Concentrations of 5% hydrogen could be ignited if the fans were used to circulate the mixture. Figure 5.2 shows the burn completion of the dry tests as a function of the initial hydrogen concentration for both the "fans off" and "fans on" tests. Neither the glow plug nor a one-joule spark source was capable of initiating detonations in stoichiometric mixtures of hydrogen and air.

Steam tests were conducted with hydrogen concentrations from 8% to 12%, for steam concentrations of up to 50%. Combustion occurred consistently for steam concentrations as high as 40%. Figure 5.3 shows the burn completion as a function of initial hydrogen concentration for the steam tests. The mixtures with steam concentrations of 50% could not be ignited due to the presence of suspended water droplets.

Several condensation-type tests were conducted at 50% steam and 10% hydrogen where the steam was allowed to condense slowly while the glow plug remained activated. Combustion was not indicated by discrete pressure rises in most of the tests, even though hydrogen was being consumed. This could have been the result of thermal recombination or limited combustion. The presence of condensation water droplets in the vessel mixture could also have suppressed pressure rises.

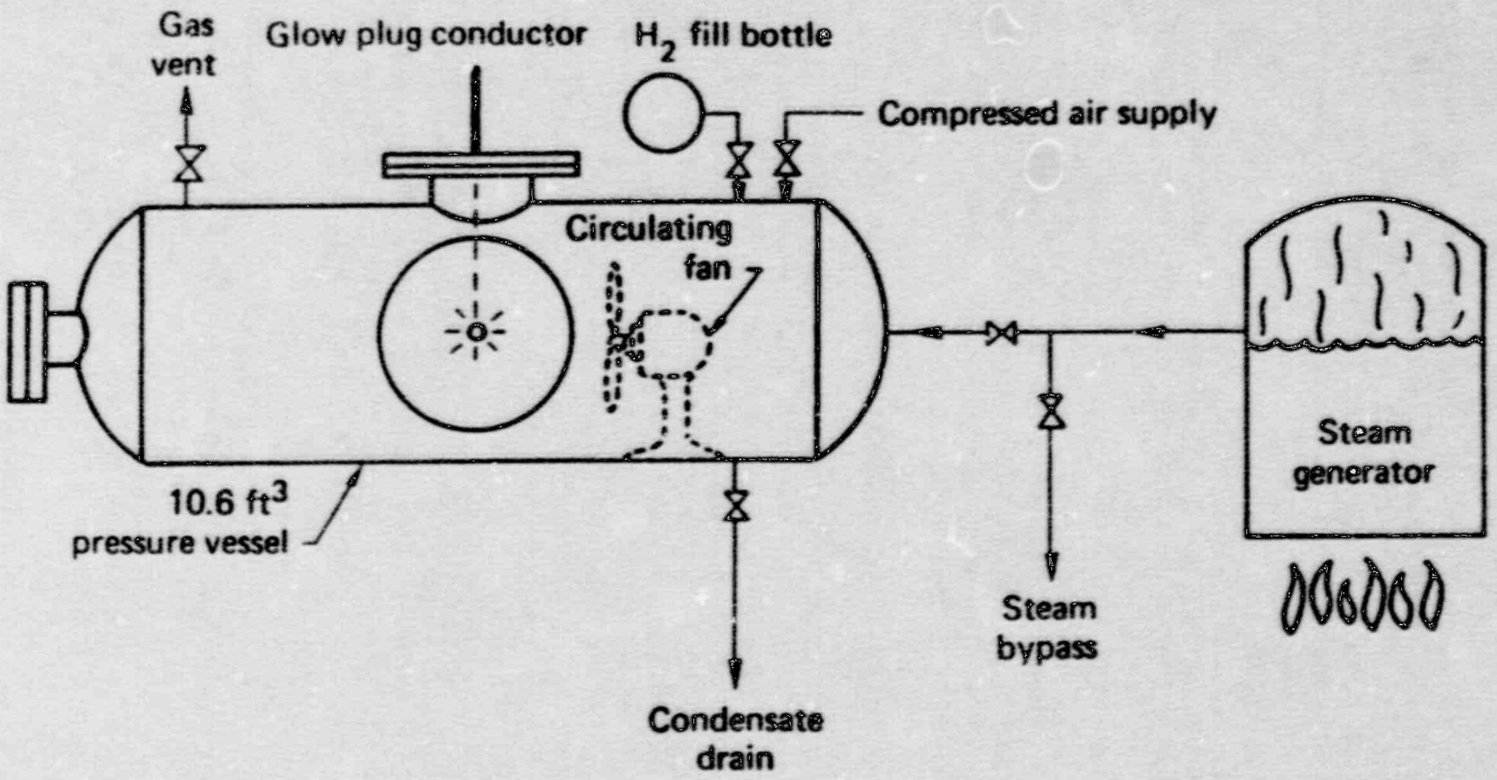


Figure 5.1 Schematic of LLNL facility (taken from Reference 14).

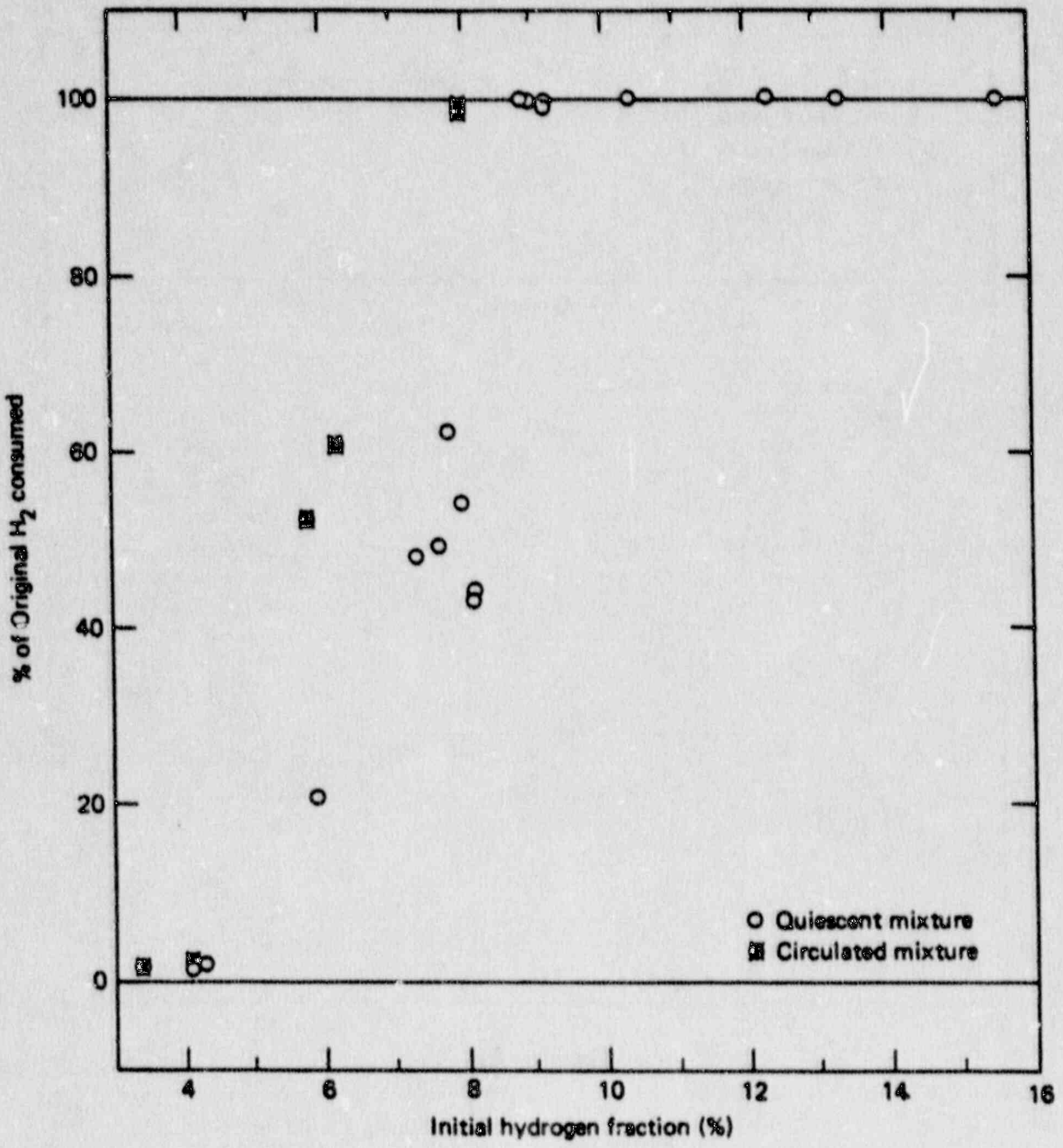


Figure 5.2 Combustion completeness for LLNL dry tests (taken from Reference 14).

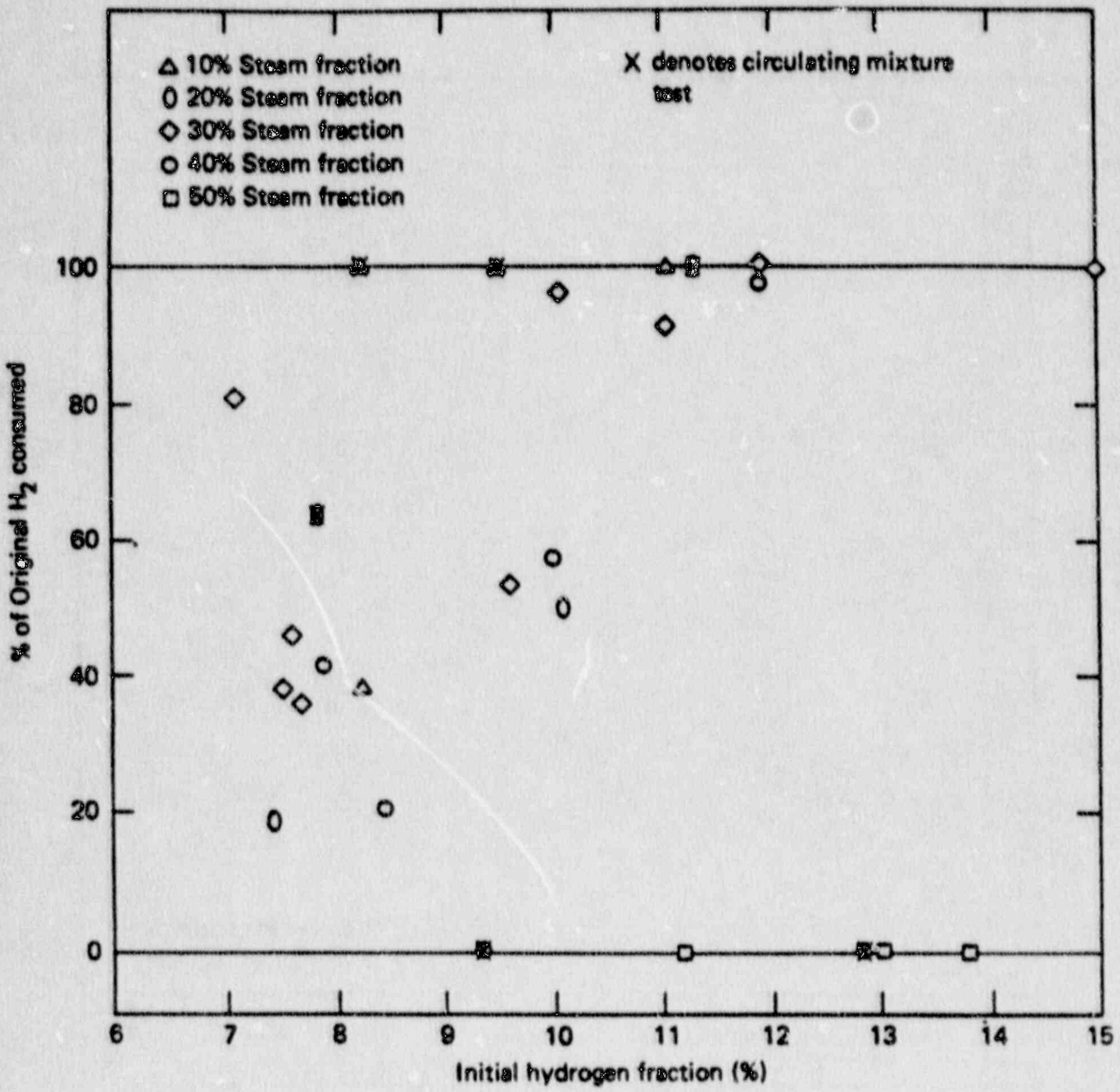


Figure 5.3 Combustion completeness for LLNL steam tests (taken from Reference 14).

5.3 Combustion Pressure Rises

Combustion pressure rise for the dry tests is shown plotted as a function of initial hydrogen concentration in Figure 5.4. The corresponding adiabatic isochoric complete combustion (AICC) value is also shown in this figure. Burns with the fans on produced higher peak pressures for hydrogen concentrations below 8% due to an increase in combustion completeness, while both approached the theoretical maximum peak pressure for concentrations greater than 8%.

The combustion pressure rise for the steam tests is shown in Figure 5.5. The presence of steam tended to decrease the pressure rise when compared to equivalent dry burns (i.e., burns with equivalent hydrogen-to-air ratio), with the 10-30% steam tests more closely resembling the dry tests than those with 40-50% steam. Circulation of the hydrogen:air:steam mixtures with the fan increased the peak pressure and burn completeness as in the dry tests.

5.4 Flame Speeds

The pressure and temperature history data from many of the dry tests and steam tests was analyzed to determine flame speeds during the combustion events. The results show that the average speed for a test increased with initial hydrogen concentration. Speeds were generally greater for flames propagating upward, and also greater for ignition in the center of the chamber rather than on the bottom.

5.5 Glow plug Reliability

The GM AC 7G glow plug consistently ignited mixtures at surface temperatures between 700°C and 800°C, with the higher temperatures necessary to ignite steam mixtures, and showed no appreciable deterioration throughout the series of tests.

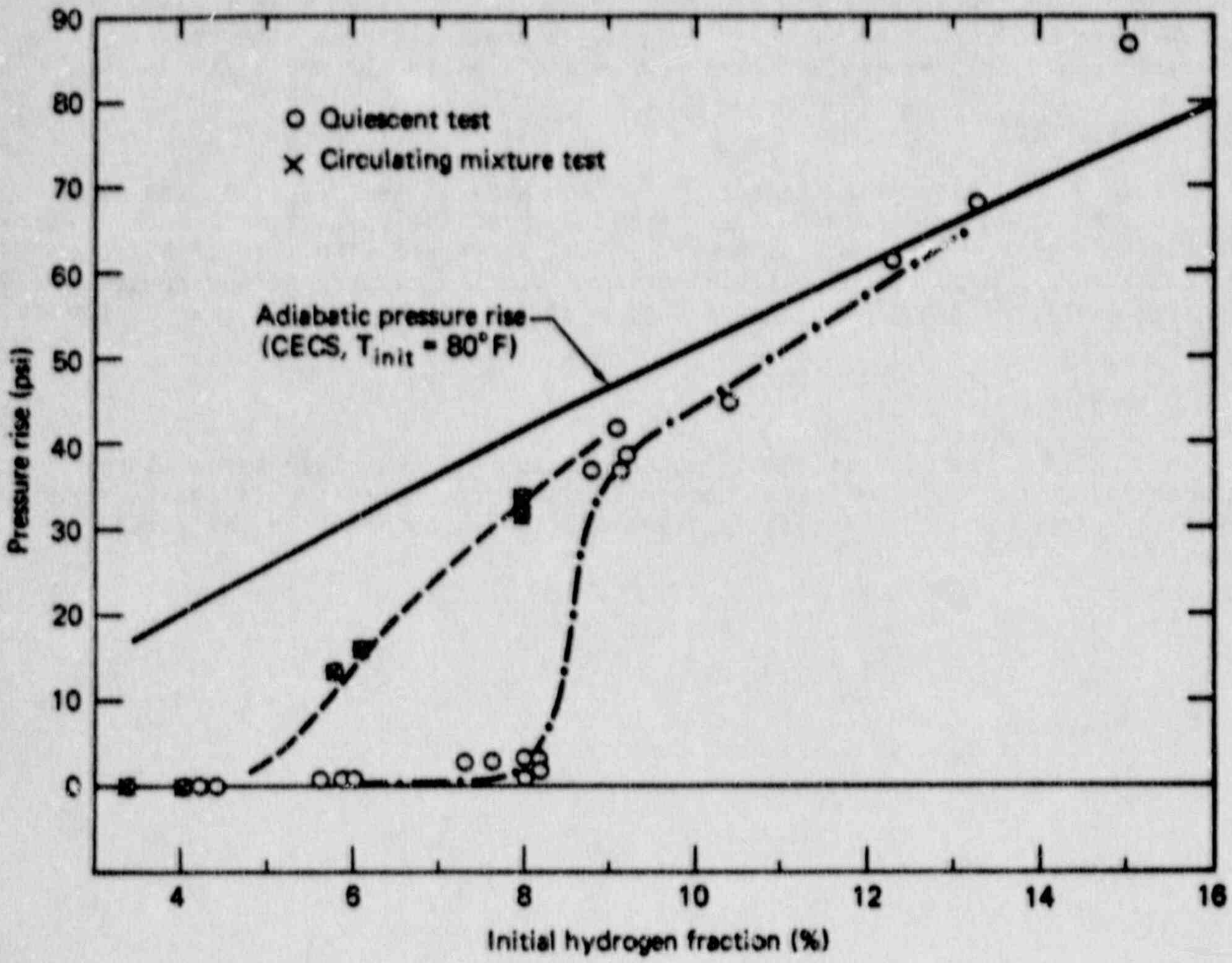


Figure 5.4 Combustion pressure rise for LLNL dry tests (taken from Reference 14).

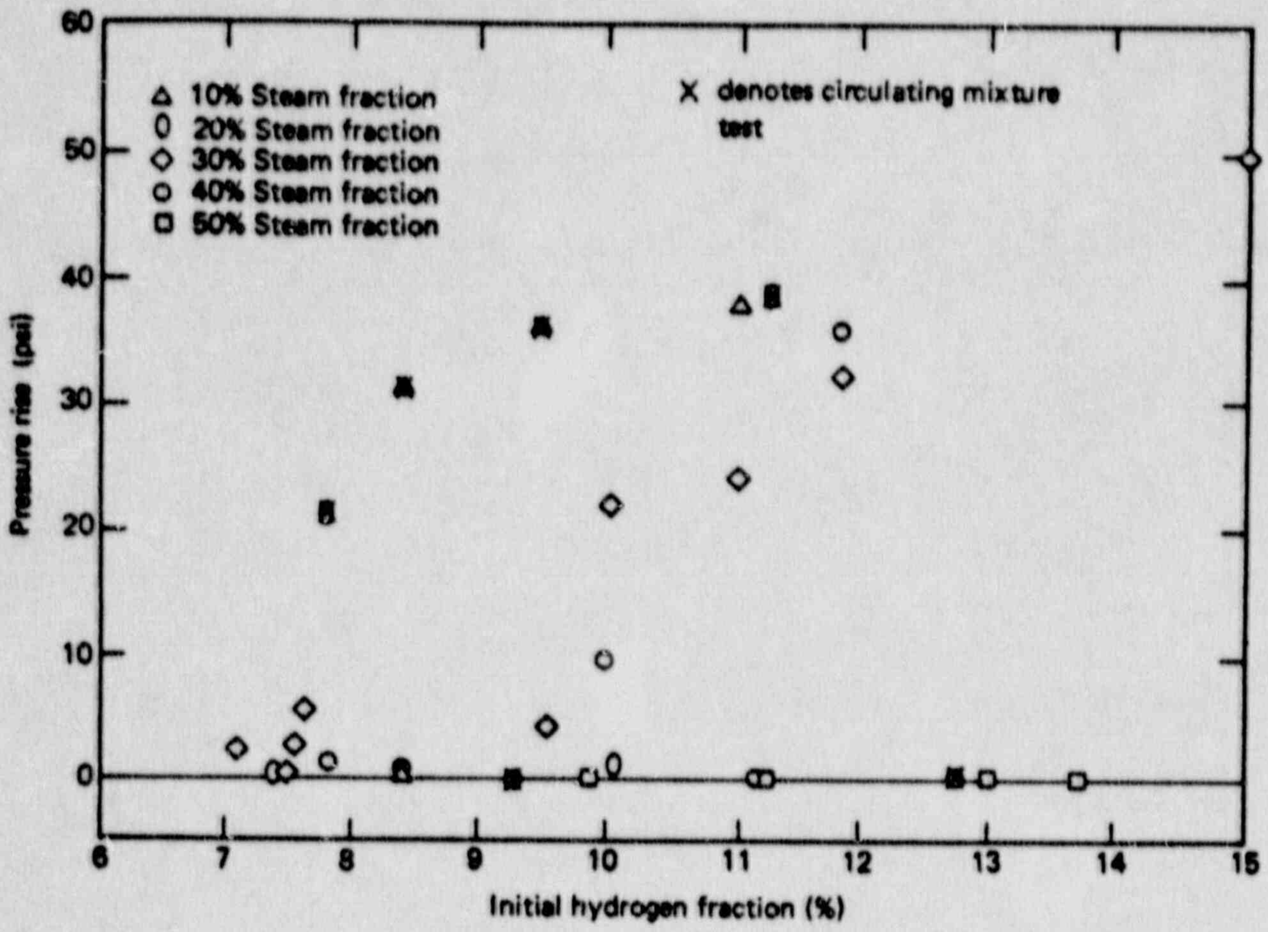


Figure 5.5 Combustion pressure rise for LLNL steam tests (taken from Reference 14).

6. WHITESHELL TESTS

The Electric Power Research Institute (EPRI) sponsored a series of over 300 premixed hydrogen combustion tests at the Whiteshell Nuclear Research Establishment in Pinawa, Manitoba [15,16]. The program was intended to confirm the effectiveness of a deliberate ignition system in controlling hydrogen which might be released to containment during a postulated degraded core accident. Experiments were performed to determine the hydrogen:air:steam concentration regimes in which thermal igniters would be effective, for both hydrogen-lean and hydrogen-rich mixtures.

6.1 Facility Description

The Whiteshell tests were conducted in a 17-liter quasi-spherical vessel with a pressure rating of 4 MPa. Figure 6.1 shows a schematic of the test vessel with the components used in the experiments. A penetration on one of the hemispherical walls is used for gas injection and sampling. Instrumentation is provided to measure static and transient pressures as well as vessel and gas temperatures throughout the tests. Flame visualization and photography can be achieved through a pair of 10 cm diameter viewports. A small fan with a 7.4 cm diameter blade is available for experiments involving turbulent mixing.

Two types of igniters were tested in the Whiteshell experiments -- the GM AC 7G cylindrical glow plug and the Tayco Model 193-3442-4 helical igniter. Both have been utilized in deliberate ignition systems installed in BWR Mark III and PWR ice condenser containments.

6.2 Ignition Limits

Figures 6.2 and 6.3 show the ignition limit results for the glow plug igniter, for both the quiescent (fan off) and turbulent (fan on) tests. Figure 6.4 shows results for the helical igniter, which was only tested in the lean hydrogen concentration range. In these figures, a mixture was classified "no ignition" if an ionization gap probe located at the top of the vessel was unable to detect a flame arrival. "Marginal ignition" was defined for burns resulting in less than a 12 kPa pressure rise, while "ignition" indicated burns resulting in greater than a 12 kPa pressure rise. Also plotted in Figures 6.2 and 6.3 for comparison is the correlation of ignition limit data from the FITS tests (Equation 2.1). This equation correlates both quiescent and turbulent flammability data.

The tests showed that both the GM glow plug and the Tayco igniter could ignite dry hydrogen:air mixtures containing more than 5.5% hydrogen under quiescent conditions. Dry hydrogen concentrations as low as 4.5% could be ignited under turbulent conditions. Mixtures containing as much as 55% steam were ignited in both quiescent and turbulent tests. For the hydrogen-rich tests, where only the GM glow plug was tested, the results indicate turbulence had less effect on the ignition limits than in the lean tests. The glow plug could ignite dry hydrogen:air mixtures containing as much as 78% hydrogen in both quiescent and turbulent tests. The igniter surface temperature required for ignition was higher in the hydrogen-rich tests but not significantly affected by steam concentration.

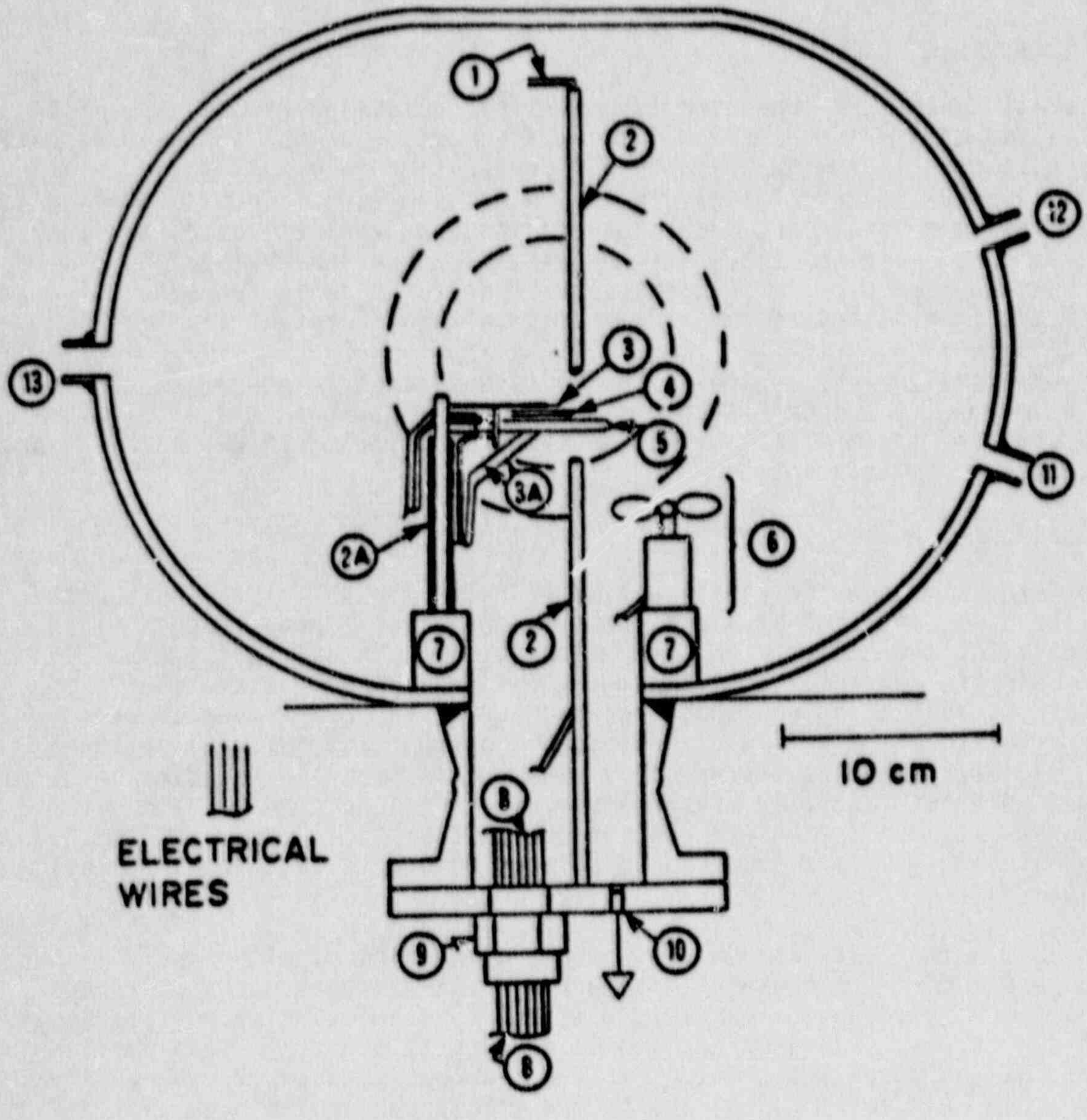


Figure 6.1 Schematic of Whiteshell test vessel (taken from Reference 17).

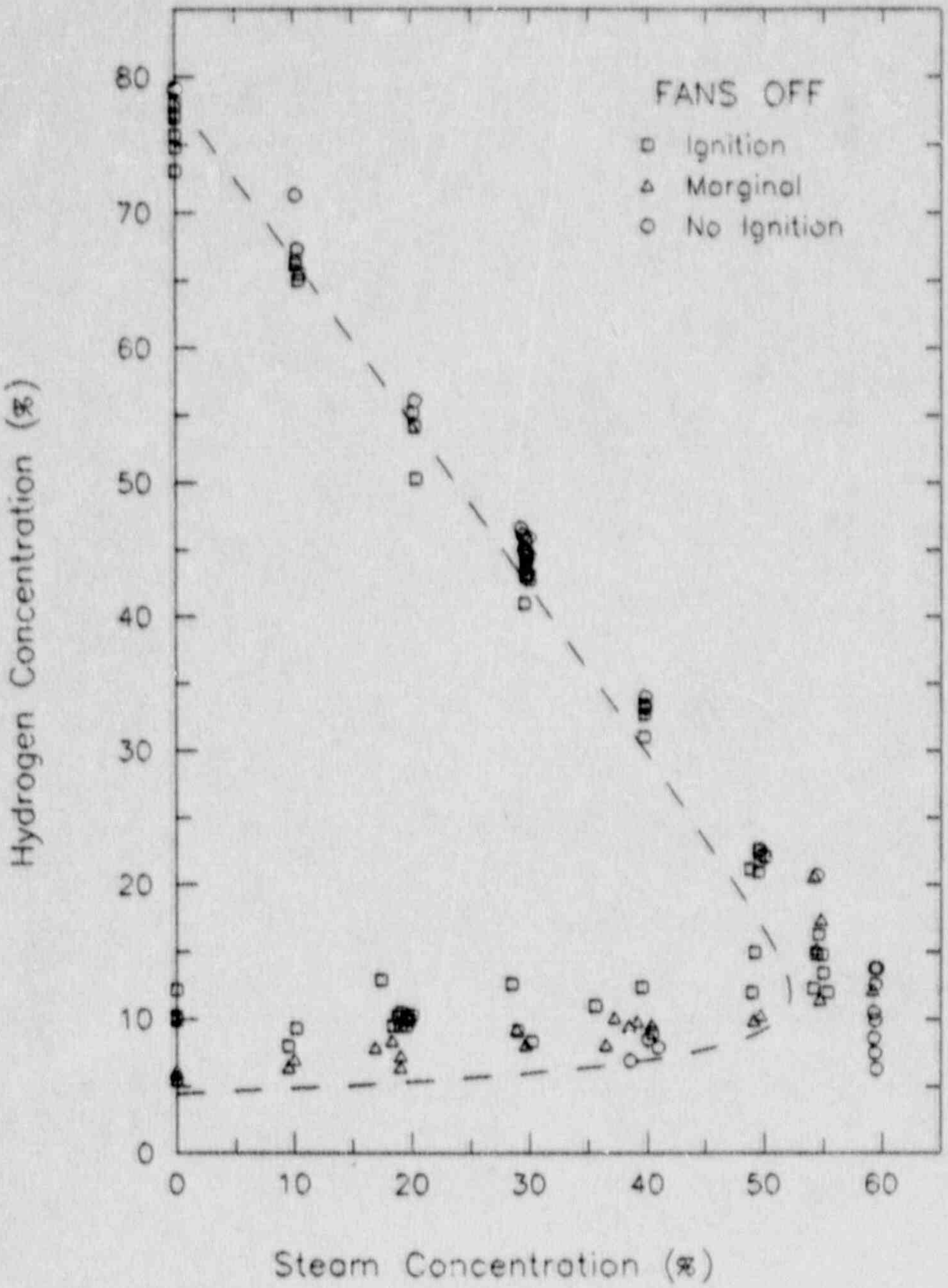


Figure 6.2 Ignition limits for Whiteshell tests with the GM AC 7G glow plug igniter (fans off). Dashed line represents flammability limit correlation from FITS tests (Equation 2.1).

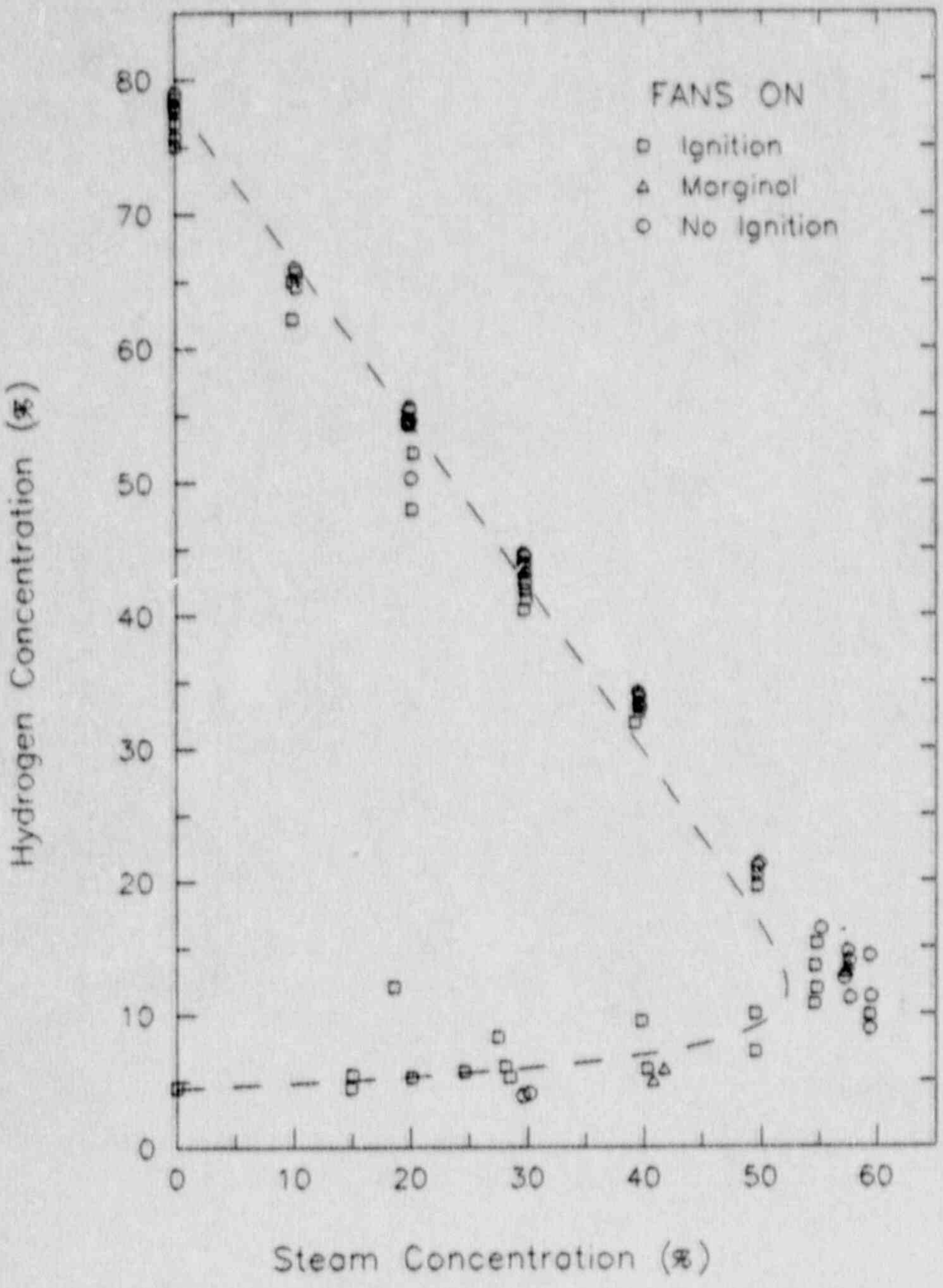


Figure 6.3 Ignition limits for Whiteshell tests with the GM AC 7G glow plug igniter (fans on). Dashed line represents flammability limit correlation from FITS tests (Equation 2.1).

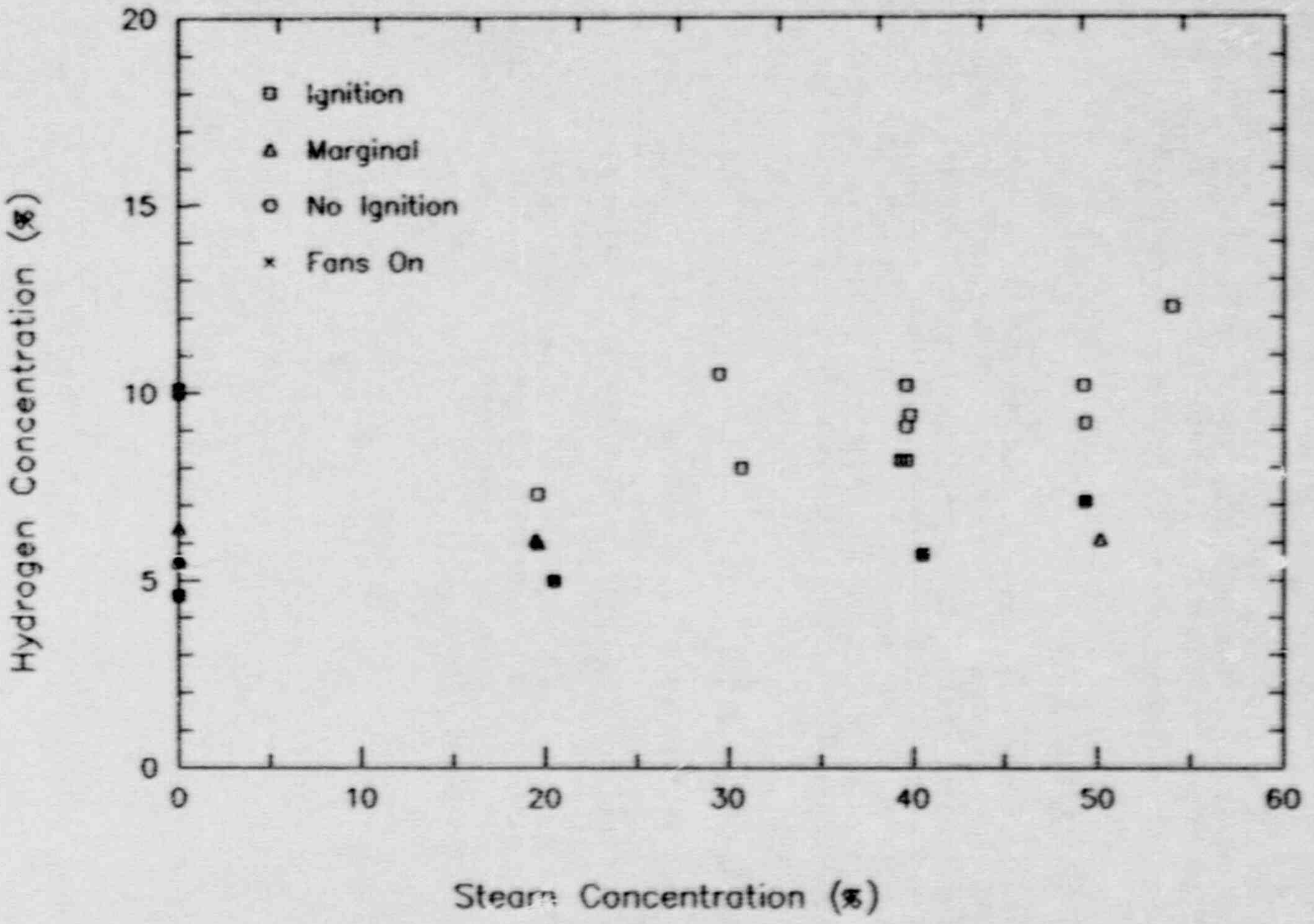


Figure 6.4 Ignition limits for Whiteshell tests with the Tayco helical igniter.

6.3 Combustion Completeness

Combustion completeness was determined for each of the tests by mass spectrometry analyses and static pressure measurements. Figure 6.5 shows the combustion completeness for the dry (hydrogen:air) tests. In these tests, complete combustion occurred for all burns with initial hydrogen concentrations greater than 9-10%. Figure 6.6 shows the combustion completeness for the steam tests, based on the initial hydrogen concentration in hydrogen:air only. The presence of steam lessened the combustion completeness, especially for mixtures with initial steam concentration greater than 30%. Both figures demonstrate that turbulent burns tended to be more complete than equivalent quiescent tests.

6.4 Combustion Pressure Rises

The normalized peak pressure (ratio of peak-to-initial pressure) for each of the Whiteshell tests is shown in Figures 6.7 and 6.8, with the steam tests shown as a function of initial hydrogen concentration in hydrogen:air only. Tests with the fans on resulted in higher peak pressures due to the increase in combustion completeness and burn rate. Steam acted as a diluent in reducing the peak combustion pressure of the hydrogen:air:steam burns when compared to equivalent hydrogen:air burns (i.e., burns with equivalent hydrogen-to-air ratio).

6.5 Condensation Experiments

Experiments were also performed at Whiteshell with steam condensing conditions where hydrogen:air:steam mixtures, initially steam inerted, were cooled to bring the concentration into the flammable regime. The results of these tests are plotted in Figure 6.9. The initial concentration and concentration at initiation of combustion is plotted for each experiment, with a connecting line to indicate its history. The figure also shows the ignition limits presented in Figure 5.2. The results of these experiments match closely with those obtained without condensation.

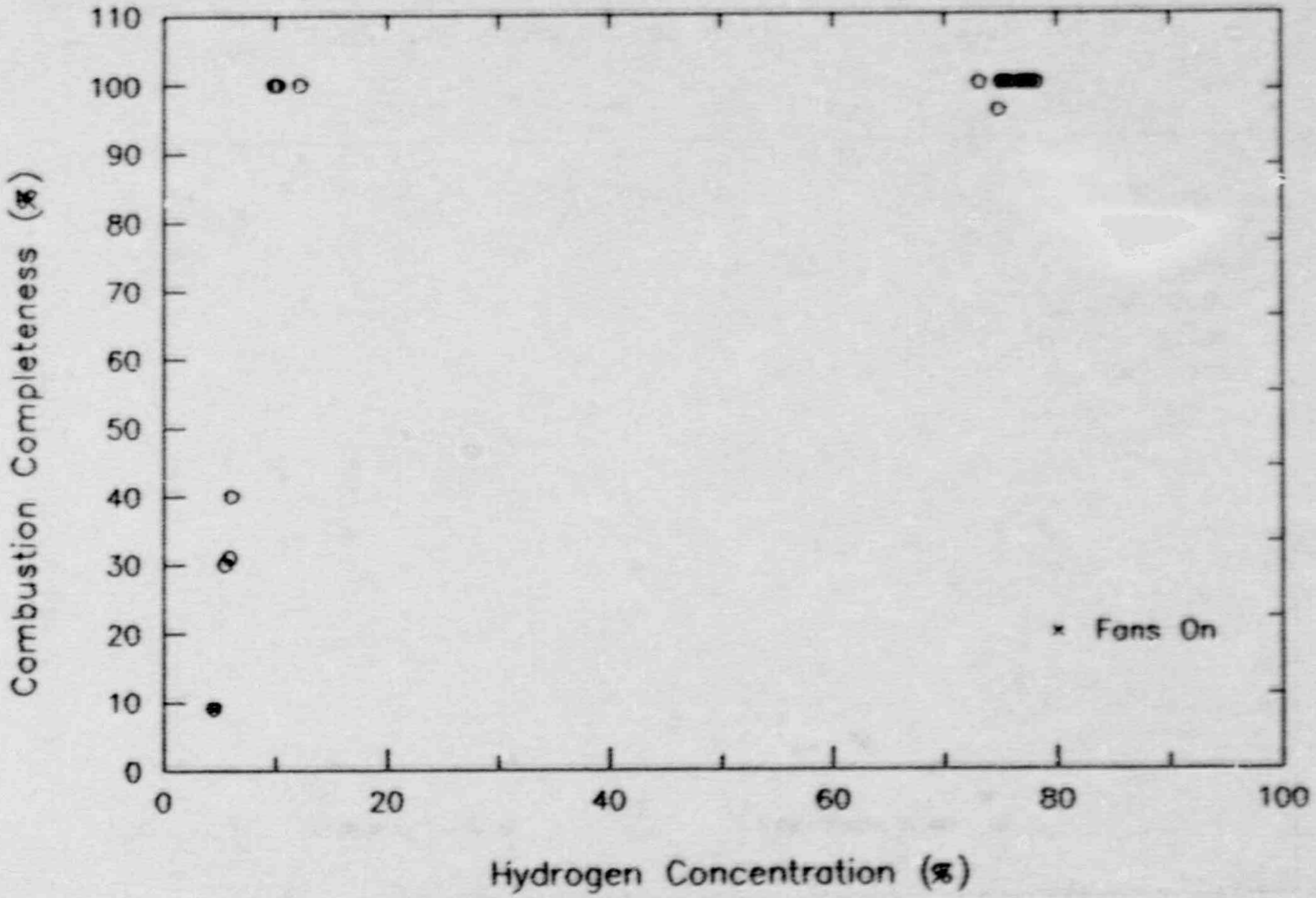


Figure 6.5 Combustion completeness for Whiteshell dry tests

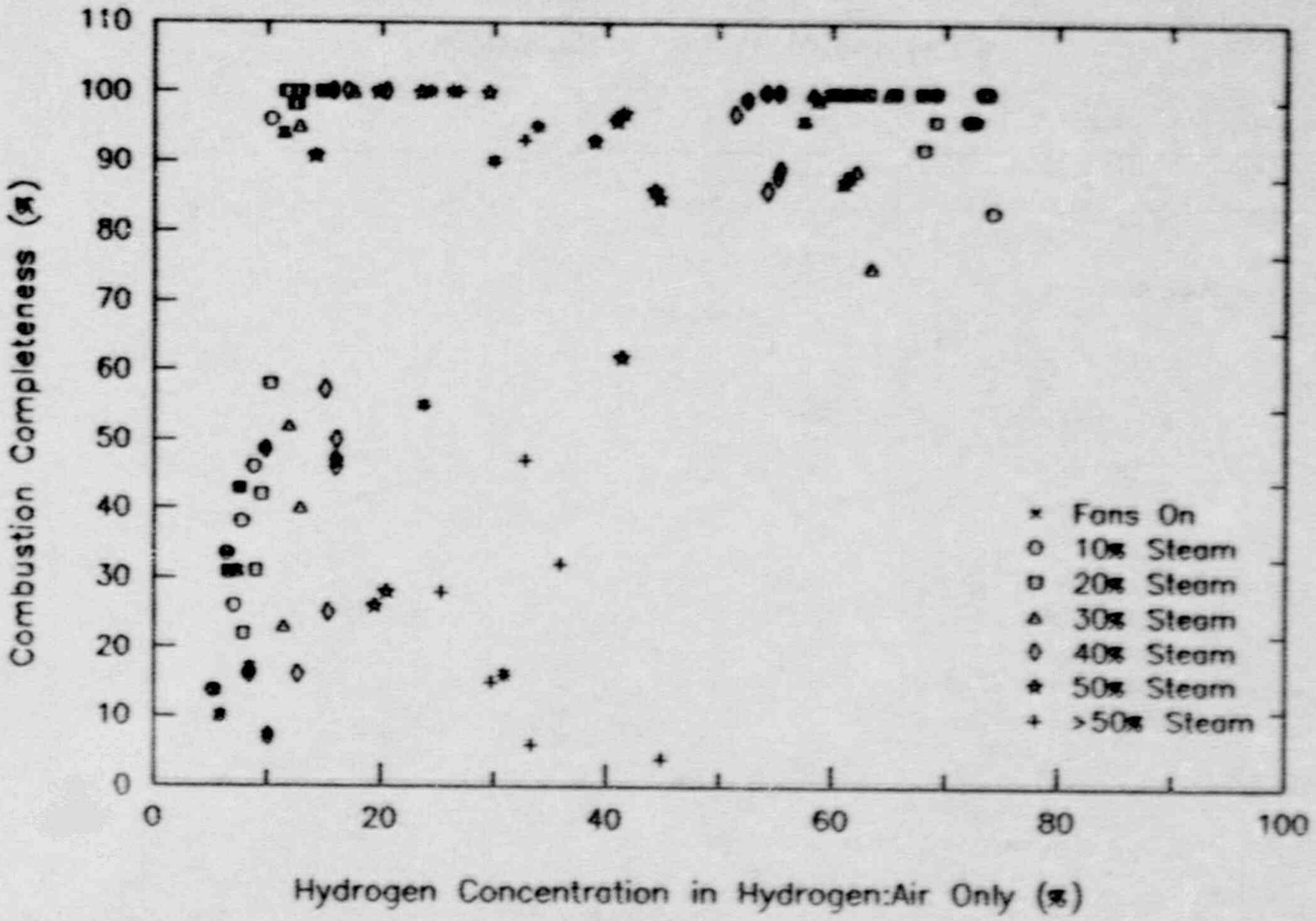


Figure 6.6 Combustion completeness for Whiteshell steam tests.

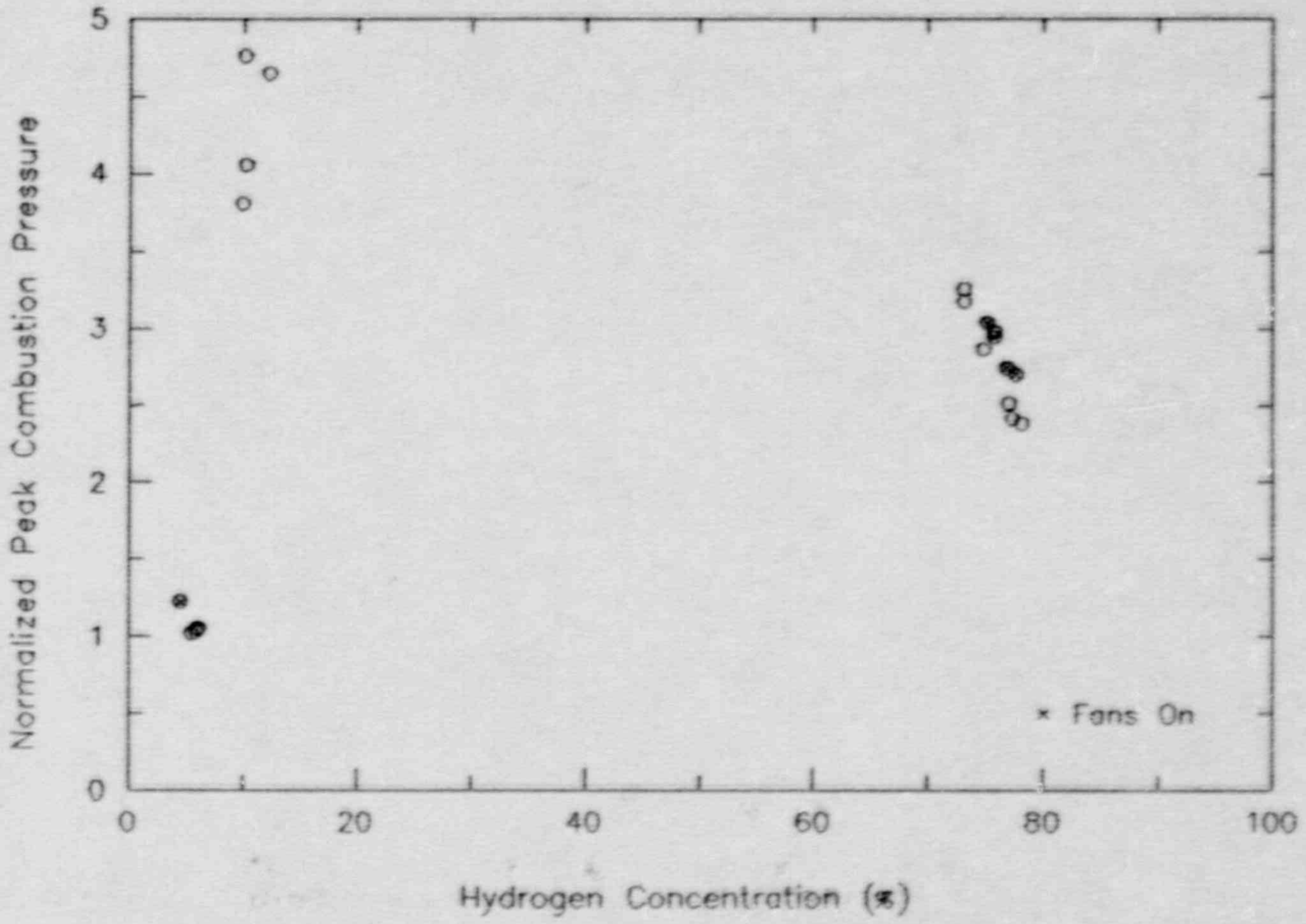


Figure 6.7 Normalized peak combustion pressure for Whiteshell dry tests.

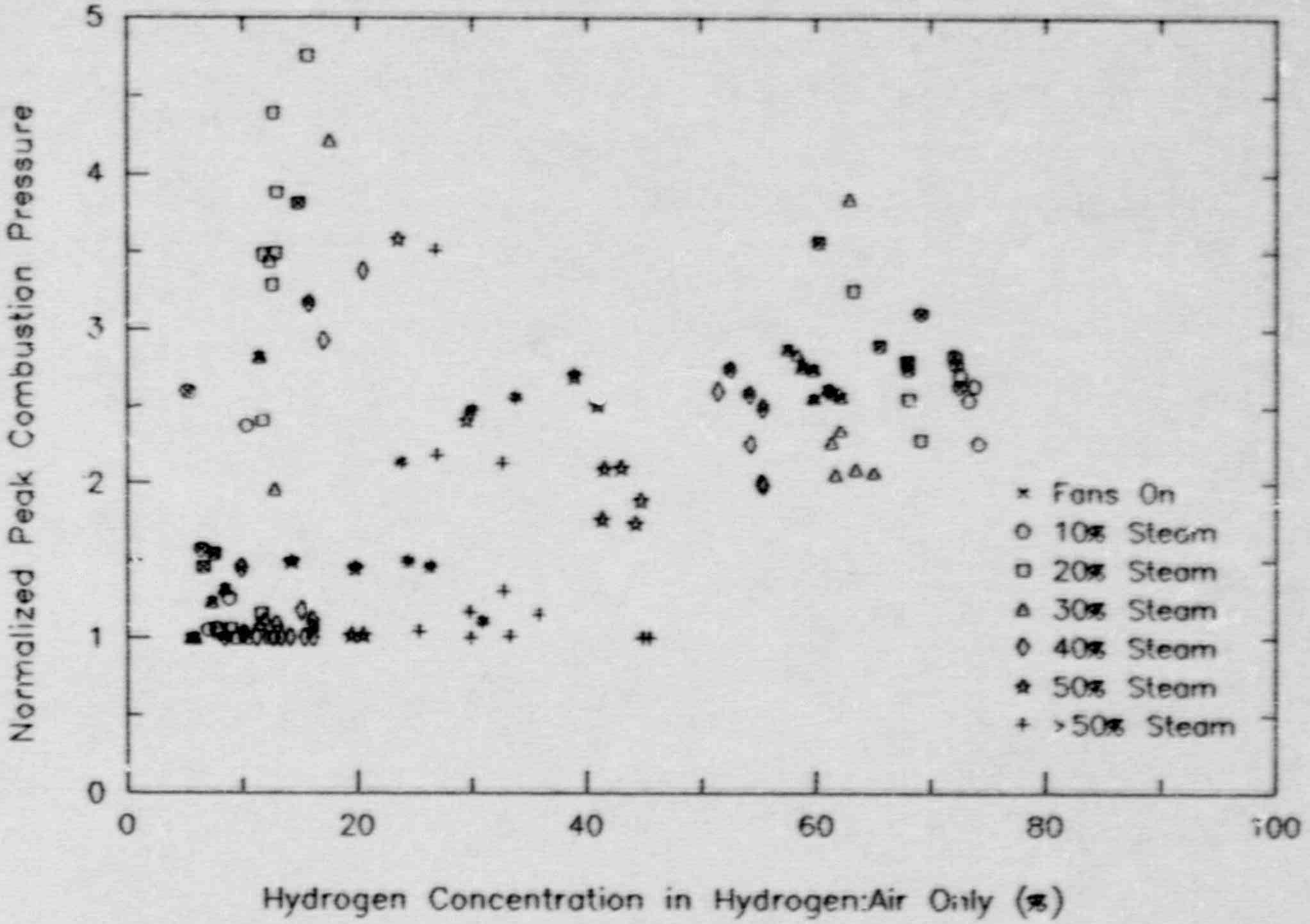


Figure 6.8 Normalized peak combustion pressure for Whiteshell steam tests.

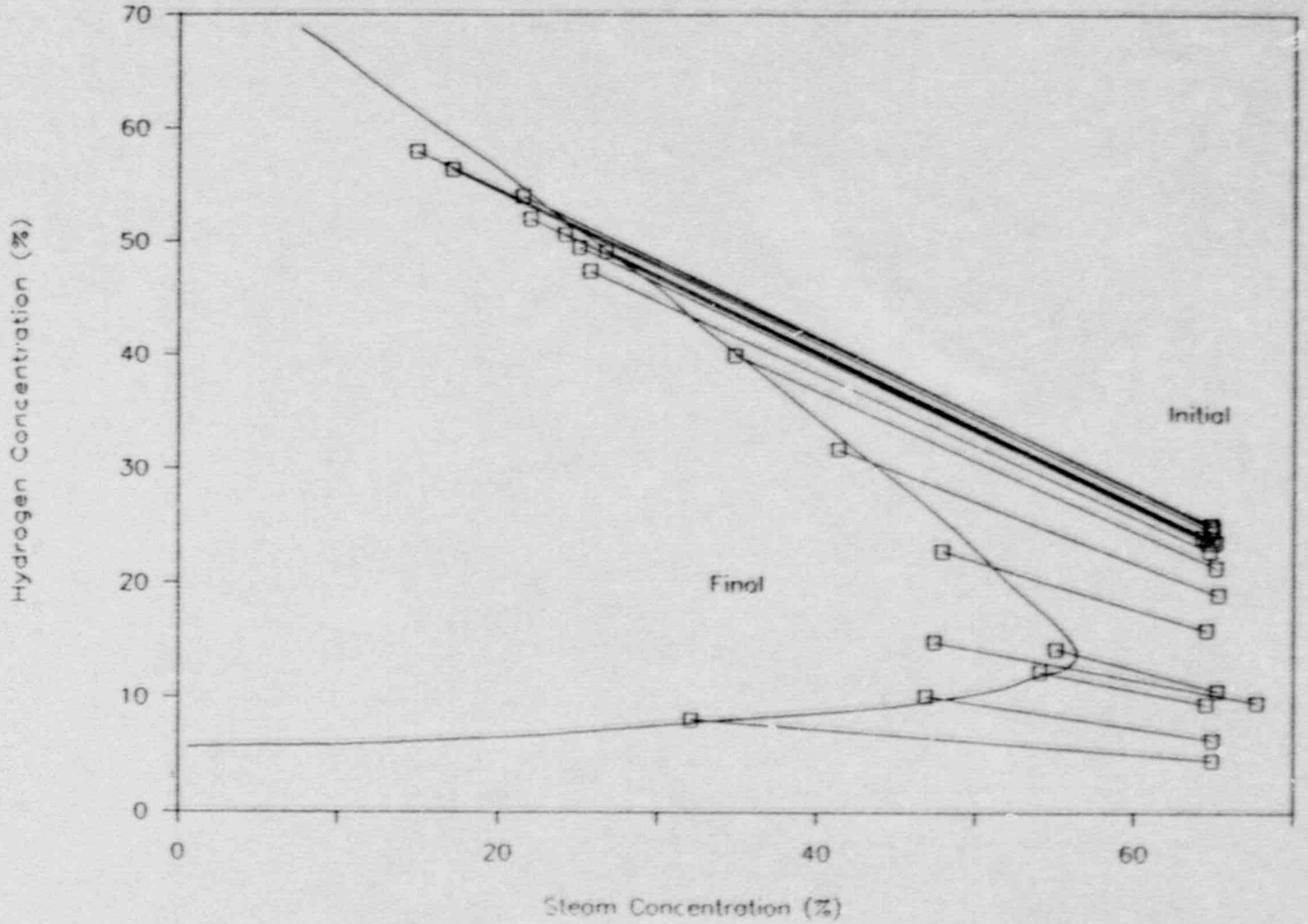


Figure 6.9 Ignition limits for Whiteshell tests in steam condensing atmosphere.

7. ACUREX TESTS

The Acurex Corporation conducted a series of intermediate-scale hydrogen combustion experiments as a part of EPRI's Hydrogen Combustion and Control Program. The Acurex program, conducted in a 17.8 m^3 cylindrical vessel, studied the combustion behavior of hydrogen:air:steam mixtures in both premixed and continuous injection tests [17,18]. The purpose of the program was to investigate the effects of hydrogen and steam flow rates, igniter location, and water sprays and fogs on the deliberate ignition of flammable containment atmospheres resulting from postulated degraded core accidents.

7.1 Facility Description

A schematic of the Acurex facility is shown in Figure 7.1. The vessel is 5.2 m tall with a 2.1 m inside diameter and has penetrations for injecting hydrogen or hydrogen:steam and water spray or microfog. The ignition sources are 14 Vac GM AC 7G glow plugs mounted with spray shields. An air-powered fan is used to mix the vessel atmosphere before the premixed tests and to investigate the effects of turbulence and mixing on burning during the continuous injection tests. Instrumentation is present to measure vessel wall and gas temperature, dynamic and static pressure, flame front location, and pre- and post-test gas concentrations.

7.2 Burn Characteristics in Premixed Tests

A limited number of premixed combustion tests were performed and are summarized in Table 7.1. Nominal hydrogen concentrations of 5, 7.5, and 10.7% were examined in dry hydrogen:air tests; hydrogen concentrations of 7.5 and 10.7% were tested with the addition of microfogs of different droplet sizes.

Table 7.1 Results of Acurex Premixed Tests

Nominal H_2 Concentration (vol%)	Spray	Measured H_2 Concentration (vol%)	Combustion Completeness (%)	Burn Overpressure (kPa)
5	——	4.7	30	55
7.5	——	7.8	90	235
	138 kPa microfog	7.2	>99	275
	207 kPa microfog	7.6	>99	270
10.7	138 kPa microfog	9.7	>99	327
	207 kPa microfog	10.2	>99	337
	——	10.2	>99	332

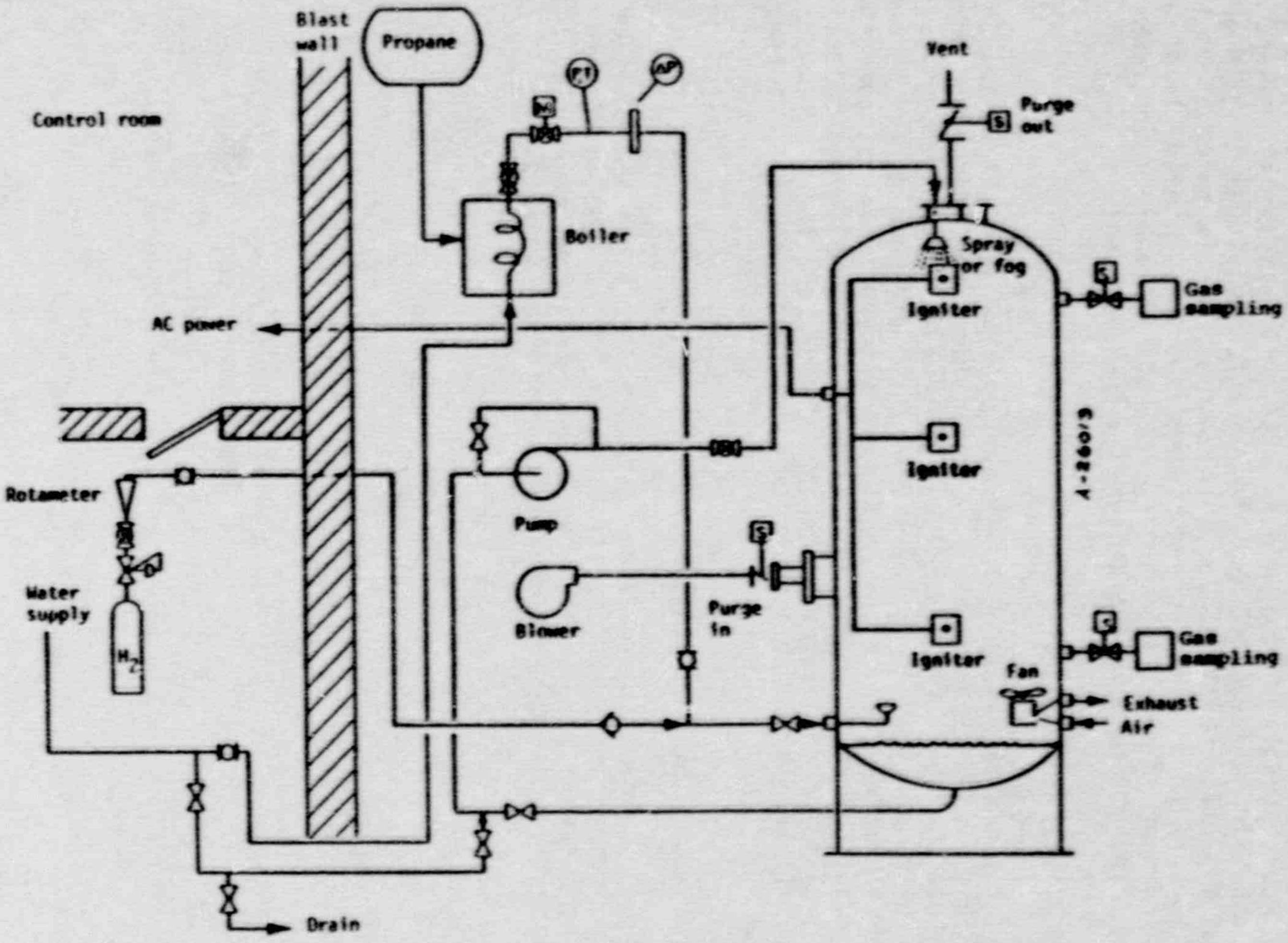


Figure 7.1 Schematic of Acurex test facility (taken from Reference 19).

A fog nozzle with a pressure drop of 138 kPa produced droplet diameters of 11μ, while a 207 kPa nozzle produced 8μ diameter droplets. The combustion pressure rise, as well the completeness of combustion, was observed to increase with increasing initial hydrogen concentration. The presence of microfog had the effect of increasing the combustion completeness and pressure rise, due to induced turbulence created by the fog flow and microturbulence caused by the presence of the water drops themselves.

7.3 Effect of Igniter Location

The effect of igniter location on burn characteristics can be seen in Figure 7.2 for three continuous injection tests without steam or sprays. For the case of bottom igniter location, the position of the injector caused hydrogen to bypass the igniter, with a subsequent buildup of hydrogen throughout the vessel until a global burn occurred at about 450 sec. With the igniter in the center position, earlier and frequent intermittent local combustion took place, resulting in lower pressure rises and more complete combustion. The test with the igniter located near the top showed a partial burn occurring at about 300 sec as the ignition limit for lateral flame propagation was reached. A global burn eventually occurred at about 500 sec as the limit for downward propagation was reached.

7.4 Effect of Steam, Spray, and Fog

Figure 7.3 shows the effect of steam injection and water sprays on the combustion characteristics for continuous injection tests. The three tests were conducted with the igniter in the center position. When large quantities of steam were added to the hydrogen flow, the combustion pressure rise was lowered slightly and the combustion was more erratic, taking place over a longer time period. When a water spray was introduced to the conditions of the previous test, multiple combustion events occurred much more uniformly, and the combustion pressure rise was considerably less than that for dry hydrogen injection.

The effects of water fog in the continuous injection tests is shown in Figure 7.4. The water fog aided mixing in the vessel, contributing to local combustion near the igniter (rather than global burns) and very little pressure rise. Steam injection with the fog produced several discrete burns spread out over the experiment, and slightly greater combustion pressure rises than the hydrogen-only tests.

Varying the hydrogen flow rate in the continuous injection tests from 0.016-0.048 kg/min (0.035-0.105 lb_m/min) had little effect on the general combustion characteristics and pressure rises, even in the presence of steam. In all tests of this type, increasing the hydrogen injection rate caused burning to start earlier.

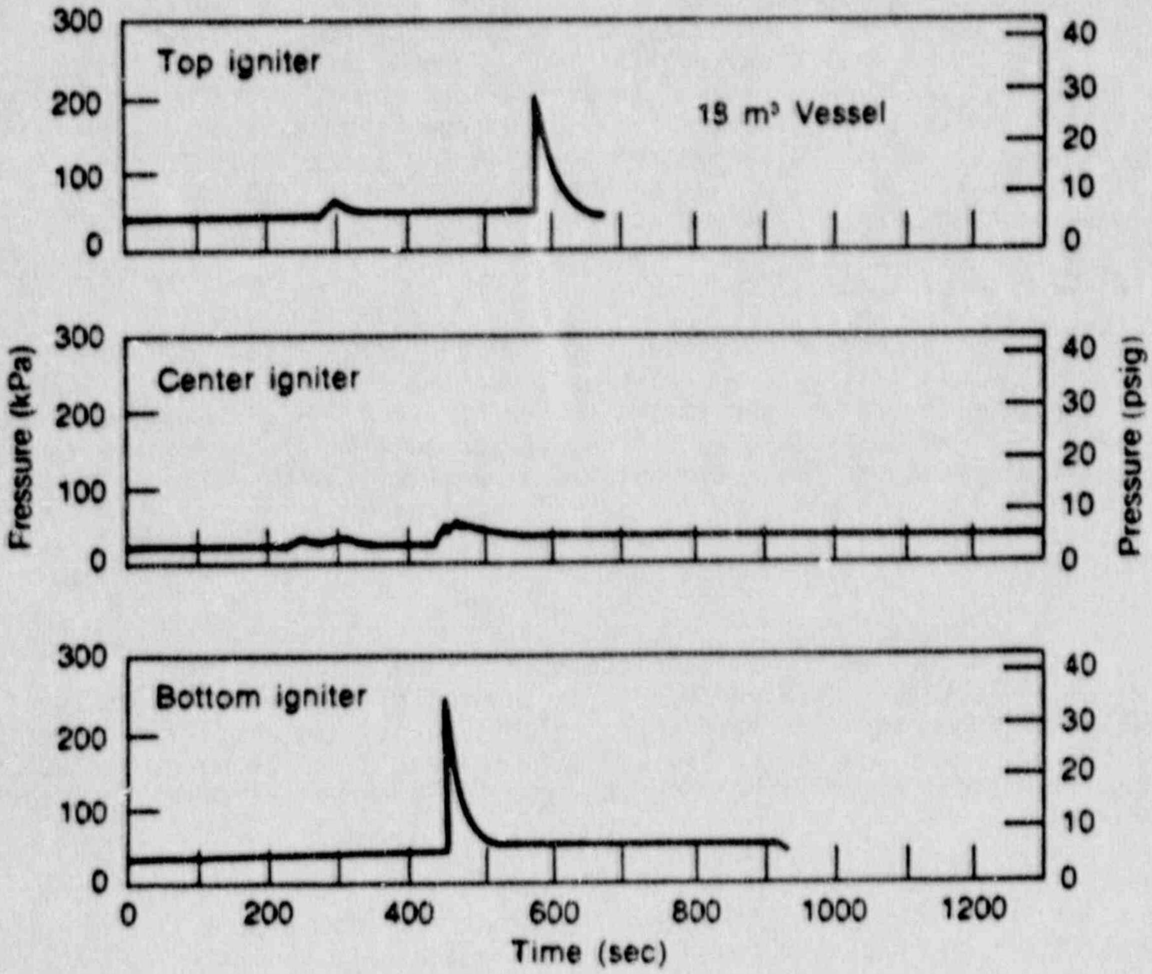


Figure 7.2 Effect of igniter location in Acurex continuous injection tests (taken from Reference 19).

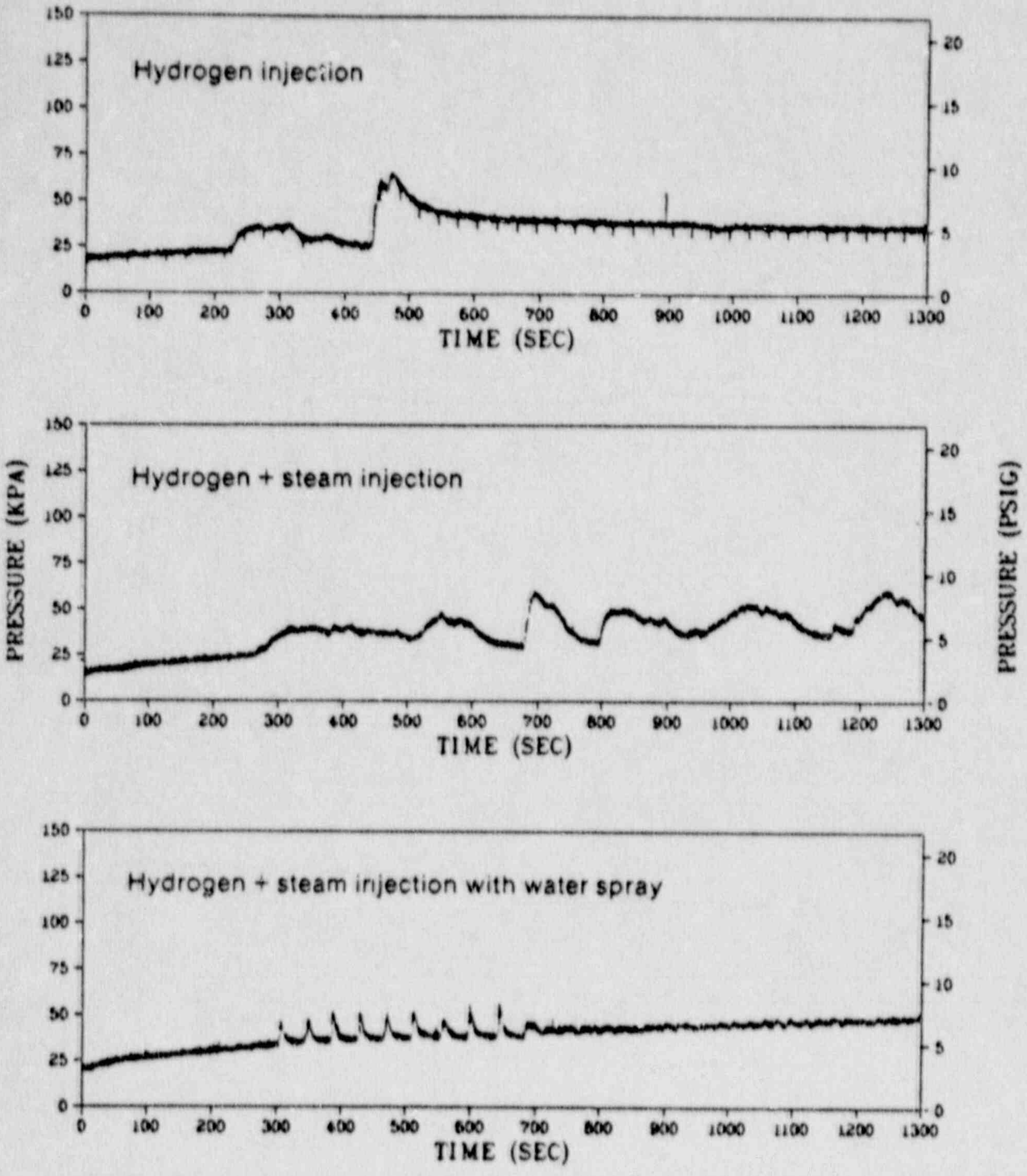


Figure 7.3 Effects of steam injection and water sprays in Acurex continuous injection tests (taken from Reference 19).

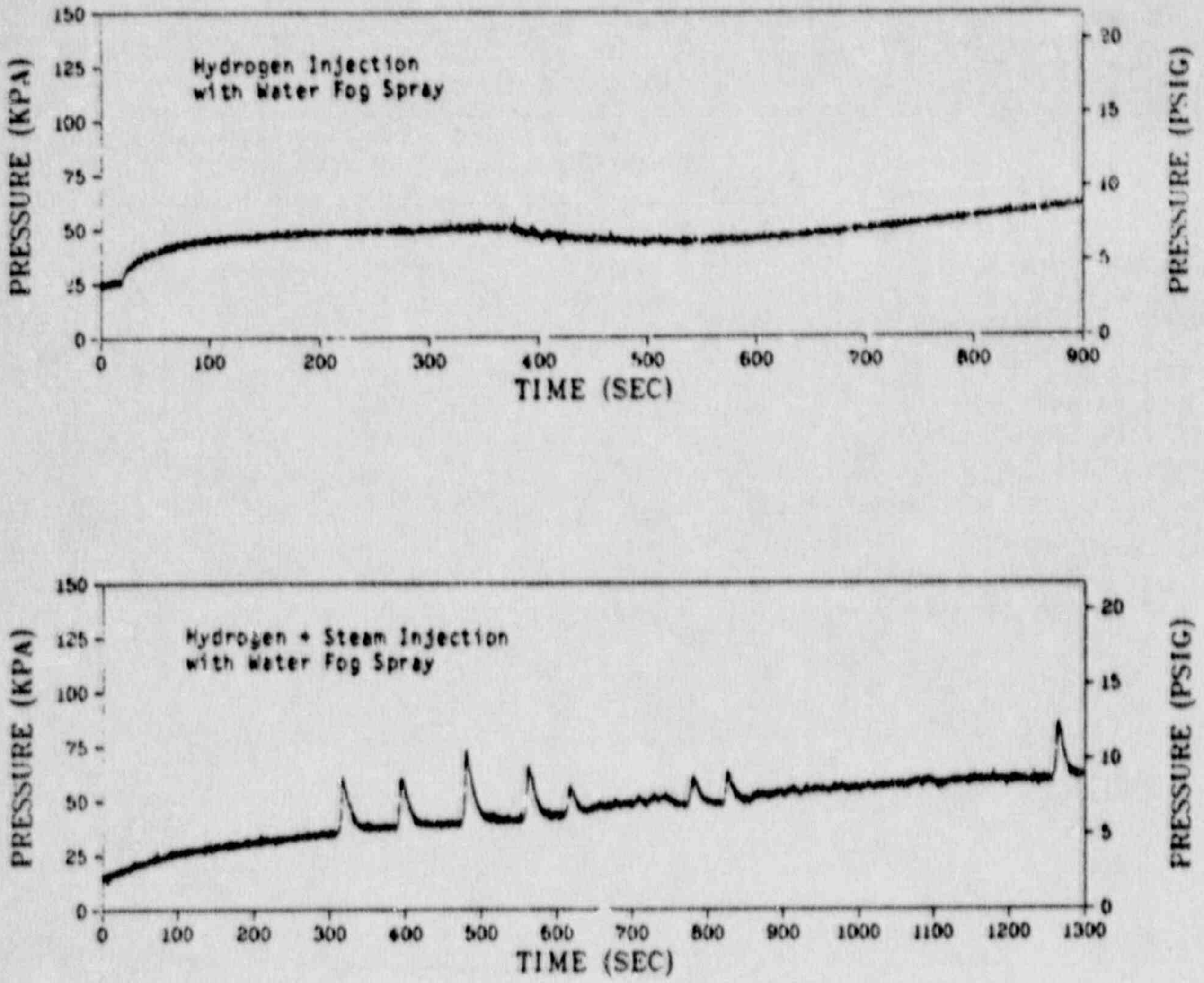


Figure 7.4 Effects of steam injection and water fog in Acurex continuous injection tests (taken from Reference 19).

8. FENWAL TESTS

Fenwal Incorporated conducted an experimental program for Westinghouse Electric Corporation and several utilities to determine the effectiveness of glow plug igniters in deliberate ignition systems [19]. Both premixed and continuous injection combustion tests were conducted with various mixtures of hydrogen, air, and steam to test the performance and durability of the glow plug igniter. The effect of fans and water sprays on the combustion process was also investigated here.

8.1 Facility Description

A schematic of the Fenwal facility is shown in Figure 8.1. The Fenwal tests were conducted in a 3.8 m^3 (1000 gal) spherical carbon steel vessel with a stainless steel liner and a pressure rating of 3.5 MPa (500 psig). The outside surface is insulated with 8 cm thick fiberglass insulation and there are penetrations for hydrogen injection, steam and water spray supply, and vessel drainage. Mixing of the gases in the vessel is accomplished with a 10 cm diameter fan. The igniter type used throughout the experiments is the GM AC 7G glow plug, installed with a spray shield to prevent direct water spray impingement.

8.2 Combustion Pressure Rises

Figure 8.2 presents the normalized peak pressure (ratio of peak-to-initial pressure) as a function of hydrogen concentration in hydrogen:air for each of the Fenwal premixed tests. Hydrogen concentrations tested ranged from 5 to 12% by volume, with steam fractions of up to 40%. The results show a sharp rise to nearly complete combustion at ~8% hydrogen. The presence of steam tended to decrease the peak pressure when compared to equivalent dry burns (i.e., burns with equivalent hydrogen-to-air ratio). The presence of water sprays tended to increase the peak pressure by inducing turbulence in the vessel mixture and introducing microturbulence due to the presence of water drops. Fans had a similar effect on the combustion peak pressure. The effect of sprays and fans was less at higher hydrogen concentrations.

8.3 Burn Characteristics in Premixed Tests

The Fenwal premixed tests confirmed the presence of a flammability threshold for hydrogen combustion. Figure 8.3 illustrates this effect for combustion in hydrogen:air (dry) mixtures. The figure shows that a burn can propagate upward at ~4% hydrogen concentration. A burn can propagate sideways at ~6% concentration, and at ~8.5% a burn can proceed in all three directions. For concentrations of 8.5% or greater, a substantial fraction of the hydrogen will burn and a significant pressure rise will occur. The figure also shows the theoretical deflagration/detonation ranges for hydrogen:air combustion at ambient conditions [20].

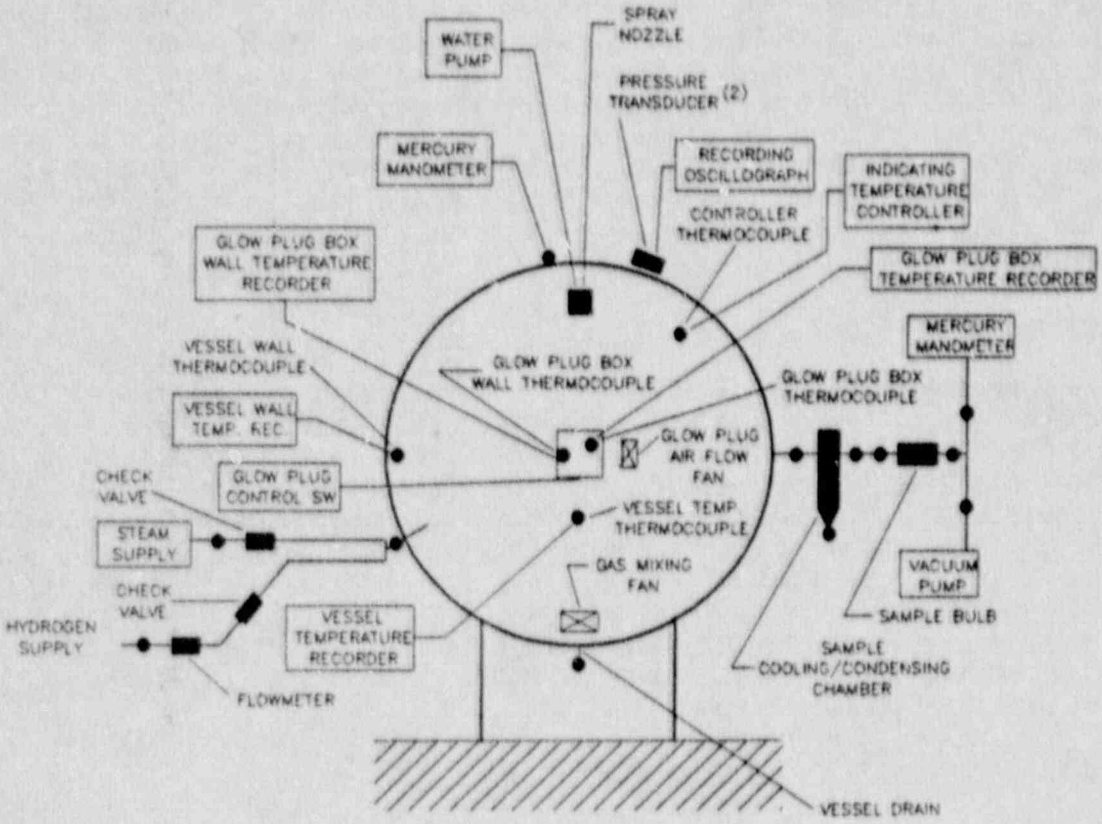


Figure 8.1 Schematic of the Fenwal test facility.

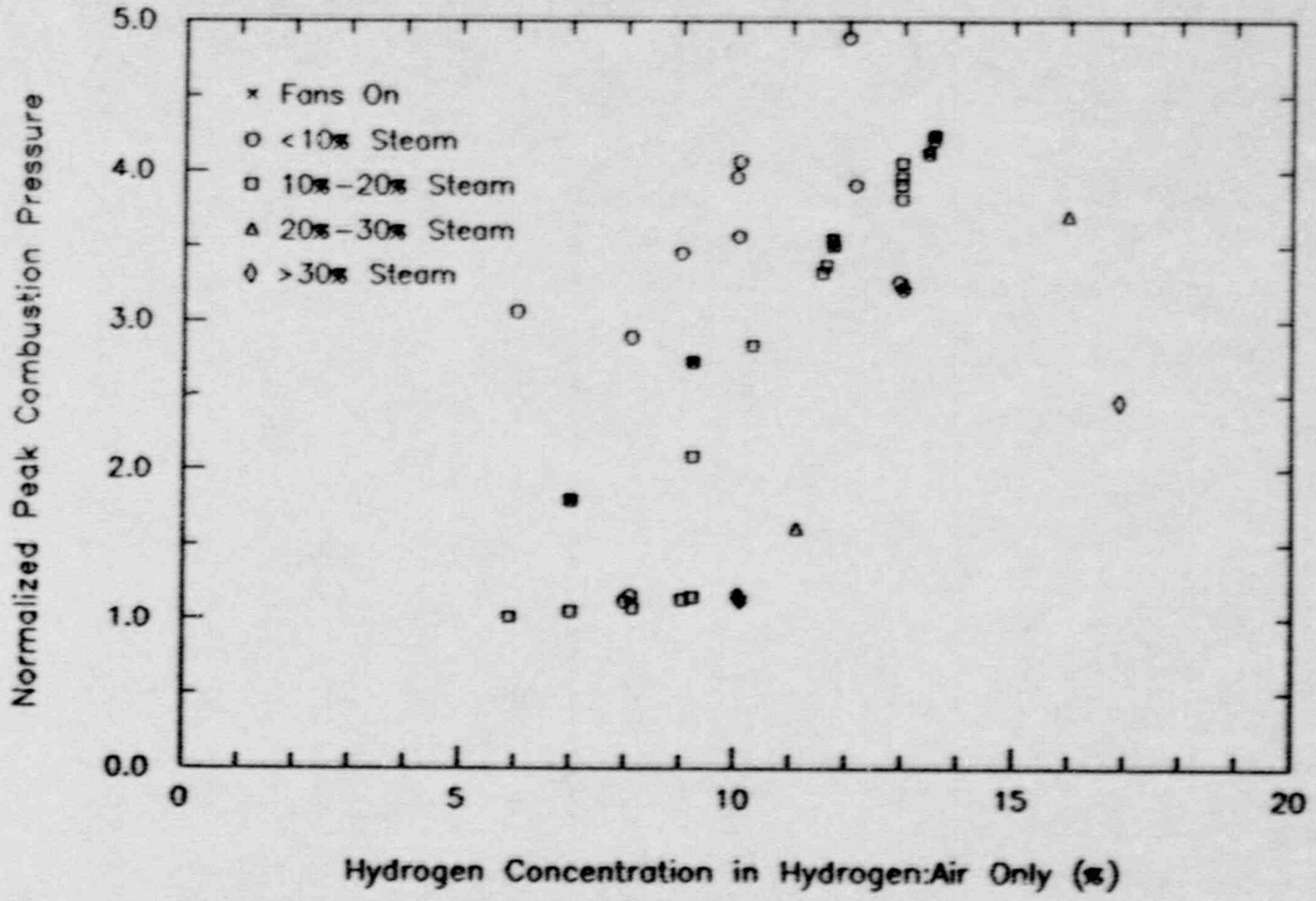


Figure 8.2 **Normalized peak combustion pressure for the hydrogen:air:steam burns in the Fenwal vessel as a function of the hydrogen concentration in hydrogen:air only.**

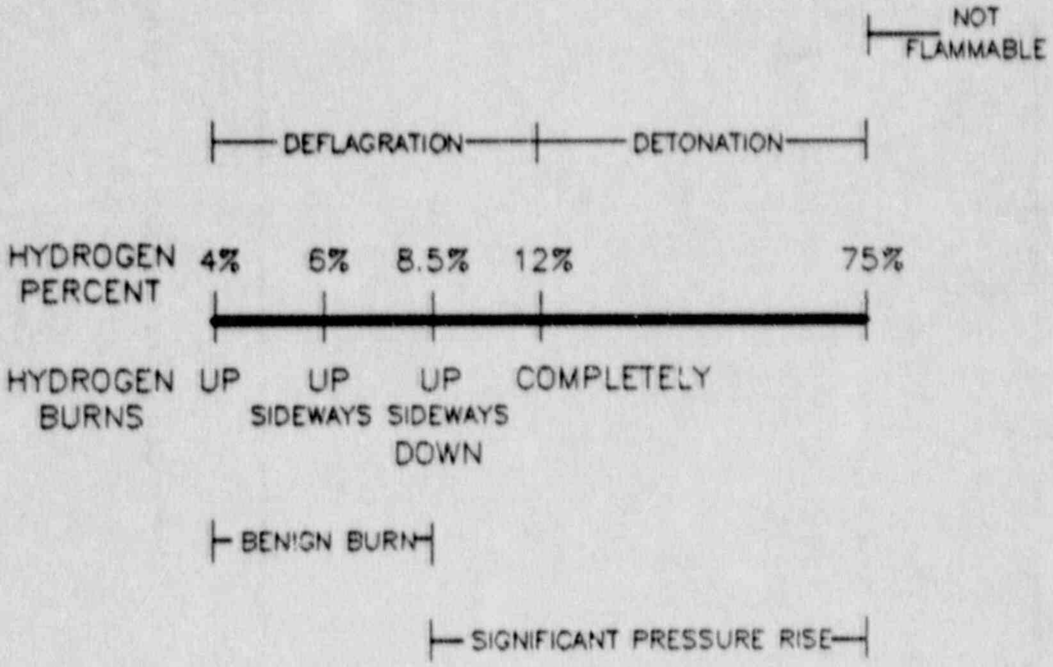


Figure 8.3 Combustion characteristics of hydrogen:air (dry) burns.

8.4 Burn Characteristics in Continuous Injection Tests

The dynamic combustion tests involved the continuous injection of hydrogen and steam (when specified) into the vessel with the glow plug energized. The hydrogen flow rate was ~0.01 kg/min (4 ft^3/min) for all cases, with a steam flow rate of ~1.4 kg/min (3 lb/min) for the hydrogen:steam injection test. An additional test was performed with a water spray turned on before hydrogen injection.

All cases show an initial pressure increase due to the hydrogen (and steam) injection before ignition. The calculated hydrogen concentration in the vessel mixture was about 5% at the first ignition for all three cases. The first ignition in the dry hydrogen injection test occurred at 100 sec, compared to 84 sec for the hydrogen:steam injection test. The pressure response for the hydrogen:steam case indicated multiple burns with generally increasing frequency, as opposed to the dry hydrogen case, which showed only two ignitions throughout the test. The ratio of the experimental pressure rise to the adiabatic pressure rise for the first ignition was similar (~28%) in both the dry hydrogen and hydrogen:steam cases. The presence of a water spray in a dry hydrogen injection test reduced the combustion pressure rise to only 12% of the adiabatic value, but had little influence on the time of ignition.

9. 1/4-SCALE MARK III CONTAINMENT HYDROGEN COMBUSTION PROGRAM

The Hydrogen Control Owners Group (HCOG) sponsored the 1/4-Scale Mark III Containment Hydrogen Combustion Program [21] to determine the thermal environment to which critical plant equipment in a Mark III containment may be subjected as a result of hydrogen combustion during a postulated degraded core accident. Results from this program provide an extensive data base for input to the evaluation of equipment thermal response and survivability under hydrogen burn conditions. The 1/4-Scale Program also provides a significant increase in the quality of hydrogen burn data applicable to Mark III containment facilities. This is due to improved modeling of internal structures and an increase in overall scale in comparison to earlier experiments, such as those conducted in a 1/20-scale model of a Mark III containment [22].

9.1 Facility Description

The test facility is a 1/4 linear scale model of a Mark III containment designed and constructed by Factory Mutual Research Corporation and located in West Glouster, Rhode Island. The facility was designed so that it could be easily modified to simulate the internal geometry of the various existing Mark III containments. The four plants studied were Perry Nuclear Power Plant, Grand Gulf Nuclear Station, River Bend Station, and Clinton Power Station. The facility was designed using Froude modeling [23] and provides a reasonably accurate simulation of the details of the containment systems which are expected to have an important effect on the modeling of the combustion phenomenon. These include a simulation of the distributed ignition system installed in Mark III containments, modeling of SRV sparger geometry and suppression pool characteristics, containment sprays, and fan coolers. The facility is capable of simulating the programmed simultaneous release of hydrogen and steam to the suppression pool.

A schematic of the 1/4-Scale Test Facility is shown in Figure 9.1. The test vessel is 15 m (49.4 ft) high and 9.6 m (31.5 ft) in diameter, containing a smaller tank (7.0 m (22.9 ft) high and 6.3 m (20.8 ft) in diameter) to simulate the drywell. The gap between the two tanks is fitted with modules to simulate the floors and large enclosed volumes present in actual containments. A body of water at the bottom of the gap simulates the suppression pool. The entire test facility is heavily instrumented to measure gas and surface temperatures, velocities, gas concentrations, heat fluxes, and pressure.

9.2 Approach of the 1/4-Scale Tests

Tests were performed in the 1/4-scale facility for four different facility configurations, simulating the internal geometries of Perry Nuclear Power Plant, Grand Gulf Nuclear Station, River Bend Station, and Clinton Power Station. Hydrogen was released either through the spargers of the automatic depressurization system (ADS) and through another sparger unit simulating a stuck-open relief valve (SORV) or through the simulated LOCA vents. Two hydrogen release histories were studied, using stepwise simulations obtained by hand fitting predictions from the BWRCHUC computer model [24], which calculates

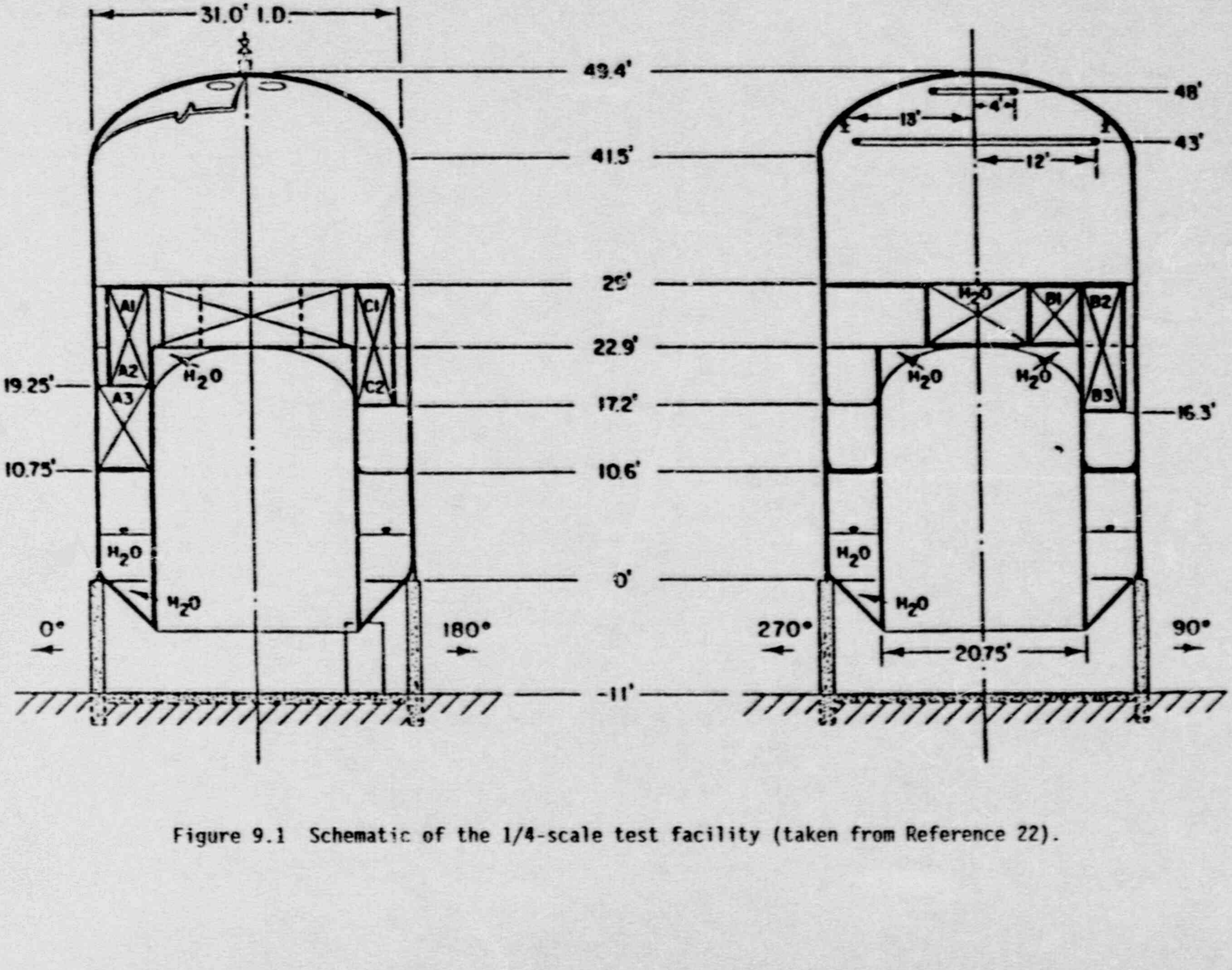


Figure 9.1 Schematic of the 1/4-scale test facility (taken from Reference 22).

core response to loss of coolant. The release histories presented here are for Grand Gulf; the rate of hydrogen release for the other plants was adjusted in proportion to core size. The first release history corresponds to a 0.57 m^3/min (150 gpm) reflood of the core at 3100 seconds in the accident sequence. The hydrogen release rate in this case reaches a peak of ~0.45 kg/s (1.0 lb/s) at ~3500 seconds, dropping during the following 1000 seconds to less than 0.07 kg/s (0.15 lb/s). The total release up to this portion of the transient corresponds to 23.8% MWR. The 1/4-Scale stepwise simulation extends the release by appending a tail of constant 0.07 kg/s up to a total release corresponding to 75% MWR. The second release history corresponds to a 19 m^3/min (5000 gpm) core reflood at 3870 seconds. In this case, the hydrogen production rate reaches a peak of 4.3 kg/s (9.5 lb/s) for a very short period, then decreases to essentially zero in the next 160 seconds. This peak value exceeded the capability of the hydrogen metering system. Since the peak value could not be simulated, the total hydrogen released in it was matched by providing full flow (~1.1 kg/s (2.4 lb/s) full scale) for the time needed to simulate the total hydrogen release, in this case corresponding to 17.3% MWR.

9.3 Results of the 1/4-Scale Tests

Results from the 1/4-Scale Test Program were presented for experiments conducted in a geometry applicable to the Perry Nuclear Power Plant. Results of additional tests for the other plant geometries were still being analyzed by HCOG at the time of this writing. The results presented so far demonstrate that, over the conditions tested, the distributed glow plug igniter system provides an effective means for limiting the accumulation of hydrogen in Mark III containments. Hydrogen concentrations throughout the test facility were maintained below 4-5% by volume (dry basis) even when the oxygen was depleted to a level of 7.2%, regardless of the magnitude of the hydrogen release rate.

For the first release history (peak of 0.45 kg/s full scale followed by drop to 0.07 kg/s), the global hydrogen concentration typically increased to about 2% by volume before ignition occurred in the wetwell. Ignition transients were modest, with no pressure excursions over 10 kPa (1.4 psi). Following ignition, diffusion flames became established on the surface of the suppression pool. This was the dominant mode of combustion, and occurred for oxygen concentrations above 8% and hydrogen injection rates greater than 0.07 kg/s. Flames were fairly steady during this phase and reached a maximum height of about 2.4 m (8 ft) full scale for a hydrogen injection rate of 0.45 kg/s (1 lb/s). Combustion was essentially complete during this high-release portion of the transient, indicated by a fairly constant background hydrogen concentration. Gas temperatures over the bulk of the test volume were generally low (below 90°C (200°F)) for this type of burning, with selected areas (above the hydraulic control unit (HCU) floors) over 180°C (350°F). Actual absolute maximum temperatures (i.e. flame temperatures) were not detected by the instrumentation, and would be higher than those of the bulk gas.

As the hydrogen flow decreased to 0.07 kg/s (0.15 lb/s), combustion became less complete and the flames less stable. Flame extinction on the suppression pool surface would occur for a period until the hydrogen concentration increased. The pool surface would be reignited and the background hydrogen concentration in the wetwell stabilized at about 4.5%. As the oxygen concentration decreased, the flames became weaker and the flame height increased slightly. Under certain conditions in which the oxygen concentration fell below 8%, the diffusion flames on the surface of the pool were extinguished and re-established at the HCU floor level above the SORV. This phenomenon, which was also observed in 1/20-scale testing, is referred to as secondary burning, or lifted diffusion flames. Conclusions regarding lifted diffusion flames cannot be made with certainty from the 1/4-Scale tests due to lack of available data.

At very low hydrogen injection rates of 0.03-0.01 kg/s full scale (0.07-0.022 lb/s), flames were extinguished on the pool surface and localized combustion was measured above the HCU floor, concentrated mostly in chimney areas. This type of burning appeared to be relatively benign, but there was insufficient instrumentation to fully assess the effects. Localized combustion was more widespread and more intense at low oxygen conditions, and was accompanied by slightly higher background hydrogen concentrations. The activation of sprays at the low hydrogen injection rates had the effect of concentrating the burning in one chimney and reducing it in the others.

Scoping tests demonstrated that varying the injection rate of steam by a factor of 2.0-3.5 with the same hydrogen release had no measurable effect on flame behavior and peak gas temperatures. Therefore, this parameter was not varied during production tests, and a constant steam injection rate of 2.5 m^3/min (90 ft^3/min) was used. The presence of a grating near the suppression pool tended to increase the heat losses from the hydrogen flames, resulting in a cooler environment at the HCU floor. This was indicated by a 2 kPa (0.3 psi) or ~10% difference between the average combustion pressure rise for tests with and without the grating. The major effect of containment sprays was to lower the background gas temperature to the spray water temperature. Though improved gas mixing is a likely result of spray operation, there was no evidence of change in the overall flow circulation patterns as a result of containment sprays. Results do indicate, however, that spray operation may cause a slight decrease in the flame extinguishment limit.

10. SUMMARY

This report summarizes the results of eight experimental research programs regarding the performance of thermal igniters for deliberate ignition systems in LWR's. The results of the research programs provide a broad data base covering nearly all aspects of hydrogen combustion related to the performance of deliberate ignition systems (See Table 1.1, p. 5). Though clear conclusions regarding certain combustion characteristics can be difficult to draw due to uncertainties in the scaling of experimental data and differences in testing methods (test apparatus, initial conditions, instrumentation, data reporting), general trends regarding most aspects of the combustion processes can clearly be defined.

10.1 Flammability Limits

Data regarding the flammability limits of hydrogen:air:steam mixtures were reported for the FITS, LLNL, and Whiteshell tests. Figures 2.2, 2.3, and 6.2-6.4 present the flammability data for the FITS and Whiteshell tests. A correlation of the FITS data was developed to describe the three-component flammability limit (Equation 2.1). The Whiteshell data includes a comparison of the lean flammability limits for the GM AC 7G glow plug and the Tayco helical igniter, and matches the FITS correlation for the lean and rich flammability limits and steam-inert concentration. Data from LLNL and other test programs provides useful information on hydrogen:air:steam flammability over a smaller range of hydrogen and steam concentrations.

For mixtures of hydrogen and air only, the lower flammability limit for glow plug ignition is approximately 5% hydrogen (by volume) for quiescent mixtures and between 4% and 5% hydrogen for turbulent mixtures. The upper flammability limit for hydrogen:air mixtures is approximately 75% hydrogen for both quiescent and turbulent mixtures. Turbulence has less of an effect on the flammability limits for hydrogen-rich mixtures than for lean mixtures.

In the presence of steam, mixtures of hydrogen and air can be inerted if the steam concentration is greater than ~55% by volume. The VGES tests demonstrated that CO_2 has a comparable effect, and that ~54% CO_2 by volume will inert a hydrogen:air mixture.

10.2 Combustion Pressure Rises

Combustion pressure rises were measured and presented for all of the test programs, usually in terms of normalized peak pressure (ratio of peak-to-initial pressure) as a function of hydrogen concentration in hydrogen:air only. When presented in this manner, various trends can be observed. Peak combustion pressure increases rapidly with hydrogen concentration from 5% to 8%, and becomes a substantial fraction of the adiabatic isochoric complete combustion peak pressure for hydrogen concentrations above 8%. The normalized peak pressure increases with increasing hydrogen concentrations up to ~30%, at which point it decreases with further increases in hydrogen concentration.

Pre-combustion gas motion is <u>very</u> important for hydrogen concentrations below 10%, as demonstrated in the VGES tests (Figure 3.3). Burns in turbulent mixtures produce higher peak pressures than burns in quiescent mixtures, due to an increase in combustion completeness and energy release rate. Water sprays tend to induce more turbulence than fans for both pre-mixed combustion and burns involving continuous injection of hydrogen. This is illustrated in Figures 4.4 and 4.5 for the NTS experiments. Sprays also introduce microturbulence due to the mere presence of water droplets. The effect of sprays and fans is diminished at higher hydrogen concentrations.

The presence of steam in mixtures of hydrogen and air tends to lessen the combustion severity when compared to burns with equivalent hydrogen:air volume ratios in the absence of steam. This is shown in all test programs involving steam. Steam acts as a heat sink and inert diluent in reducing combustion pressure excursions and peak gas temperatures. Pre-combustion gas pressure can influence the combustion characteristics of hydrogen:air and hydrogen:air:steam burns. Reducing the pre-combustion gas pressure causes a slight decrease in the normalized peak pressure due to a reduction in the number of moles available for combustion.

10.3 Combustion Completeness

Data on combustion completeness, or the fraction of original hydrogen consumed, were presented for all the test programs investigating premixed combustion. Figures 4.2, 5.2-5.3, and 6.5-6.6 present combustion completeness data from the NTS, LLNL, and Whiteshell test programs, respectively. Generally, there is a direct relationship between the initial concentration of hydrogen and the fraction of hydrogen burned. Complete combustion occurs in hydrogen:air mixtures if the hydrogen concentration is greater than ~8% by volume. The activation of fans or water sprays will induce turbulence and increase the completeness (compared to equivalent quiescent burns) in mixtures with less than 8% hydrogen. The presence of steam tends to lessen the combustion completeness, especially for mixtures with initial steam concentrations greater than 30%.

10.4 Effect of Igniter Type and Location

The two types of igniters currently installed in deliberate ignition systems are the GM AC 7G glow plug and the Tayco helical igniter, shown in Figures 1.1 and 1.2. The VGES and Whiteshell programs compare the effectiveness of the two igniter types. Both igniters prove reliable in igniting hydrogen:air mixtures at the lower flammability limit. Table 3.1 shows some performance parameters for the GM AC 7G glow plug and the Tayco helical igniter. The surface temperature required for ignition is about 100°C higher for the glow plug than for the helical igniter. The helical igniter, however, is more strongly affected by impinging water sprays than is the glow plug. The VGES tests demonstrate that the Tayco igniter does not operate properly in unshielded spray fluxes above 24 $L/m^2 \cdot min$, while the GM glow plug is able to operate in spray fluxes of more than twice that value. In addition, these threshold spray fluxes are reduced if the igniters are not allowed to heat up before the sprays are activated. VGES also demonstrates that gas flows between 10 and 20 m/s are sufficient to cool both igniter types to temperatures below which they will satisfactorily ignite lean (6%) hydrogen:air mixtures.

The effect of igniter location was investigated in most test programs. Igniter location is only important in the combustion of lean (<8%) hydrogen mixtures, since downward flame propagation is limited in these cases. The combustion completeness is lowered if an igniter is located high in a volume because the flame propagates only upward. Igniters distributed throughout a volume, as they are in containments employing deliberate ignition systems, are more effective in igniting and preventing the accumulation of combustible mixtures of hydrogen. The distributed glow plug system utilized in the 1/4-Scale tests maintained global hydrogen concentrations below 4-5% by volume (dry basis) over the range of hydrogen injection rates investigated.

10.5 Flame Speeds

Data on combustion flame speeds were reported for nearly all the test programs. Figures 3.4, 3.5, and 4.7 present data on flame speed or burn duration for the VGES and NTS tests. The results show that the average flame speed increases with initial hydrogen concentration. Higher flame speeds are attained in burns with fans on (turbulent) as opposed to burns with fans off (quiescent). This is especially true for hydrogen concentrations below ~10%. Figures 3.4 and 3.5 show that upward flame propagation is generally faster than downward propagation. A comparison of data between test programs suggests that upward flame speeds at lean hydrogen concentrations increase with vessel size, presumably due to buoyancy effects.

The NTS tests demonstrated that flame spherical propagation is not meaningful for representing large volumetric burns with low hydrogen concentration (5%-8%) due to variations in geometry. A more accurate representation of large scale combustion phenomena is burn duration, defined as the time interval from combustion initiation to the time of peak pressure. Figure 4.7 shows that burn duration decreases with increasing hydrogen concentration due to increased turbulence in the flames, and that sprays are more effective than fans in inducing turbulent mixing.

10.6 Heat Transfer Characteristics

Measurements of heat transfer or energy deposition to vessel walls were carried out for the FITS, VGES, Fenwal, and 1/4-Scale test programs. Figures 2.6 and 2.7 present ratios of radiative to total energy deposition in the FITS vessel for both hydrogen:air and hydrogen:air:steam burns. Figures 4.8 and 4.9 show the peak radiative and total heat flux results from the NTS program for 5% steam and >10% steam tests.

Convection is the dominant energy transfer mechanism for lean (<10%) hydrogen:air and hydrogen:air:steam burns. Radiation is slightly more prevalent for dry burns of near stoichiometric mixtures. Radiation is the dominant cooling mechanism for hydrogen:air:steam burns with moderate quantities of steam (<20%) due to the increase in bulk gas emittance. Convection and radiation are equally important mechanisms for very rich steam concentrations due to the reduced combustion severity and lower post-combustion gas temperature.

10.7 Combustion Characteristics of 1/4-Scale Tests

The 1/4-Scale tests are unique when compared to the other test programs reviewed here in that these are the only tests carried out in a scale model of a containment. Due to the increased overall scale and modeling of internal containment structures, the 1/4-Scale program provides a significant increase in the quality of hydrogen diffusion flame data applicable to Mark III containment facilities.

The 1/4-Scale experiments demonstrated that, over the conditions tested, the distributed glow plug igniter system provides an effective means for maintaining the hydrogen concentration below 4-5% by volume. Ignition transients during the tests were modest, with no pressure excursions over 1.4 psi, and ignition usually occurred at average hydrogen levels of 1-2%.

The dominant mode of combustion for oxygen concentrations above 8% and hydrogen injection rates greater than 0.15 lb/s (full scale) was diffusion flames anchored to the surface of the suppression pool. The injection rate for flame stability, however, was dependent on background hydrogen concentration, and could decrease to ~0.03 lb/s (full scale) as hydrogen concentrations approached 4.5%. Gas temperatures over the bulk of the test volume were generally low (below 200°F) for diffusion flame burning, with selected areas (above the hydraulic control unit floors) over 350°F. At low oxygen concentrations (below 8%), lifted diffusion flames were observed as flames were extinguished on the pool surface and re-established at the HCU floor level. In experiments involving very low hydrogen injection rates (0.02-0.07 lb/s full scale), relatively benign localized combustion was measured above the HCU floor, but there was insufficient instrumentation to fully assess the effects.

10.8 Scaling Considerations

The experimental research programs reviewed here provide deflagration and diffusion flame data in test vessels varying in volume from 0.02 to 2000 m^3, in addition to data obtained from the 1/4-Scale experiments. Although scaling relationships are available for diffusion flame lengths and temperature and velocity distributions (See Ref. 25), direct extrapolation of the test data to full-scale containment volumes (30,000 to 40,000 m^3) is not feasible due to geometric dissimilarities and the lack of direct scaling laws for the turbulent combustion and heat transfer phenomena associated with lean hydrogen:air:steam mixture burns. The subscale test data presented here are useful in identifying scaling trends and providing insights into relevant combustion phenomena. The test data also provides validation and input for containment system computer codes, which are well-equipped to incorporate geometry and heat transfer effects in modeling actual containment combustion scenarios.

11. REFERENCES

1. Rasmussen, N.C., H.J.C. Kouts, E.K. Dabora, G.M. Faeth, A.K. Oppenheim, D.J. Seery, and R.G. Zalosh, "Technical Aspects of Hydrogen Control and Combustion in Severe Light-Water Reactor Accidents," National Research Council Committee on Hydrogen Combustion, 1986.

2. Orrin, J.E., I.M. Vince, and F.J. Weinberg, "A Study of Plasma Jet Ignition Mechanisms," The Combustion Institute, Eighteenth Symposium (International) on Combustion, Pittsburgh, Pa., 1981.

3. Mittinti, D.N.R., and E.K. Dabora, "Plasma Jet Ignition Studies," The Combustion Institute, Twentieth Symposium (International) on Combustion, Pittsburgh, Pa., 1984.

4. Thorne, L.R., J.V. Volponi, and W.J. McLean, "Platinum Catalytic Igniters for Lean Hydrogen/Air Mixtures," NUREG/CR-5086, SAND88-8201, Sandia National Laboratories, Livermore, CA, September 1988.

5. Renfro, D., L. Smith, L. Thompson, and R. Clever, "Development and Testing of Hydrogen Ignition Devices," Proceedings of the Second International Conference on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, NM, October 3-7, 1982.

6. Marshall, B.W., "Hydrogen:Air:Steam Flammability Limits and Combustion Characteristics in the FITS Vessel," NUREG/CR-3468, SAND84-0383, Sandia National Laboratories, Albuquerque, NM, December 1986.

7. Ratzel, A.C., S.N. Kempka, J.E. Shephard, and A.W. Reed, "SMOKE: A Data Reduction Package for Analysis of Combustion Experiments," NUREG/CR-4136, SAND83-2657, Sandia National Laboratories, Albuquerque, NM, September 1985.

8. Benedick, W.B., J.C. Cummings, and P.G. Prassinos, "Combustion of Hydrogen: Air Mixtures in the VGES Cylindrical Tank," NUREG/CR-3273, SAND83-1022, Sandia National Laboratories, Albuquerque, NM, May 1984.

9. Thompson, R.T., R.C. Torok, D.S. Randall, J.S. Sullivan, L.B. Thompson, and J.J. Haugh, "Large-Scale Hydrogen Combustion Experiments," EPRI NP-3878, Vols. 1 and 2, 1985.

10. Hacking, D.B., "Nevada Test Site Data Evaluation," Hydrogen Control Owners Group Program Plan Task 14, HGN-100, July 1986.

11. Ratzel, A.C., "Data Analyses for Nevada Test Site Premixed Combustion Tests," NUREG/CR-4138, SAND85-0135, Sandia National Laboratories, Albuquerque, NM, May 1985.

12. Shepard, J.E., "Analysis of Diffusion Flame Tests," NUREG/CR-4534, SAND86-0419, Sandia National Laboratories, Albuquerque, NM, August 1987.

13. Lowry, W.E., B.R. Bowman, and B.W. Davis, "Final Results of the Hydrogen Igniter Experimental Program," NUREG/CR-2486, UCRL-53036, February 1982.

14. Altenbach, T.J., B.W. Davis, R.W. Martin, and T.A. Reitter, "Data Analysis of the LLNL Hydrogen Igniter Experiments," NUREG/CR-3225, UCRL-53049, May 1983.

15. Tamm, H., R. McFarlane, and D.D.S. Liu, "Effectiveness of Thermal Ignition Devices in Lean Hydrogen-Air-Steam Mixtures," EPRI NP-2956, March 1985.

16. Tamm, H., M. Ungurian, and R.K. Kumar, "Ignition Effectiveness of the GM AC 7G Glow Plug in Rich Hydrogen-Air-Steam Mixtures," Hydrogen Control Owners Group Final Whiteshell Ignition Test Report, HGN-017, October 1983.

17. Torok, R.C., K. Siefert, and W. Wachtler, "Hydrogen Combustion and Control Studies in Intermediate Scale," EPRI NP-2953, June 1983.

18. Torok, R.C., K. Siefert, and L.B. Thompson, "Hydrogen Control Tests in Intermediate Scale," Proceedings of the Second International Conference on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, NM, October 3-7, 1982.

19. Liparulo, N.J., J.E. Olhoeft, and D.F. Paddleford, "Glow Plug Ignitor Tests in H_2 Mixtures," Proceedings of the Workshop on the Impact of Hydrogen on Water Reactor Safety, Albuquerque, NM, January 26-28, 1981.

20. Tieszen, S.R., M.P. Sherman, W.B. Benedick, and M. Berman, "Detonability of H2-Air-Diluent Mixtures," NUREG/CR-4905, SAND85-1263, Sandia National Laboratories, Albuquerque, NM, June 1987.

21. Tamanini, F., E.A. Ural, J.L. Chaffee, "Hydrogen Combustion Experiments in a 1/4-Scale model of a Mark III Nuclear Reactor Containment," Research Project Y101-1 Interim Report, Factory Mutual Research Corporation, May 1987.

22. Brown, R., S. Suttmann, and K. Wolfe, "Hydrogen Combustion Testing in a One-Twentieth-Scale Model of a BWR6/Mark III Containment. Volume I: Facility Description and Results Summary," Technical Report on EPRI Research Project 1932-32/Y101-3, Acurex Corporation, February 1984.

23. Tamanini, F., "Reduced-Scale Modeling of Diffusion Flames in Enclosures (The Case of Hydrogen Burning in the Mark III Containment)," FMRC Technical Report J.I. OH5R8.RK, February 1983.

24. Letter from J.R. Langley (HCOG) to R. Bernero (NRC), "BWR Core Heatup Code Report," HGN-096, dated June 30, 1986.

25. Shepard, J.E., "Hydrogen-Steam Jet-flame Facility and Experiments," NUREG/CR-3638, SAND84-0060, Sandia National Laboratories, Albuquerque, NM, 1985.

Distribution:

U.S. Nuclear Regulatory Commission (3)
Office of Nuclear Regulatory Research
Attn: A. Notafrancesco
T.J. Walker
P. Worthington
Washington, DC 20555

U.S. Nuclear Regulatory Commission (12)
Office of Nuclear Reactor Regulation
Attn: R. Palla
C. Poslusny
C.G. Tinkler (10)
Washington, DC 20555

Enercon (1)
Attn: E. Holcomb
520 W. Broadway, Suite C
Broken Arrow, OK 74012

Electric Power Research Institute (1)
Attn: J.J. Haugh
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Oak Ridge National Laboratory (2)
Attn: S.R. Greene
S.A. Hodge
Bldg. 9104-1, MS-8057
P.O. Box 2009
Oak Ridge, TN 37831

Sandia Distribution:

1512	J.C. Cummings
1513	R.E. Hogan
1513	A.C. Ratzel
1555	C.C. Wong
3141	S.A. Landenberger (5)
3151	W.I. Klein
6344	E.D. Gorham-Bergeron
6400	D.J. McCloskey
6410	D.A. Dahlgren
6412	A.L. Camp
6412	L.A. Miller
6412	A.C. Payne
6413	R.J. Breeding
6413	T.D. Brown
6413	J.J. Gregory
6415	R.M. Cranwell
6416	E.J. Bonano
6418	J.E. Kelly
6418	M.K. Carmel (16)
6418	S.E. Dingman

6419	M.P. Bohn
6420	W.B. Gauster
6420	F.E. Haskin
6429	K.D. Bergeron
6429	N.A. Russell
6517	M. Berman
6517	L.S. Nelson
6517	T.L. Pong
6517	D.W. Stamps
6517	S.R. Tieszen
8524	J.A. Wackerly

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-5079
SAND87-3139

2. TITLE AND SUBTITLE

Experimental Results Pertaining to the Performance of Thermal Igniters

3. DATE REPORT PUBLISHED

MONTH	YEAR
October	1989

4. FIN OR GRANT NUMBER

FIN A1301

5. AUTHOR(S)

Michael K. Carmel

6. TYPE OF REPORT

Topical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION – NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Sandia National Laboratories
Albuquerque, NM 87185

9. SPONSORING ORGANIZATION – NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering and Systems Technology
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report summarizes the results of various experimental programs regarding the performance of thermal igniters for the deliberate ignition of hydrogen in light water reactors. Experiments involving both premixed combustion and combustion with continuous hydrogen injection are reviewed. Combustion characteristics examined include flammability limits of hydrogen:air and hydrogen:air:steam mixtures, combustion pressure rises, combustion completeness, flame speeds, and heat transfer aspects. Comparisons of igniter type and igniter reliability under simulated reactor accident conditions are included. The results of the research programs provide a broad data base covering nearly all aspects of hydrogen combustion related to the performance of deliberate ignition systems.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

hydrogen combustion, igniters, deliberate ignition

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)
Unclassified

(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE

*U.S. GOVERNMENT PRINTING OFFICE:1989-262-435:00290

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

120555139531 1 1AN1R4
US NRC-OADM
DIV FOIA & PUBLICATIONS SVCS
TPS PDR-NUREG
P-209
WASHINGTON DC 20555

PERFORMANCE OF THERMAL IGNITERS