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Final Results of the Hydrogen Igniter Experimental Program

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FINAL RESULTS OF THE HYDROGEN IGNITER EXPERIMENTAL PROGRAM

ABSTRACT

Thermal igniters proposed by the Tennessee Valley Authority for intentional ignition of hydrogen in nuclear reactor containments have been tested in mixtures of air, hydrogen, and steam. The igniters, conventional diesel engine glow plugs, were tested in a 10.6 ft^3 pressure vessel with dry hydrogen concentrations from 4% to 29% hydrogen, and in steam fractions of up to 50%. Dry tests indicated complete combustion between 8% and 9% H_2, and no combustion for concentrations below 5%. Steam tests were done with hydrogen volume fractions of 8%, 10%, and 12%. Steam concentrations of up to 30% consistently resulted in ignition. Most of the 40% steam fraction tests resulted in combustion. In a few isolated cases the 50% steam fraction tests indicated a pressure rise. Circulation of the mixture improved combustion in both the dry and the steam tests, most notably at low H_2 concentrations. An analysis of the high steam fraction test data showed a high probability for the presence of small, suspended, water droplets in the test mixture. The suppressive influence of this condensation-generated fog on combustion is evaluated.

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FOREWORD

This document reports the final experimental results of the LLNL Hydrogen Igniter Test Program. The project was undertaken at the request of the Nuclear Regulatory Commission to provide technical assistance in the licensing process for the Tennessee Valley Authority's Sequoyah Unit 1 nuclear power plant. The program was funded and directed by the Containment Systems Branch (Division of Systems Integration) of the NRC Office of Nuclear Reactor Regulation. Its purpose was to independently test thermal igniters, proposed by TVA, as combustion initiators in environments containing known concentrations of hydrogen, air, and steam.

The test program was administered by the Reactor Safety Program of the LLNL Nuclear Systems Safety Program. Experimental design and project management were supplied by the Thermo Fluid Mechanics Group of the Nuclear Test Engineering Division.

Design, fabrication, and conducting the first phase of the tests was to be completed in three months. The ability of this program to produce experimental results in such a short time was due to the excellent support provided by various organizations at LLNL. The authors would like to acknowledge the contributions of the following people:

- Bill Comfort and Dick Martin who provided conceptual design and subsequent technical assistance;
- Bill Shay and John Holm, who provided instrumentation support;
- Del Eckels and Gary Power, who provided mechanical support;
- Rex Blocker and John Mellor who were responsible for program coordination; and
- Bob Kaster, Fred Sator, and Hal Vyverberg, who carried out the Site 300 bunker operation.

Additional appreciation is extended to US NRC contacts, Charles Tinkler and Walt Butler, for their patience and cooperation.

EXECUTIVE SUMMARY

The US Nuclear Regulatory Commission (NRC) has engaged the Lawrence Livermore National Laboratory (LLNL) to evaluate the capability of glow plugs to function as ignition sources in hydrogen/air/steam environments. The glow plugs are the active components of a hydrogen mitigation system, proposed by the Tennessee Valley Authority, used to control hydrogen released into the containment from a loss of coolant accident involving core degradation.

Tests were conducted in a 10.6 ft^3 insulated pressure vessel. Primary data recorded included temperature, pressure, and gas concentration measurements. Dry hydrogen/air tests were conducted with hydrogen concentrations as high as 29% by volume, and steam tests with 8% to 12% hydrogen concentrations and steam fractions as high as 50%.

Dry tests showed the glow plug to be capable of at least partially igniting hydrogen/air mixtures as low as 6% H_2, and down to 5% H_2 if the mixture was circulated. As the hydrogen concentration approached 9%, a jump to relatively complete combustion took place. Stoichiometric hydrogen/air tests (29% H_2) produced no detonation pressures with either the glow plug or a one-Joule spark source.

Steam tests with H_2 fractions from 8% to 12% and steam fractions of 10% to 30% consistently produced burns. Three 40% steam tests did not combust, as would be indicated with discrete pressure/temperature rises. With a few exceptions, no 50% steam fraction test ignited. In most steam tests, circulation of the mixture increased the degree of burn completeness.

In order to explore more severe, but less likely, conditions under which glow plugs must function, several condensation-type tests were conducted in which the vessel was charged up to a 50% steam, 10% H_2 condition. The steam was then allowed to condense slowly while the glow plug remained activated. Frequently, the steam would condense enough so the bulk vessel conditions appeared to be similar to previous tests in which the mixture combusted. Rarely was any discrete pressure rise noted, although hydrogen had been consumed as indicated by the gas analysis. Subsequent examination of the data had indicated a high probability of enough suspended water droplets in the vessel mixture to suppress combustion. It was clear that thermal

recombination was taking place in the longer tests. Another effect noted was the possibility of a fuel-lean zone around the glow plug due to the evaporation of local suspended water droplets, which would increase the local steam fraction.

Throughout the test series no deterioration was noted in the glow plug's heat-up characteristics.

CHAPTER 1: INTRODUCTION

TMI-2 AND THE HYDROGEN PROBLEM

During the Three Mile Island Unit 2 accident in March 1979, gaseous hydrogen produced in the reactor vessel was released into the containment building and combusted to produce a substantial pressure rise of 28 psi. The fact that hydrogen was produced was not unexpected, since reactors are equipped with thermal recombiners designed to assimilate hydrogen from radiolytic decomposition of water in a design-basis loss-of-coolant accident (LOCA). However, the TMI-2 event was not a design-basis LOCA; the open relief valve and subsequent operator errors closely represented a small LOCA compounded by Emergency Core Cooling System override. This led to a gross uncovering of the core fuel assemblies for a significant length of time, releasing excessive hydrogen as a result of the interaction of steam with the zirconium fuel cladding. The conventional thermal recombiners were not capable of handling the high rate of hydrogen produced from this degraded-core metal-water reaction.

It is suspected that most of the hydrogen was released into the containment atmosphere during the first four hours of the accident. Steam generator pressure transducers sensed a rapid 28 psi pressure rise, and temperature sensors noted a $50^{o}F$ increase approximately ten hours after the accident. Varied opinions exist regarding both the amount of hydrogen present and the probable source of ignition. It is generally agreed that the pressure rise was a result of a hydrogen burn. Post accident analyses have estimated that approximately 45% of the fuel cladding had reacted (the design basis assumes only 5% of the fuel cladding would react). Subsequent entrances into the containment building have produced confirming evidence, in the form of charred equipment and overpressure damage, that a burn did occur.

NRC AND INDUSTRY RESPONSE

The observed 28-psi pressure spike was well below the TMI-2 design pressure of 55 psig; however, this event was clearly not one included in design basis accident scenarios. The containment building at TMI-2 is classified as a "large dry" containment. This means that its net free volume is about two to three million cubic feet. Containment buildings classified as "intermediate" have volumes of 1.2 to 1.5 million cubic feet (with corresponding design pressures of 12 to 15 psig); those classified as "small" containments have volumes of approximately 0.3 million cubic feet (45 to 62 psig design pressures).

The vulnerability of a containment building to hydrogen combustion is a function of several variables. Included among these are: 1) quantity and rate of hydrogen combustion; 2) volume of the containment; and 3) pressure capability of the containment. Examination of the design of light water reactor containments reveals that the pressure suppression containments are more vulnerable because of their smaller volume or lower pressure capacity. The pressure suppression containments include the small Mark I and II boiling water reactor (BWR) containments, the intermediate-sized Mark III BWR, and the ice condenser PWR containments.

The NRC has determined that small containments (BWR Mk I & II) might fail if 6 to 9% of the fuel cladding reacted with steam and subsequent combustion of the hydrogen produced an adiabatic pressure rise (Ref. 1). Consequently, an interim rule, posted October 1980, required that the atmospheres of these units be made inert by purging the containment with nitrogen. Most Mark I and II BWR's already operate in this manner so this ruling only affected new plants and two existing plants. The large PWR dry containments, by virtue of their large volume (2-3 million ft^3)and higher design pressures (50-60 psig), are capable of withstanding pressures resulting from combustion of hydrogen produced by the reaction of 100 % of the fuel cladding. Consequently, for these structures no near-term mitigation measures were required.

Similar calculations indicate that the intermediate containments may fail if 25% of the fuel cladding were to react and the resulting hydrogen released into the containment to ignite instantaneously. These plants have not been purged with an inert gas in the past because frequent entry is required for maintenance and inspection. Consequently, the NRC has required, pending a rulemaking on degraded core accidents, that owners of intermediate containments provide additional control capability to accommodate hydrogen produced by a 75% reaction of the cladding.

The first utility to address the issue of degraded-core hydrogen control was the Tennessee Valley Authority (TVA) in the process of licensing the Sequoyah Unit 1 plant, an ice condenser unit (see Fig. 1). TVA has proposed to use an array of 45 thermal igniters, called the Interim Distributed Ignition System (IDIS). These igniters are conventional diesel-engine glow plugs (shown in Fig. 2), which are to be spaced throughout the containment volume and activated at the start of an accident sequence. The purpose of the IDIS is to ignite the gas mixture at lower concentrations of hydrogen, preventing the accumulation of a mixture which could threaten the integrity of the containment structure. Each igniter is mounted on a metal housing powered by a 120 Volts ac (VAC) to 14 VAC step-down transformer.

TVA received its license to operate Sequoyah Unit 1 in September 1980. For operation of the plant beyond January 31, 1982, the NRC must confirm that the hydrogen control measures installed will provide adequate safety margins. At the time of this writing, TVA was in the process of developing the permanent hydrogen mitigation system. The permanent system is envisioned to represent an improvement of the IDIS while retaining the concept of locating thermal igniters throughout the containment.

PREVIOUS RESEARCH

Although hydrogen combustion has been studied for years, information applicable to the utilization of thermal ignition sources in containment environments is not plentiful. Most ignition sources studied have been either

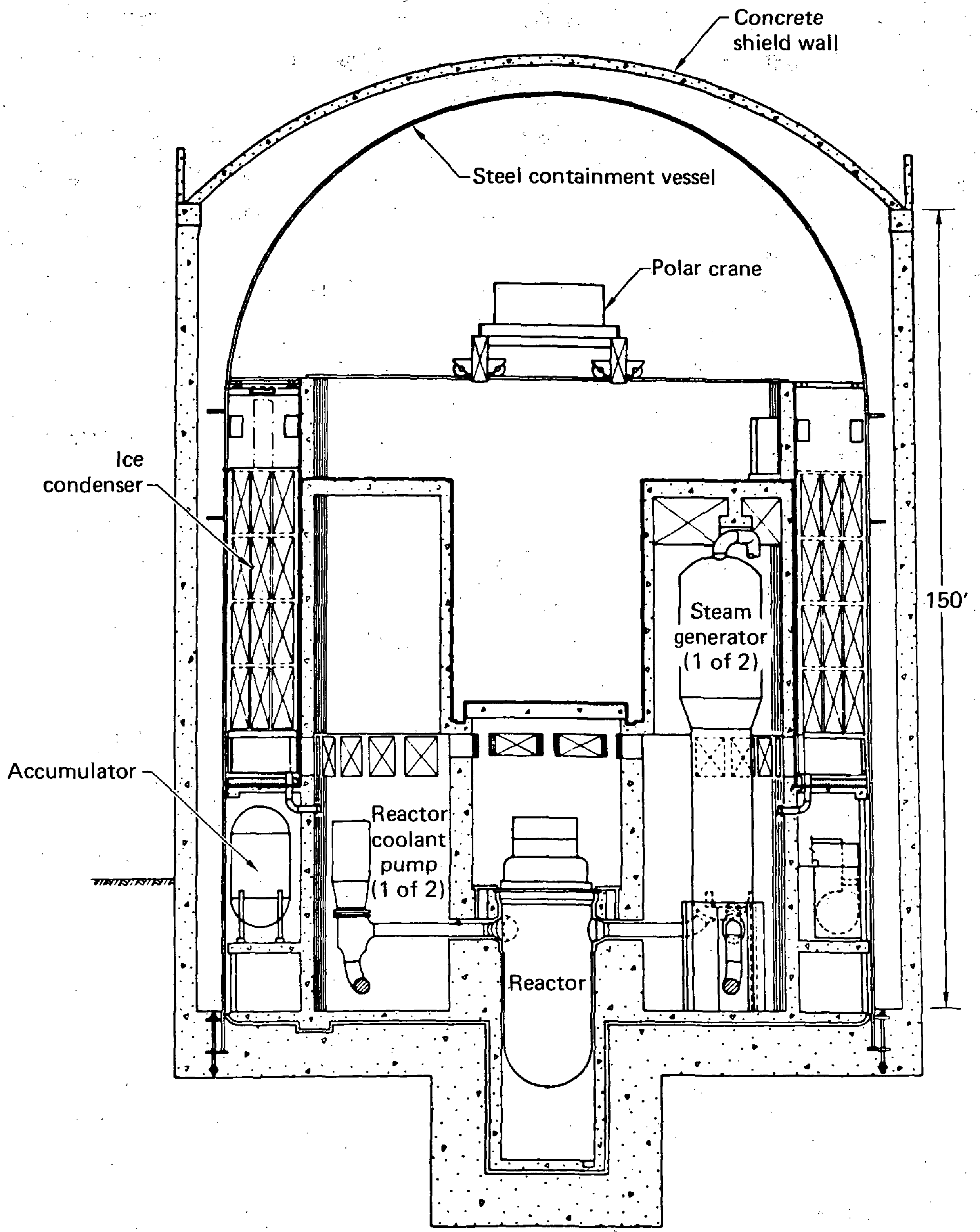


FIG. 1. The Sequoyah Unit 2 containment vessel encloses approximately 1 million cubic feet of free volume. Forty-five igniters are spaced throughout that volume.

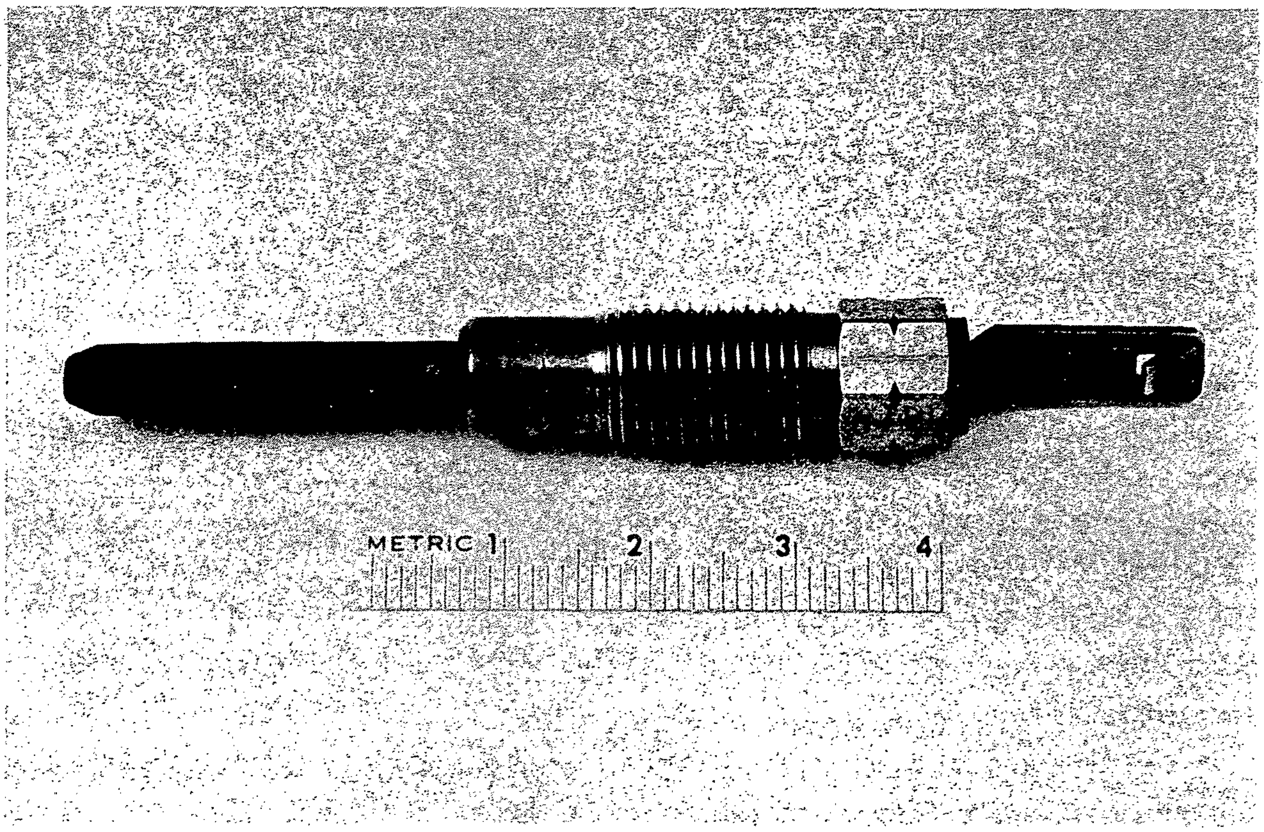


FIG. 2. TVA chose the GM AC-7G glow plug as the thermal ignition source in their Interim Distributed Ignition System (IDIS). The heating element is the 1-in.-long by 3/16-in.-diameter rod on the left.

of the spark or pyrofuse type, capable of imparting large amounts of energy to a small volume in a short time. The TVA glow plugs, however, are of low power density and require a heat-up period of 12 to 20 seconds before reaching the hydrogen ignition temperature. At that temperature, they emit from 150 to 220 W/in.^{2} over a surface area of 0.6 in.,^{2} depending on the input voltage (which varied from 12.0 to 14.4 VAC in the LLNL tests). An area of concern is whether the igniters will function as intended in the post LOCA containment environments. Typically, the post-LOCA atmosphere will contain some fraction of steam and suspended water droplets. These water droplets may be created by the expulsion of water from a break in the reactor coolant system, condensation of steam in the atmosphere, or by operation of the containment spray system.

Previous research has generally applied to dry hydrogen-air mixtures ignited in small volumes. Extensive examination of dry hydrogen combustion in enclosed spaces has been conducted by the United States Bureau of Mines (Refs. 2 and 3). They have emphasized the identification of flammability and detonation limits. In the last several years the nuclear power industry has directed more attention to hydrogen management safety issues. Canadian researchers (Ref. 4) have studied the effects of steam on hydrogen combustion near the lower flammability limit and the effect of initial temperature on burn velocities. Utility-sponsored experiments at Atomics International (Ref. 4) utilized a shock tube to study flame and detonation initiation and propagation in hydrogen-air mixtures, which included an assessment of spray system effects. Work sponsored by General Electric (Ref. 6) assessed characteristics of lower-explosion limit hydrogen-air mixtures with a variety of ignition sources. More recently, TVA has sponsored a program to evaluate the operational characteristics of the glow plugs installed in the Sequoyah plant (Ref. 7). This study will include an evaluation in both dry and steam environments.

At this time, both the Electric Power Research Institute and Sandia National Laboratory (Albuquerque) are in the midst of extensive analytical and experimental programs dealing with the hydrogen mitigation issue. The breadth of involvement by various research institutes in the US and abroad was realized when over 40 papers on hydrogen control were presented at the workshop on the Impact of Hydrogen on Water Reactor Safety, sponsored by Sandia at Albuquerque in January 1981.

THE LLNL PROGRAM

In July 1980 the NRC Office of Nuclear Reactor Regulation requested that Lawrence Livermore National Laboratory conduct a short-term test program to evaluate the use of the glow plugs selected by TVA in environments containing known concentrations of hydrogen, air, and steam. The experiment, initiated on August 1, 1980, was designed, constructed, and completed within three months, as reported in Ref. 8. A follow-on series of tests was conducted from February through June 1981, bringing the total number of tests to 100.

The specific objective of the LLNL test program was to evaluate the capability of the glow plugs proposed by TVA to ignite various mixtures. Conditions and parameters studied included:

- Dry hydrogen-air mixtures ranging from 4% to 16% hydrogen, with some stoichiometric (29% hydrogen) tests;

- Standard steam tests with steam fractions from 10% up through 50% with various hydrogen concentrations;
- Condensation tests with bulk conditions starting at 50% steam and 10% hydrogen. The steam fraction was allowed to drop (via condensation) to as low as 25% while the glow plug was activated continuously or intermittently; and
- Circulation studies to assess the influence of fan-induced circulation on ignition and flame propagation.

MECHANICAL SYSTEM DESCRIPTION

Due to the short term nature of the program, it was necessary to use available hardware and to design the equipment with emphasis on simplicity, versatility to accommodate change, and rapid turnaround between tests. Major components at the facility included the insulated and instrumented test vessel, gas and air supplies, a commercial boiler, and the control/instrumentation system. The experimental assembly was mounted on a flat bed trailer and set on a firing table at the LLNL high explosives test facility. All operations were conducted remotely from a firing bunker, once instrumentation and the hydrogen supply were prepared. This procedure assured personnel safety without requiring qualification of equipment for hydrogen combustion pressures and temperatures.

A schematic of the igniter test facility is provided in Fig. 3. The burns were contained in a 20-in.-diameter by 60-in.-long compressed air storage tank with 3/16-in. thick walls, a working pressure of 200 psi, and a free volume of 10.6 ft^3. The vessel was modified by the addition of two 8-in. ID ports and

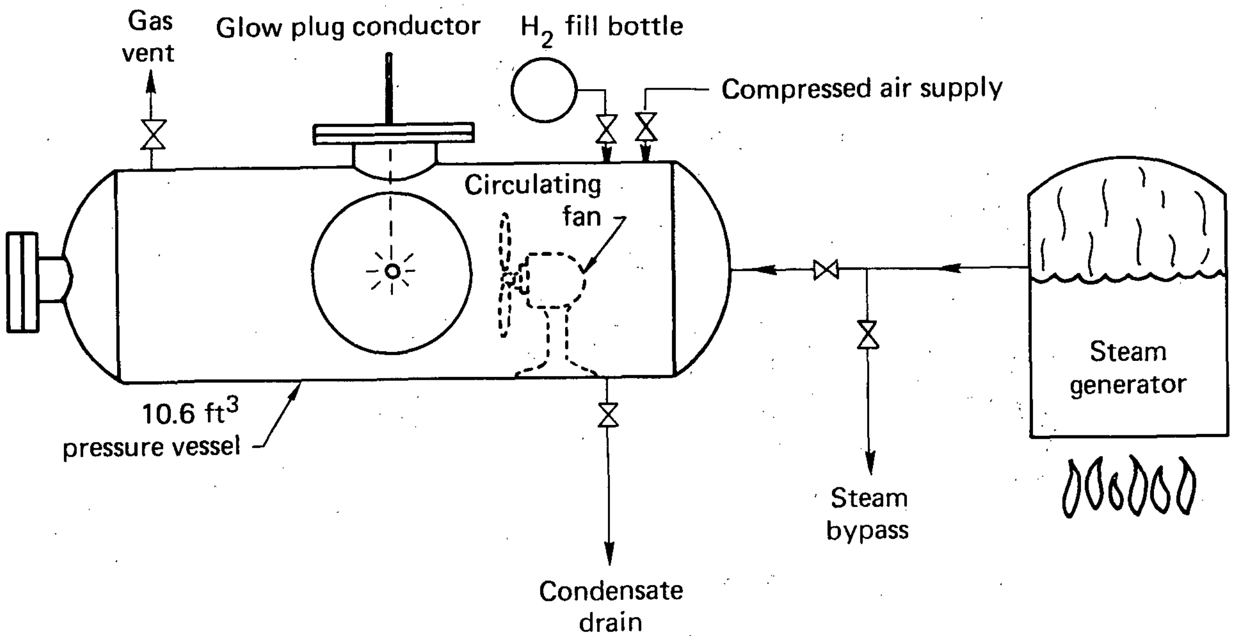


FIG. 3. The LLNL igniter tests were conducted in a modified compressed air storage vessel. The fluid and mechanical systems are shown in schematic form.

one 4-in. port, several threaded penetrations for plumbing and instrument connection, and R-11 fiberglass insulation on the exterior. Saturated steam was supplied by a 300 lb/hr boiler at approximately 75 psi. The vessel was equipped with both a gas vent and a condensate drain valve. Filtered compressed air provided purging and pressurization. The contents were mixed by a fan placed at one end of the chamber. Glow plug positioning and power supply were provided by the assembly shown in Fig. 4.

Several mechanical changes were made after the first phase of testing (tests #1 through #43). These are described below.

Glow Plug Location and Voltage. In the first test series, the glow plug was located three inches above the bottom of the vessel. Later tests positioned the plug at the bottom, center, and top of the vessel. Glow plug voltage throughout the first series was 14.4 VAC, producing 130 Watts. For some of the later tests, this was dropped to 12.0 VAC, producing 90 Watts.

Hydrogen Fill. Hydrogen was injected into the test vessel from a small bottle mounted on the vessel. During the first series of experiments, the bottle was filled to a pre-determined pressure and allowed to empty its contents into the test vessel to achieve the desired hydrogen concentration. Later experiments were conducted by slowly releasing hydrogen into the test vessel until a desired overpressure was detected. This allowed several tests to be made before the fill bottle had to be recharged.

Post-Test Vessel Purging. An additional change during the second test series was in the vessel purging procedure. Originally, a vacuum pump was used to reduce vessel pressure to about one-half an atmosphere; then the vessel was refilled with filtered compressed air. This process was repeated several times before the vessel was prepared for the next test. In some cases, the post-burn mixture had a high moisture content which caused operating problems for the vacuum pump. The purging procedure was then changed to circulate dry-filtered compressed air through the vessel for five minutes after a test.

Circulating Fan. An air-powered fan was used in the first test series to mix the vessel contents at various times during the test. This was changed to an electric-induction type AC fan (4-in. diameter) and later to a variable

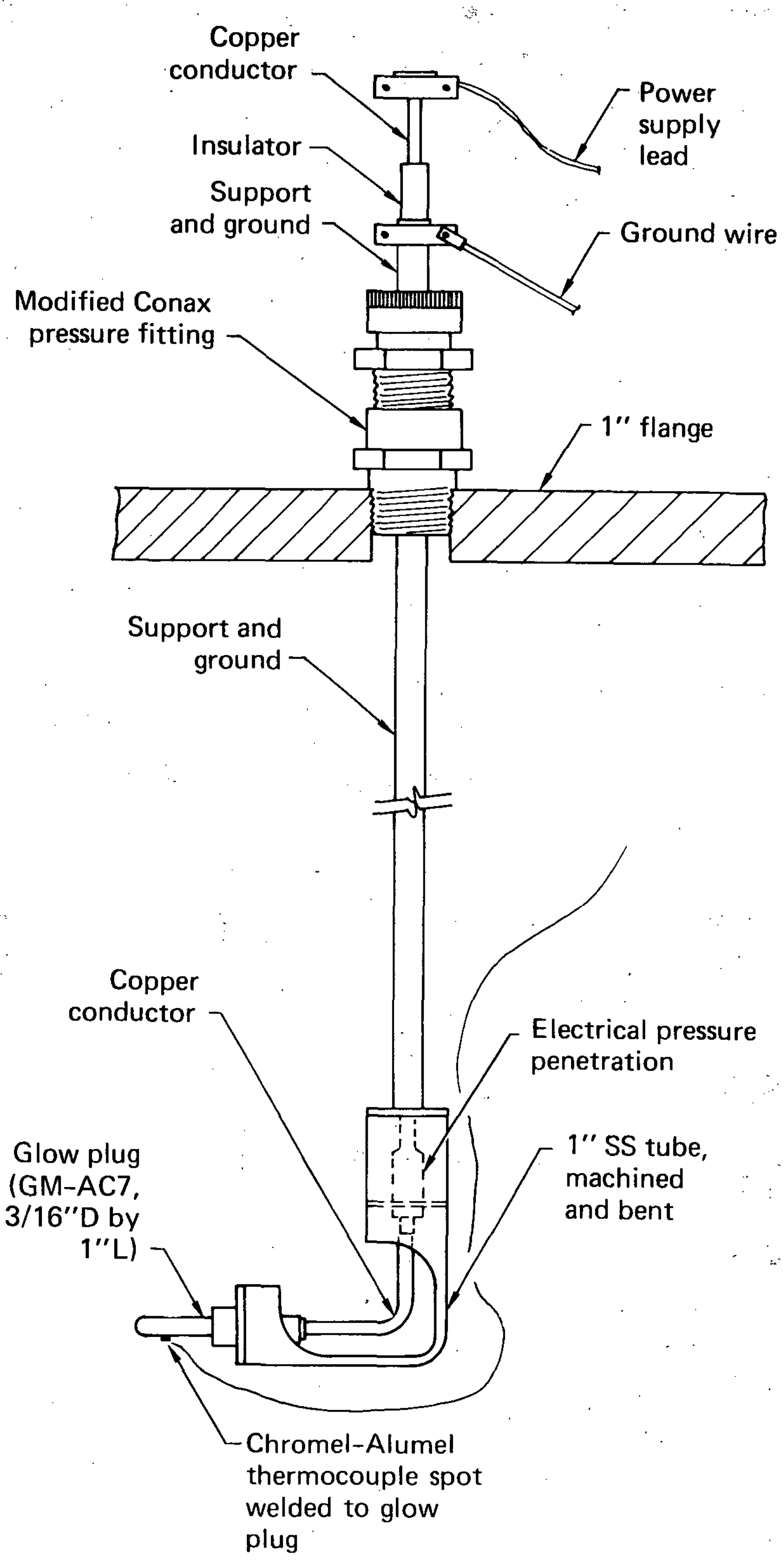


FIG. 4. The glow plug holder could place the plug at various elevations in the center of the vessel.

speed DC motor/fan combination (6-in. diameter) for the second series. Both of these later fans produced air speeds at the glow plug of approximately one ft/sec.

INSTRUMENTATION

Primary data for the igniter tests included temperature, pressure, and gas concentration measurements. Table 1 lists the instrument type and application, and Fig. 5 shows the transducer locations.

Most temperature measurements were made with Chromel-Constantan (Type E) thermocouples. These thermocouples were placed at five locations to sense the

TABLE 1. Instrumentation specifications for the hydrogen igniter tests.

Measurement	Instrument	Quantity	Recorder
Vessel internal peak and static pressure	Kulite #XTM-1-190 Strain guage type transducer	2 recessed, 1 flush mounted	2-channel strip chart, magnetic tape, oscillograph, digital read-out
Vessel mixture temperature	Chromel-Constantan (Type E) thermocouple	5	Magnetic tape, oscillograph, digital read-out
Vessel outer surface temperature	Chromel-Constantan thermocouple	2	Point plotter, magnetic tape
Ambient air temperature	Chromel-Constantan thermocouple	1	Point plotter
Glow plug temperature	Chromel-Alumel (Type K) thermocouple	1	Magnetic tape, oscillograph, X-Y recorder
Glow plug voltage, current	Shunts	1 ea.	X-Y recorder

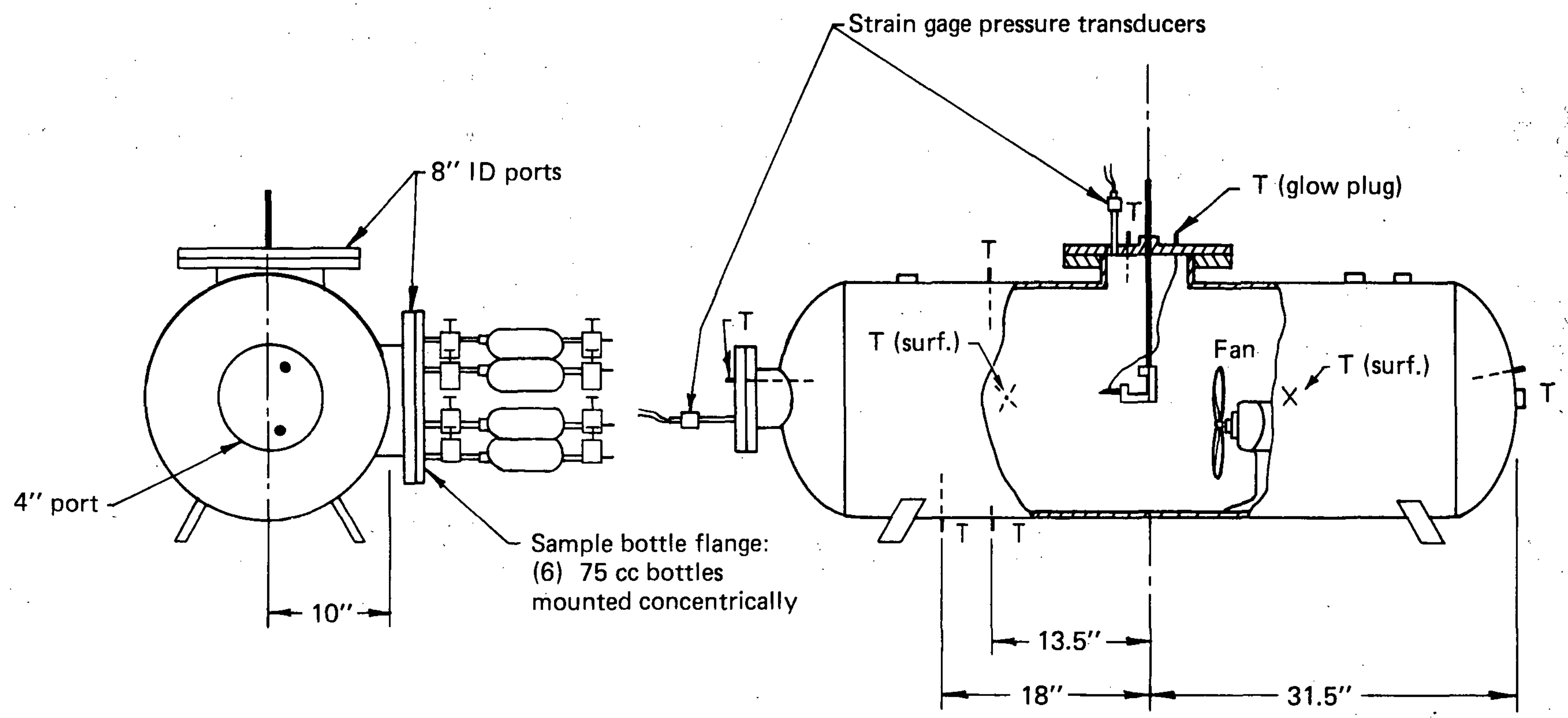


FIG. 5. Primary measurement locations are shown. Thermocouples are indicated by T's.

mixture temperature inside the vessel. Two indicated the vessel outer wall temperature, and an external thermocouple measured the ambient air temperature at the facility. A typical installation for measurement of the mixture temperature is shown in Fig. 6a.

Pressure measurements were made using two strain-gage pressure transducers located on the top flange next to the glow plug penetration and at the 4-in. port at the end of the vessel. These were offset with 1/8-in. pipe for thermal protection (see Fig. 6b). Two additional pressure transducers were added later. A low range sensor was added to assist in the hydrogen injection operation, and another (identical to the two original transducers) was mounted flush with the inner wall of the vessel.

Glow plug dynamic performance data included measurements of surface temperature, input voltage, and input current. One Chromel-Alumel (type K) thermocouple was spot-welded directly to the glow plug surface as shown in Fig. 7.

Pressures and most temperatures were recorded on high-speed frequency-modulated magnetic tape at 20,000 samples per second. This data was then digitized and transferred to computer tape for filtering, reduction, and plotting on the LLNL CDC 7600 computers. Other recorders used included an X-Y plotter, a point plotter, a two-channel strip-chart recorder, and a multiple channel oscillograph (see Table 1).

Gas sampling was accomplished by a six location sampling system. Samples taken were later analyzed by mass spectrometer. The six sampling stations were located concentrically on the test vessel's side flange (see Fig. 5). The 75 cm^3 sample bottles were set up to provide "pull-through" samples. A vacuum pump was used to pull a rough vacuum on the bottle for three to five seconds. The vessel mixture was then pulled through the bottle for two seconds before the bottle was sealed. One sample was taken before each glow plug activation, and another after a burn had been indicated by an increase in the test vessel pressure. The fan was used to circulate the mixture in the vessel before each sample was taken. Mass spectrometer analysis provided mole fractions of all gases in the bottle with the exception of water vapor. Water vapor content was determined by the calculational procedure outlined in Appendix A.

The final trailer-mounted assembly is shown in Fig. 8.

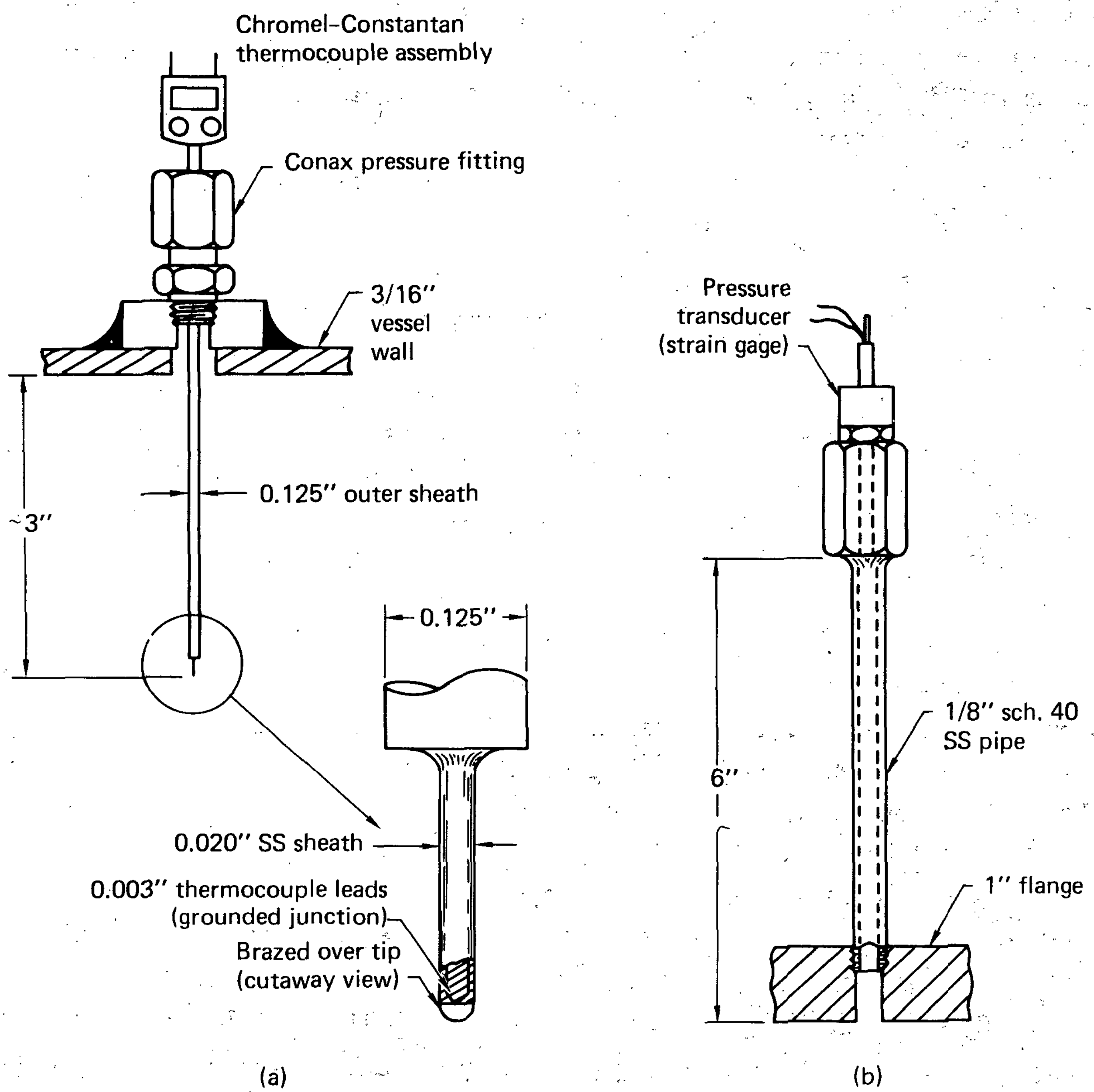


FIG. 6. (a) Vessel mixture temperatures were detected with thermocouples inserted through pressure fittings. (b) Pressure transducers were offset by 6-in. tubes to protect them from thermal transients.

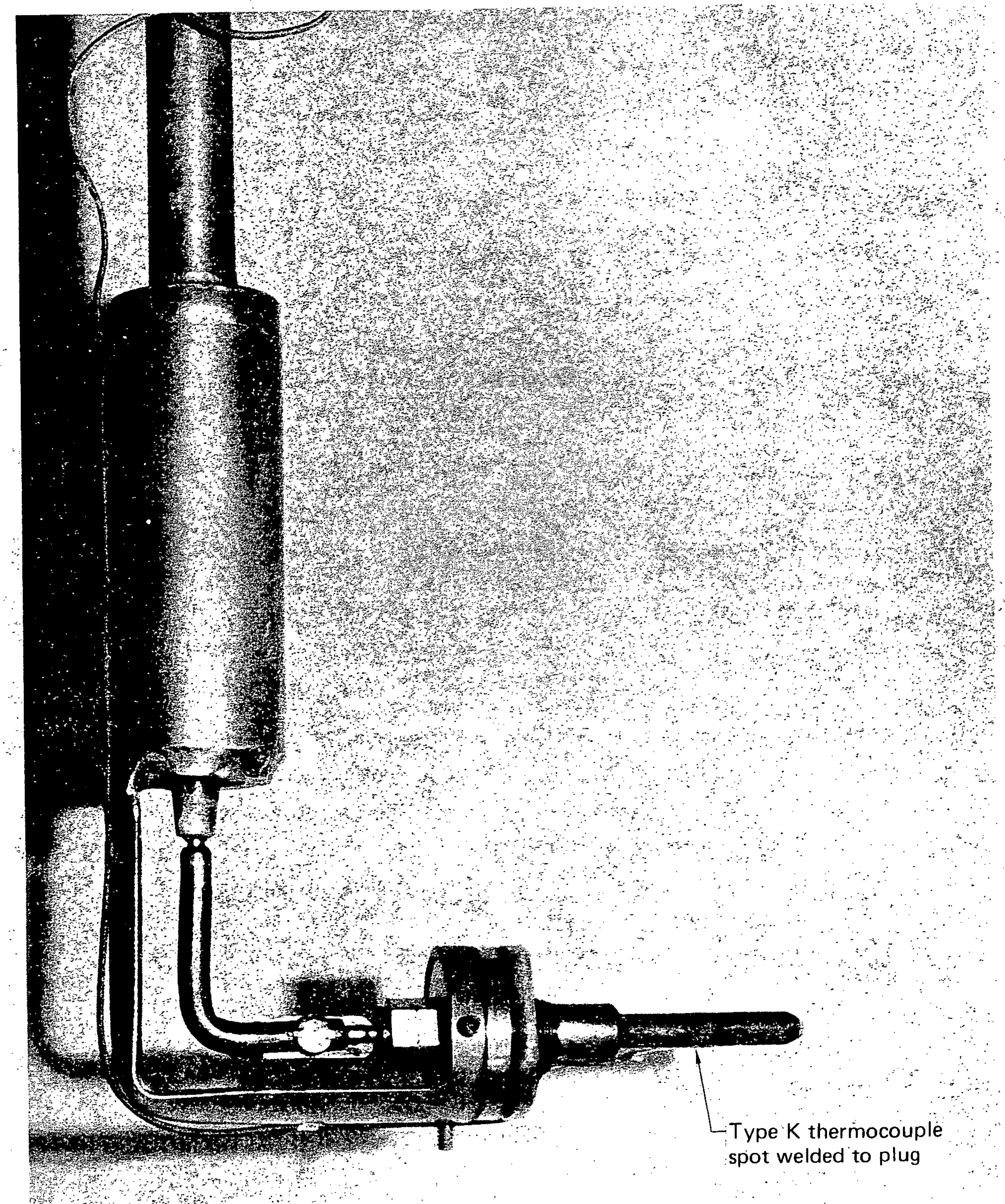


FIG. 7. A Chromel-Alumel (type K) thermocouple was spot welded to the glow plug surface for dynamic temperature recording.

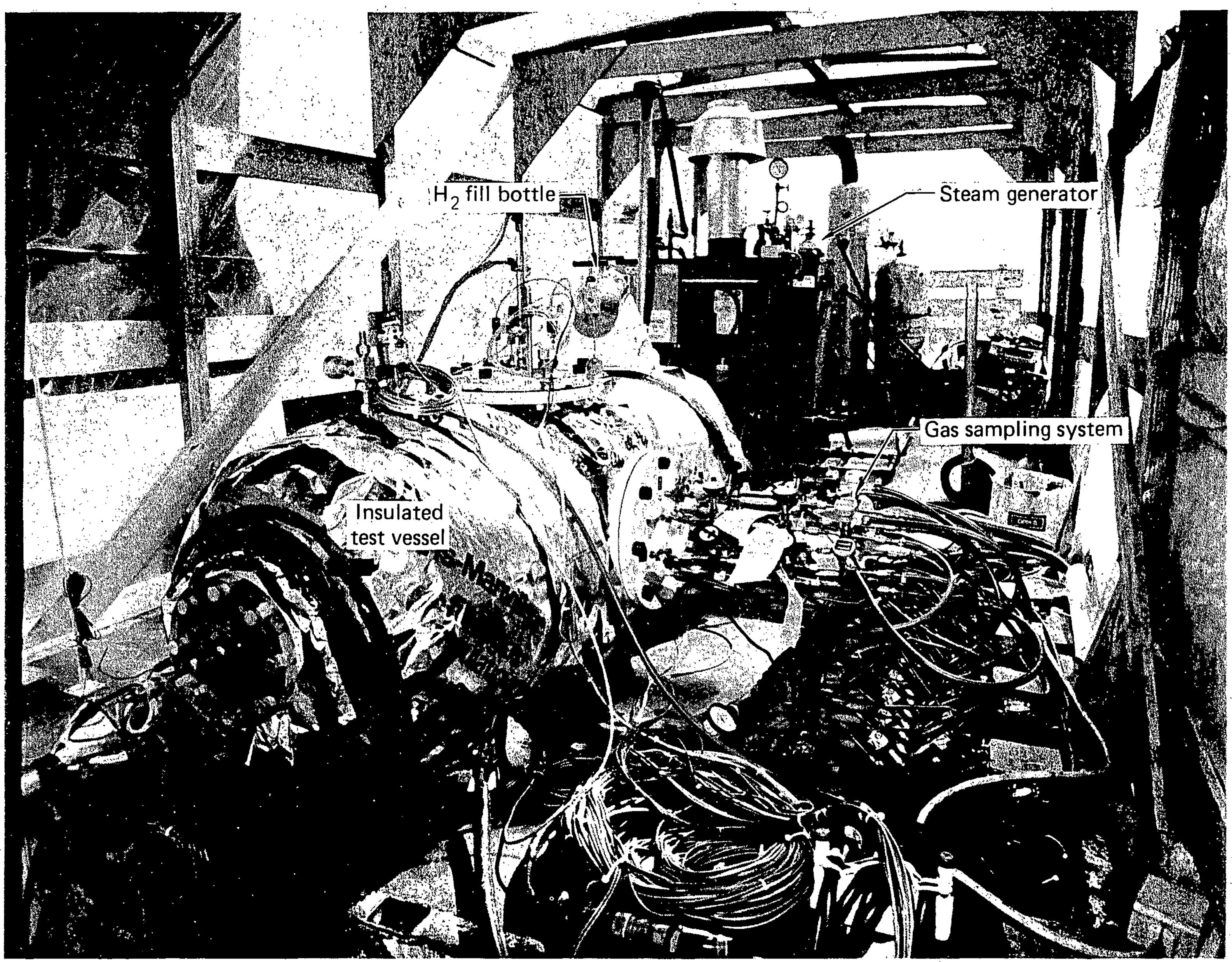


FIG. 8. The experimental assembly was mounted on a trailer and located on a firing table at the Site 300 high explosives test facility.

TEST PROCEDURES

The tests conducted can be grouped into three generic types: 1) dry air/H_2; 2) standard steam; and 3) condensation tests. In all cases before a test was started, the vessel was purged of combustion products or steam from a previous test, any remaining water was drained, and the vessel was vented to the atmosphere. Sampling bottles were prepared, and the hydrogen fill bottle was recharged. After this, the experiment was operated remotely from the bunker.

The vessel was sealed and hydrogen injected to achieve the desired concentration. To assure a homogeneous mixture, the circulating fan was operated for three to five minutes, then a pre-test gas sample was taken. This procedure was the same for all tests. Details specific to each type of test are described in the following.

Dry Air/H_2 Tests.

1. If the mixture was to be in a quiescent state at firing, the circulating fan was turned off for one minute before activating the glow plug. Otherwise, the fan was left on for the circulating mixture tests. The approximate mixture velocity at the glow plug was 1 ft/sec.
2. The glow plug was energized for 1 to 1-1/2 minutes.
3. The vessel contents were remixed for 3 to 5 minutes, and a post-burn sample taken.

Standard Steam Tests.

These tests were similar to the dry tests with the exception of the steam injection. Mixing and sampling of the contents before firing was done in the same manner as for the dry tests. The detailed procedure was as follows:

1. After the pre-burn sample was taken, steam was injected until the pressure was well above that required to yield the appropriate steam fraction. Appendix A contains a description of the calculational method used to determine the appropriate pressure at the moment of mixture ignition. The vessel was not externally heated, so the steam concentration was reduced by

condensation, which resulted in a drop in the mixture temperature and pressure. By repeatedly charging the vessel with steam at the beginning of each test, the vessel walls were pre-heated and the condensation rate reduced to a relatively slow process. Glow plug energizing was timed so that the glow plug would reach ignition temperature at a vessel pressure which represented the desired steam fraction. Typically, the plug was energized for 1 to 1-1/2 minutes.

2. After the plug was deactivated, the vessel contents were remixed for 3 to 5 minutes and a post-burn sample was taken.

Condensation Tests.

These tests were performed to confirm the results of earlier research of combustion in the presence of high steam fractions (Ref. 9). Test procedures were similar to those for the standard steam tests, except that the intended initial steam fraction was uniformly high (typically 50% with a hydrogen fraction of 10%). In addition, the duration of these tests was long, at times 30 minutes. The glow plug was either left on continually or fired for one minute at steam fraction intervals of 5% (i.e., 50%, 45%, 40%...). During some of these tests the steam fraction fell as low as 25%. Post-burn gas sampling and vessel venting and purging were done in the normal fashion.

CHAPTER 3: RESULTS

Forty-three tests were made in the first phase of the program (Ref. 2). This report presents results from the complete program.

At the completion of the first series of tests, pressure rise and burn completion data showed that the igniters were capable of igniting dry mixtures with hydrogen concentrations as low as 7% and steam mixtures with 30% to 40% steam with hydrogen concentrations as low as 8% (these were the lowest hydrogen concentrations tested in the first series). A clear transition to complete burns occurred in the dry tests between 8% and 9% hydrogen. This transition was not as well defined in the steam tests, but occurred at hydrogen concentrations of approximately 10 to 12%. It was clear that the peak pressures were lowered for the steam tests, at times yielding half the pressure of a dry test for the same hydrogen concentration. It was also noted that circulation of the mixture increased combustion, particularly for low hydrogen concentrations. Further, the glow plug performed consistently throughout all tests and showed no signs of deterioration (at 14.4 VAC).

Two tests of the first series, tests #34 and #43, surfaced as anomalies. In both cases initial assessment of the bulk test vessel conditions indicated that combustion of the mixture should take place. In neither of these cases was the mixture ignited as evidenced by pressure and temperature measurements. These were "condensation" tests, in which the vessel was charged to approximately 50% steam and 10% hydrogen. The steam was allowed to condense slowly, while the glow plug was activated continuously in test #34, and at 5% steam fraction intervals in test #43. In test #43, a significant fraction of hydrogen (30%) was consumed with no indicated pressure increase.

It was not possible to convincingly explain the cause of these anomalies; however, they caused enough concern to warrant further examination. The most promising explanation of this anomalous behavior is that enough condensation fog was present (as a result of repeated steam charge-up of the vessel) to suppress flame initiation or propagation. In subsequent similar tests, fog was observed at the start of the experiment but seemed to dissipate as the steam fraction dropped to between 40% and 30%. These results are presented in the subsection, Condensation Tests.

The second test series was begun with the following objectives:

- To re-create the conditions of the two anomalous tests to determine their inconsistent behavior;

- To examine the influence of a circulating mixture on burn characteristics, particularly at lower hydrogen fractions;
- To conduct more tests at steam fractions less than 30%;
- To determine if the glow plug voltage and vertical location significantly alters the glow plug performance;
- To determine whether the no-burn anomalies were a function of igniter characteristics by using a spark igniter as an alternate ignition source in the condensation tests;
- To determine if the igniter could initiate a detonation by executing several tests with stoichiometric hydrogen and air.

Results of the dry, standard steam, and condensation type tests are discussed separately below.

DRY TESTS

Hydrogen concentrations from 4 to 16% and stoichiometric (29%) mixtures were tested without steam under quiescent conditions. For hydrogen concentrations up to 8%, comparison tests were made with the fan circulating the mixture at 1 ft/sec past the glow plug. The purpose of these tests was to understand the flammability characteristics of dry hydrogen and air mixtures with a glow plug ignition source.

Results of these tests are listed in Table 2. Initial pressure and temperature conditions, gas concentrations, glow plug location and voltage, fan on/off data, burn temperature and pressure rise data, and post experiment concentrations are provided. Burn completeness data indicated by "% of Original H_2 Consumed" is calculated using gas analysis information. These calculations are detailed in Appendix A.

Pressure rise for the dry tests is plotted as a function of hydrogen concentration in Fig. 9. For all tests, the pressure of the vessel was approximately 14.2 psia, ambient atmospheric, before hydrogen was injected. Consequently, the initial pressure in the vessel when the glow plug was activated was not the same for all cases, but increased as the H_2 concentration increased. The corresponding maximum adiabatic pressure-rise calculated with the CECS code (Ref. 10) for these initial conditions is also indicated.

The results for both quiescent and circulating tests are shown. No pressure rise was observed in either type of test, until the hydrogen

TABLE 2. H_2 igniter dry test series.

Test #	Percent H_2 Expected	Percent H_2 Actual[a]	Fan?	Initial Cond.[b] T(°F)	Initial Cond.[b] P(psig)	Wall Temp. (°F)	Glow Plug Data Temp.[c] (°F)	Glow Plug Data Volts	Glow Plug Data Loc.[d]	Time To Peak (sec)	Burn Conditions ΔP (psi)	Burn Conditions Tmax[e] (°F)	Burn Conditions % H_2 Consumed
62	4	4.27	Off	70.0	0.44	72	-----	14.4	Center	----	None	Same	<2
63	4	4.05	Off	71.2	0.43	72	-----	14.4	Center	----	None	Same	<2
64	4	3.34	On	70.9	0.48	74	-----	14.4	Center	----	None	Same	<2
65	4	4.02	On	74.1	0.48	75	-----	14.4	Center	----	None	Same	<2
31	6	7.30	Off	67.0	1.8	---	1350	14.4	Bottom	3.5	2.5	428	48
66	6	5.61	Off	77.2	0.76	75	1300	14.4	Center	3.0	0.1	Same	31[f]
67	6	5.89	Off	81.7	0.78	80	1300	14.4	Center	3.0	0.2	Same	33[f]
68	6	5.96	Off	87.4	0.79	87	1300	12.0	Center	3.0	0.2	Same	20
69	6	6.11	On	88.0	0.90	90	1330	12.0	Center	0.2	16.0	475	61
70	6	5.78	On	90.3	0.97	91	1310	12.0	Center	0.2	13.5	450	53
17	8	8.00	Off	81.0	1.2	---	1310	14.4	Bottom	5.0	3.5	545	55
71	8	9.18	Off	60.4	1.1	64	1300	12.0	Center	0.15	37.0	975	100
72	8	8.17	Off	67.6	1.2	70	1300	12.0	Center	0.5	1.2	190	43
76	8	7.94	Off	80.2	1.1	82	1300	12.0	Center	0.5	0.6	Same	63
77	8	8.19	Off	79.5	1.1	83	1300	12.0	Center	0.2	3.0	550	44
78	8	7.59	Off	80.1	1.3	82	1300	12.0	Center	0.3	2.4	470	49
73	8	-----	On	70.0	1.2	70	1310	12.0	Center	0.1	32.0	770	97
74	8	7.97	On	74.7	1.2	75	1330	12.0	Center	0.1	33.0	850	99
75	8	7.95	On	76.6	1.1	80	1320	12.0	Top	0.1	32.0	850	99
20	9	8.80	Off	46.0	1.5	---	1310	14.4	Bottom	2.0	37.0	968	100
23	10	9.20	Off	77.0	1.6	---	1330	14.4	Bottom	1.0	38.0	1010	98
32	10	9.10	Off	75.0	1.7	---	1330	14.4	Bottom	0.8	42.0	986	100
21	11	10.4	Off	54.0	1.8	---	1360	14.4	Bottom	0.5	45.0	932	100
19	12	12.3	Off	90.0	2.0	---	1360	14.4	Bottom	0.4	62.0	965	100
22	14	13.3	Off	64.0	2.3	---	1330	14.4	Bottom	0.3	68.0	1130	100
24	16	15.1	Off	82.0	2.5	---	1360	14.4	Bottom	0.3	87.0	1260	100
98	29	~29.0	Off	183	6.0	190	1440	13.0	Center	0.2	105.0	1540	100 (est.)
99	29	32.9	Off	180	6.0	190	1440	13.0	Center	0.2	110.0	1660	100 (est.)
100	29	28.0	Off	183	6.1	190	Spark	---	Center	0.15	120.0	1850	100 (est.)

[a] Determined by gas analysis.
[b] Average temperature in vessel. Atmospheric pressure was 14.2 psia.
[c] Temperature of glow plug at ignition.
[d] Location of plug in vessel: bottom--3 in. above bottom of vessel; center--center of vessel; top--3 in. from top.
[e] Measured at T-2, adjacent to top flange of vessel. "Same" implies no rise in temperature noted at T-2.
[f] During tests 66 and 67, a second, more vigorous burn was experienced after the plug was turned off and the fan switched on to circulate the mixture before post-burn gas sampling. Burn could have been initiated by spark from fan; glow plug temperature was typically 500 - 700° F at this time. "% H_2 Consumed" value reflects second burn also.

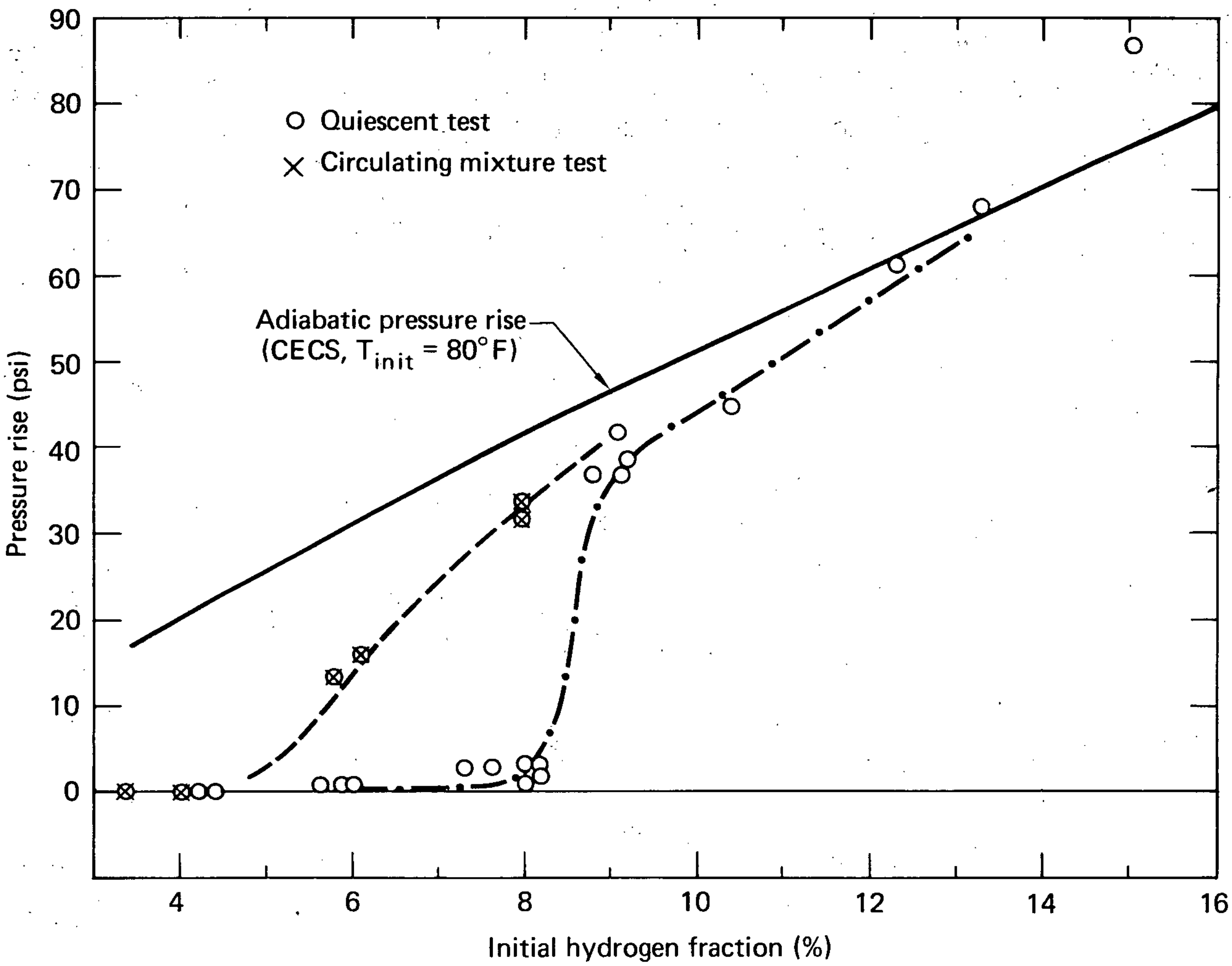


FIG. 9. Pressure rise is shown as a function of hydrogen concentration for dry H_2/air tests.

concentration reached 5 to 6%. At these concentrations the quiescent tests began to show pressure rises of less than 1 psi, while the circulated tests resulted in substantially higher pressures more closely paralleling the calculated adiabatic curve. Under quiescent conditions a stepwise jump to nearly complete burns was noted at hydrogen concentrations between 8 and 9%. This is consistent with other experimental data taken for similar tests.

To compare these results with those obtained by others at different initial pressures, the ratio of the pressure rise to the absolute initial pressure ($\Delta P/P_{init}$) is plotted in Fig. 10. Normalized LLNL test results are combined with previous work by the US Bureau of Mines (USBM), Fenwall Labs (sponsored by TVA), and Sandia National Laboratory (Refs. 3, 7, and 11). The USBM tests were conducted in a 905-ft^3 spherical vessel, initiated by a

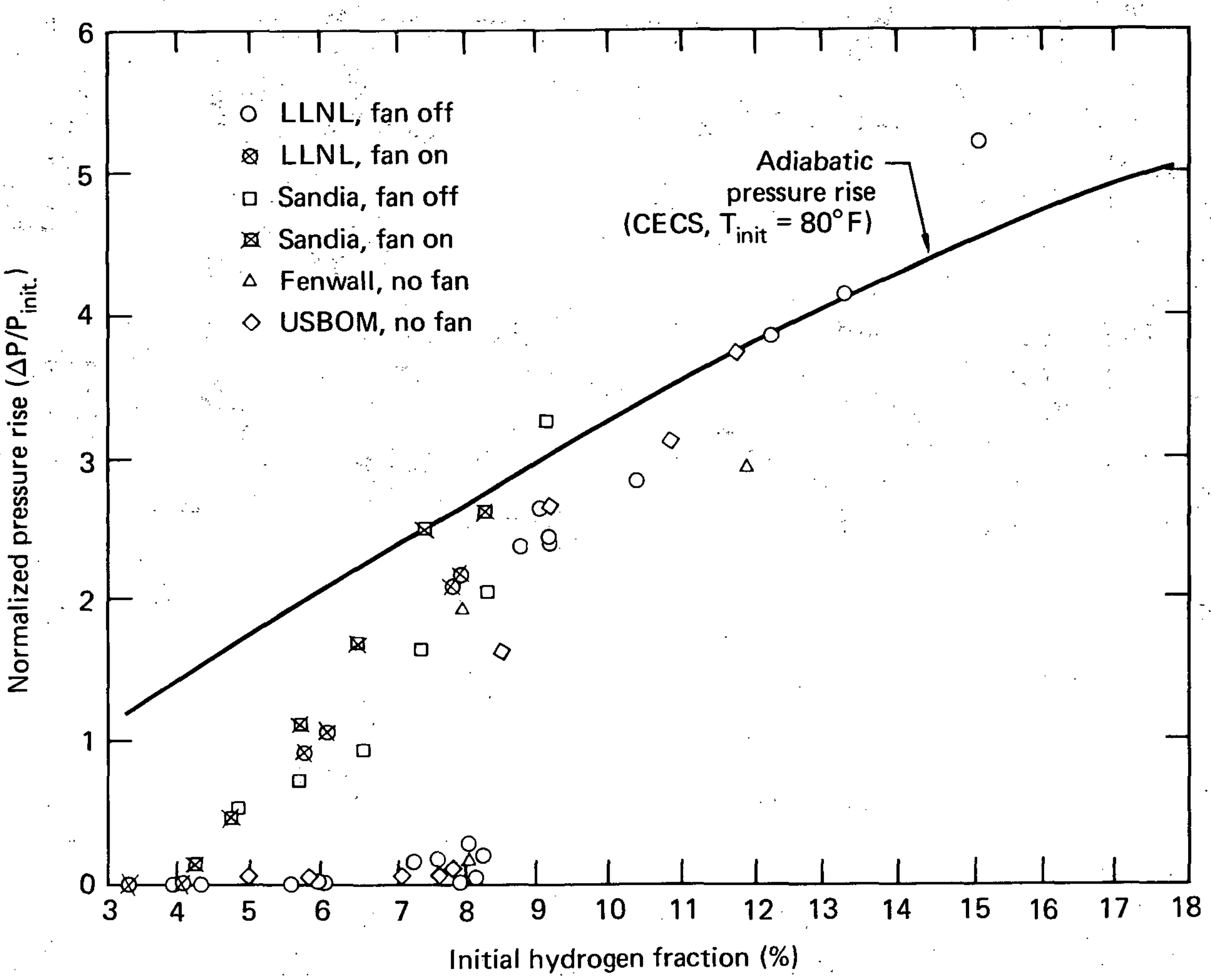


FIG. 10. To compare with results of other test programs, normalized pressure ($\Delta P/P_{init}$) is plotted as a function of H_2 concentration.

spark source. Fenwall results utilized the TVA glow plug igniter in a 134-ft^3 spherical test chamber. The Sandia program uses an ~108-ft^3 cylindrical vessel oriented vertically with the glow plug igniter at either the center or in the lower portion of the vessel.

Burn completeness as a function of hydrogen concentration is shown in Fig. 11. This plot also illustrates the transition to complete combustion at H_2 concentrations between 8 and 9%.

In general, the dry test results compare well with both the older USBM data and that of current programs. The differences indicated in Fig. 10 could be attributed to the difference in geometries of the test vessels. The Sandia test vessel, for example, presents a greater fraction of the vessel volume to the upward-propagating flame front characteristic of low H_2 concentrations. The LLNL tests and those performed in spherical vessels present less of the

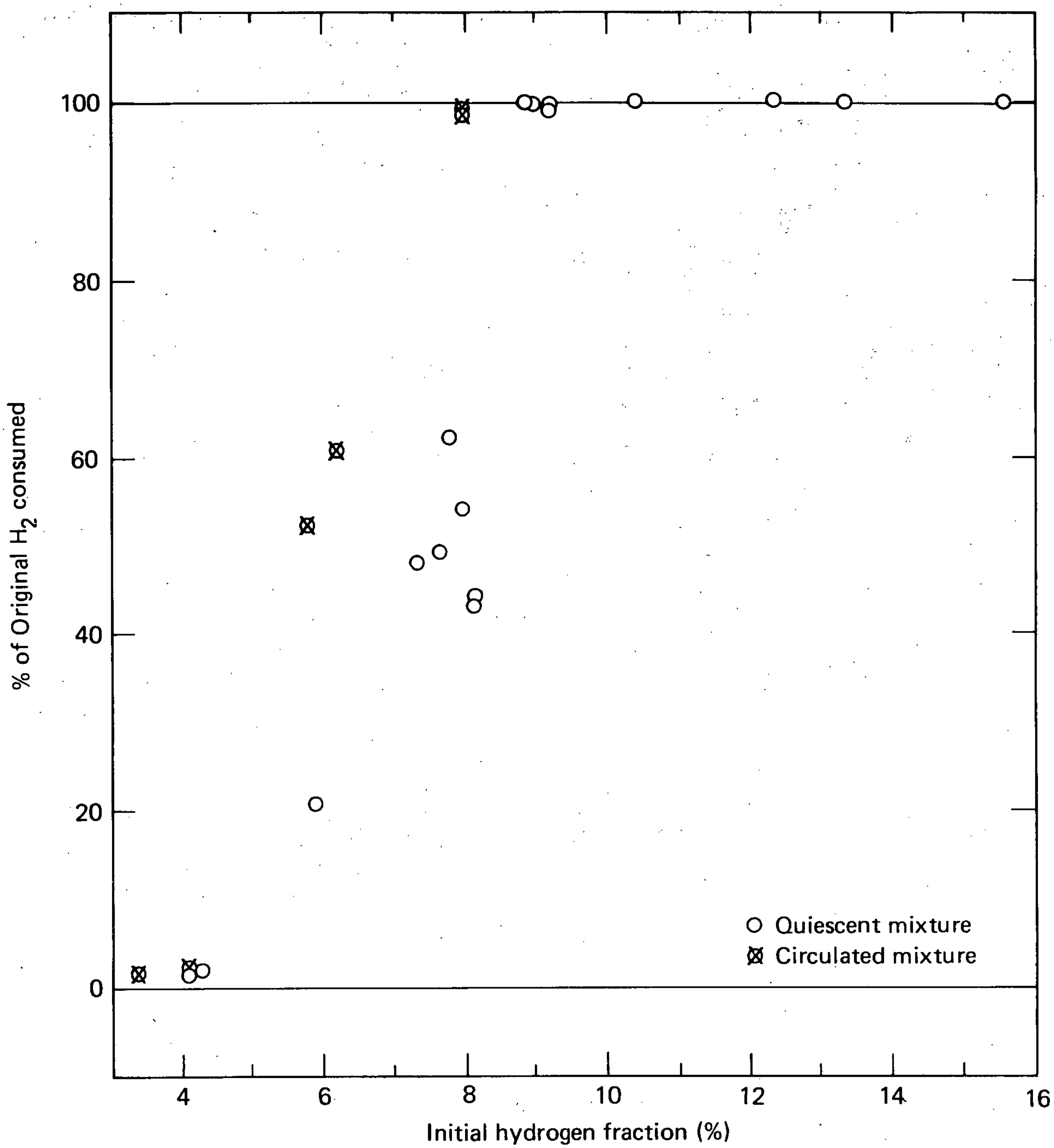


FIG. 11. Burn completion is depicted as percentage of original H_2 consumed for dry tests.

total volume to the flame under similar conditions, which may explain the more vigorous burns achieved at Sandia at low H_2 concentrations.

Variations in glow plug position and voltage produced no detectable deviations from the trends seen in other data. Decreasing the glow plug voltage to 12 VAC increased the time required for the plug to reach combustion temperature (1300 - 1400°F) by 6 to 8 seconds (see Fig. 12).

The last three tests of the series (#98-#100) were stoichiometric burns, with a hydrogen concentration of 29%. The purpose of these tests was to determine the capability of the glow plug to initiate a detonation. Tests #98 and #99 used a glow plug source. Test #100 involved an exploding-bridge-wire spark source which produced approximately 1 Joule of energy. The calculated pressure rise under these test conditions is 114 psi for simple adiabatic combustion, and 290 psi for a Chapman-Jouget detonation. The pressures listed in Table 2 (105, 110, and 120 psi) are close to the adiabatic combustion pressure rise. Some uncertainty in the pressure measurements at this rapid rate of pressure rise and at this magnitude was indicated by a significant difference in the readings of the three pressure transducers. The listed pressure was recorded by the transducer located at the end of the vessel. This transducer was recessed by a 6-in. tube. The transducer directly above

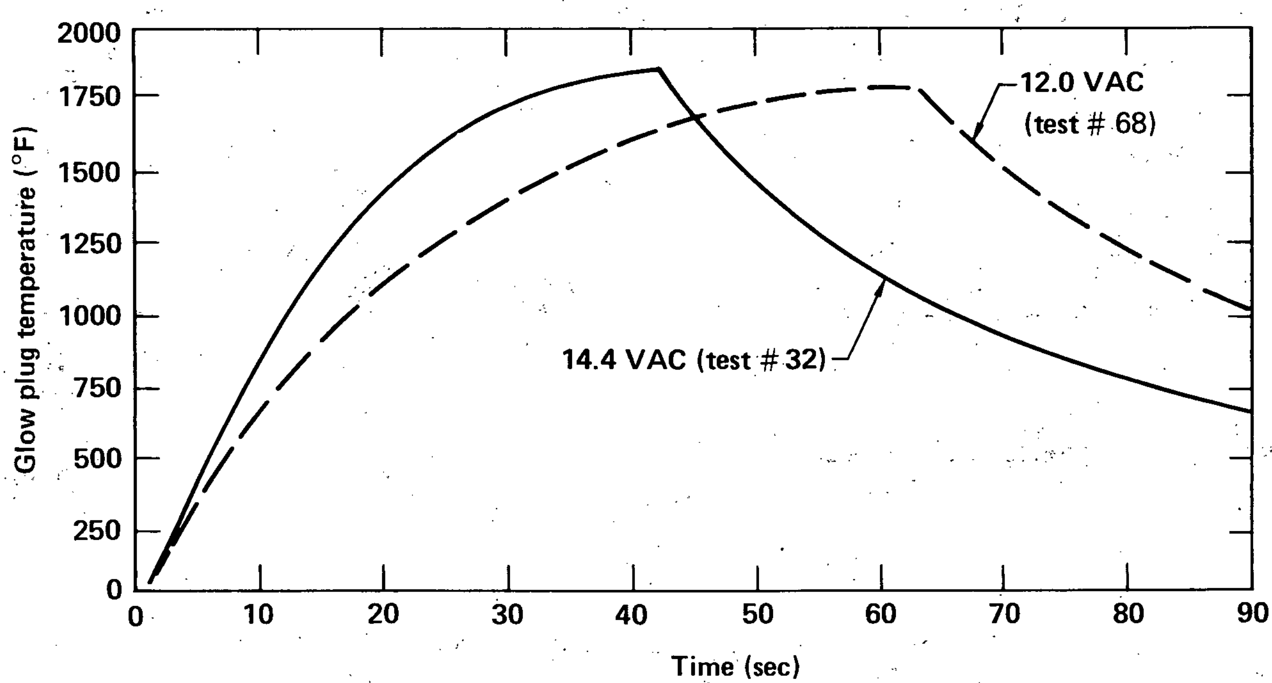


FIG. 12. Glow plug temperature traces are shown for 14.4 VAC and 12.0 VAC voltage levels.

the glow plug, also recessed, typically gave higher readings, and the flush-mounted transducer located on the sidewall halfway between the center and end of the vessel typically gave lower readings. The spark source was placed at the same central location as the glow plug for these tests. The magnitudes of the pulses are listed below:

Test #	Flush-mounted, sidewall	Recessed, top flange	Recessed, end of vessel
98	70 psi rise	115 psi rise	105 psi rise
99	78	128	110
100 (spark)	100	150	120

This scatter in pressure readings was evident only for high hydrogen concentrations. Because of the geometry differences between the recessed transducers and the flush-mounted transducer, a difference in recorded pressure is expected. It is conceivable that the small confined volume of the offset tubes produced a higher pressure pulse than would be expected in an unconfined case. The flush-mounted transducer eliminated the influence of the confining volume, but was subject to a severe temperature transient which could affect the reading. These measurements indicate uncertainty; however, they probably bound the actual pressure rise in the bulk mixture. The spark source produced the highest pressure rise, while none of the tests indicated detonations.

STANDARD STEAM TESTS

Steam concentrations between 10 and 50% were tested in the standard steam tests. Results of these tests are listed in Table 3, and plotted in Figs. 13 and 14.

Steam fractions were calculated assuming saturation conditions using the procedure in Appendix A. The likelihood that suspended water droplets were present in the vessel mixture during the tests may account for some of the scatter in the data. The presence of very small amounts of condensed water, as low as 0.05% by volume, can have pronounced suppressive effects on the pressure rise (Ref. 12). Visual observations of steam tests indicated the presence of water in the form of a condensation fog, which eventually

TABLE 3. H_2 igniter standard steam test series.

Test #	Expected Concentrations % H_2	Expected Concentrations % Steam	Actual Concentrations[a] % H_2	Actual Concentrations[a] % Steam	Fan?	Initial Cond.[b] T (°F)	Initial Cond.[b] P (psig)	Vessel Wall Temp. (°F)	Glow Plug Data Temp.[c] (°F)	Glow Plug Data Volts	Glow Plug Data Loc.[d]	Time to Peak Press (sec.)	Burn Conditions ΔP (psi)	Burn Conditions Tmax[e] (°F)	Burn Conditions % H_2 Consumed
82	8	10	8.4	10	On	135	3.5	145	1450	12.0	Center	0.1	31.0	670	100
83	8	10	8.4	9.7	Off	143	3.1	143	1400	12.0	Center	0.5	0.8	160	38
84	10	10	9.5	10	On	136	3.5	138	1440	12.0	Center	0.2	36.0	470	100
85	10	10	11.1	9.6	Off	144	3.0	145	1400	12.0	Center	0.1	38.0	880	100
86	8	20	7.8	24	On	175	7.8	175	1480	12.0	Center	0.1	21.0	470	64
87	8	20	7.4	22	Off	177	7.3	175	1450	12.0	Center	0.5	0.2	177	18
88	10	20	11.3	22	On	175	7.0	177	1480	12.0	Center	0.15	38.0	670	100
89	10	20	10.1	21	Off	178	7.2	178	1430	12.0	Center	0.3	1.2	200	50
25	8	30	7.5	30	Off	188	15.0	---	----	14.4	Bottom	---	0.5	194	38
33	8	30	7.1	32	Off	178	13.0	---	1400	14.4	Bottom	5.0	2.0	185	81
35	8	30	7.6	32	Off	181	15.0	---	1440	14.4	Bottom	4.0	2.5	338	46
26	10	30	7.7	32	Off	184	11.0	---	1490	14.4	Bottom	3.0	5.5	536	36
36	10	30	9.6	30	Off	185	11.0	---	1390	14.4	Bottom	4.0	4.5	500	53
27	12	30	11.9	33	Off	184	12.0	---	1470	14.4	Bottom	3.5	32.0	887	99
37	12	30	10.1	31	Off	180	11.0	---	1430	14.4	Bottom	4.5	22.0	1000	96
28	14	30	11.1	32	Off	176	11.0	---	1480	14.4	Bottom	4.0	24.0	968	91
29	14	30	14.9	32	Off	190	11.8	---	1440	14.4	Bottom	1.0	50.0	896	100
38	8	40	7.8	41	Off	194	14.5	---	1450	14.4	Bottom	2.0	1.5	293	41
90	8	40	8.4	41	Off	208	17.0	208	1420	12.0	Center	0.5	0.2	215	20
91	8	40	9.3	44	On	215	17.4	218	-----	12.0	Center	---	None	Same	0
39	10	40	10.0	41	Off	198	15.5	---	1450	14.4	Bottom	5.0	9.5	716	57
92	10	40	11.2	42	Off	219	17.6	218	-----	12.0	Center	---	None	Same	---
93(a)[f]	10	40	12.8	41	On	218	17.6	220	-----	12.0	Center	---	None	Same	0
93(b)	--	--	13.7	37	On	---	14.5	---	-----	12.0	Center	---	24.0	Same	45
40	12	40	11.9	42	Off	208	18.0	---	1450	14.4	Bottom	4.0	36.0	1000	98
94	10	50	11.2	52.0	Off	253	27.0	255	-----	12.0	Center	---	None	Same	0
95	10	50	9.9	52.0	Off	243	27.0	245	-----	14.4	Center	---	None	Same	---
96	10	50	13.0	53.0	Off	255	27.0	255	Spark	---	Center	---	None	Same	0
97	10	50	13.8	53.0	Off	249	27.0	245	Spark	---	Center	---	None	Same	0

a Steam fraction is calculated (Appendix A), H_2 fraction from gas analysis.
b Temperature is average of measurements inside vessel. Atmospheric pressure was 14.2 psia.
c Temperature of glow plug at ignition.
d Location of plug in vessel: center--center of vessel; bottom--3 in. above bottom of vessel.
e Measured at T-2, adjacent to top flange of vessel. "Same" implies no rise in temperature at T-2 location.
f Test 93 showed no burn at first glow plug activation. Pressure was then allowed to drop to 14.5 psig and plug activated again. Burn was indicated.

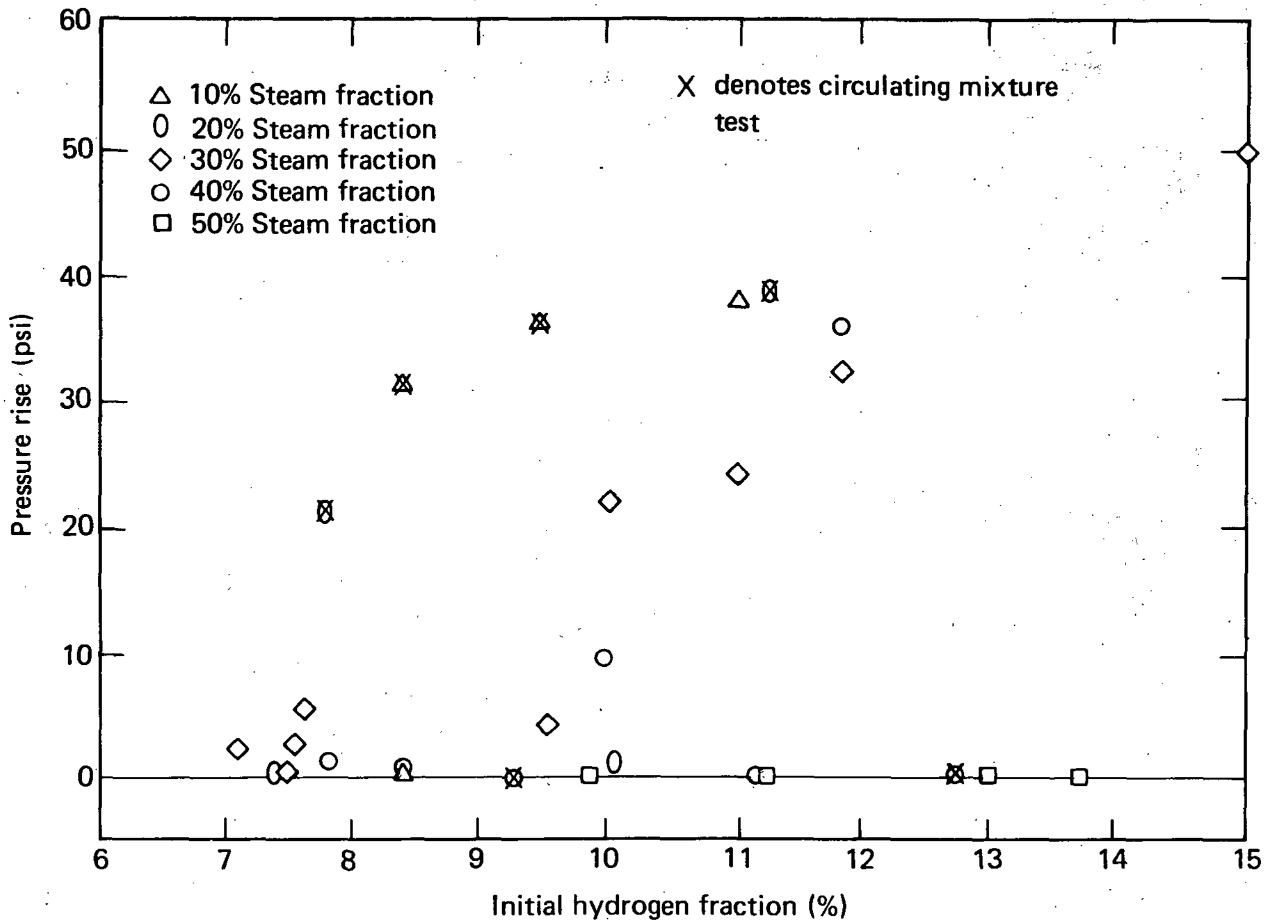


FIG. 13. Pressure rise is shown as a function of H_2 concentration for steam tests.

dissipated. Because of the uncertainty in the suspended water droplet sizes and concentration in the vessel mixture, it is difficult to identify the precise relationship between steam fraction and pressure rise or between steam fraction and burn completion. However, it is possible to see general trends in the data.

The 50% standard steam fraction tests never ignited. As discussed later, however, some of the condensation tests showed very slight pressure rises at the beginning of the test when concentrations were 10% hydrogen, 50% steam. At the 40% steam fraction, almost all of the tests ignited but produced less than 10 psi pressure rises. Tests at all steam fractions less than 40% indicated some pressure rise, with the magnitude varying with the hydrogen fraction. With the exception of two 40% steam tests, all of the circulated mixture tests ignited and produced substantial pressure rises. The 10%, 20%,

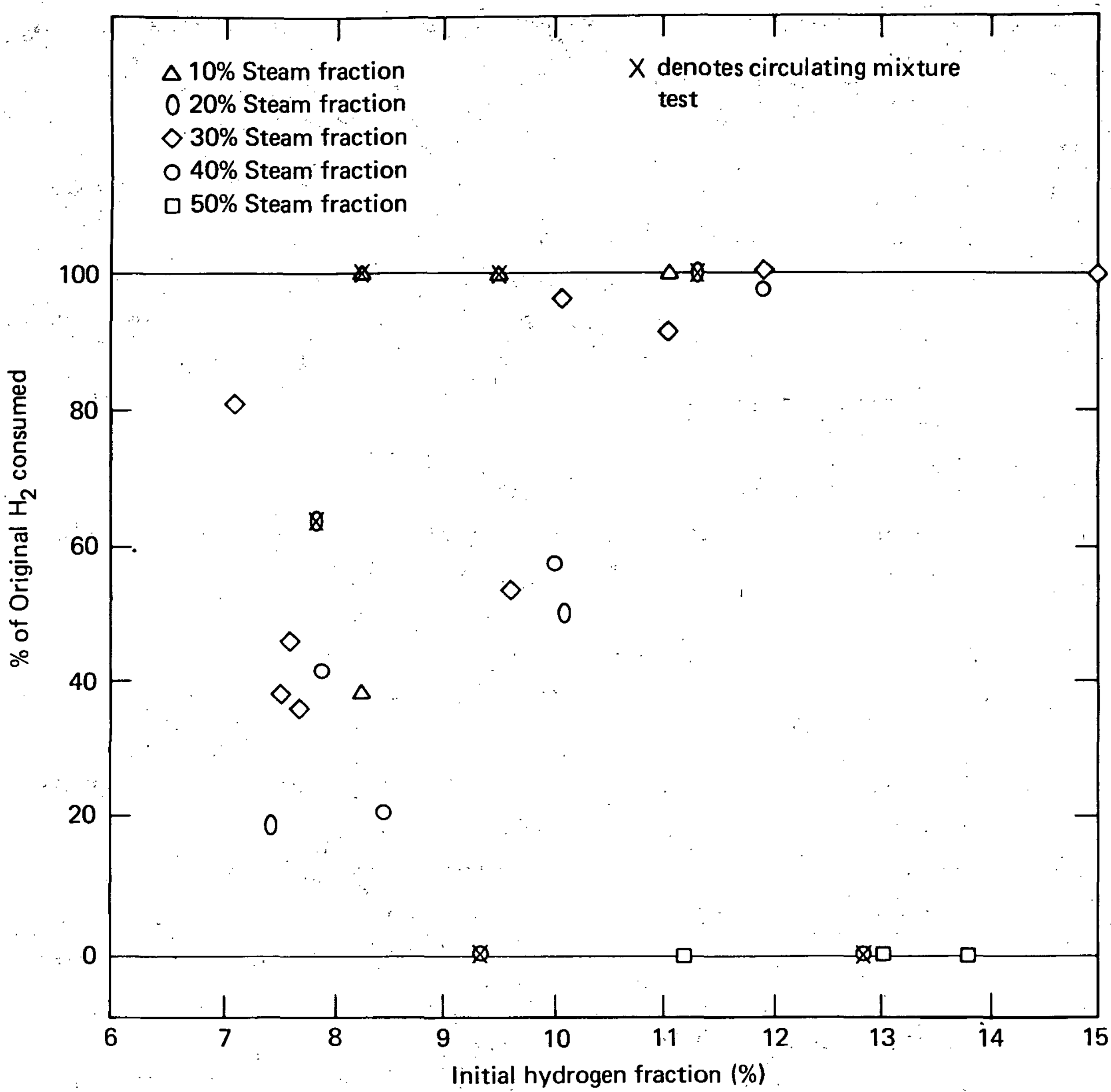


FIG. 14. Burn completion plotted vs. percentage of H_2 for standard steam tests.

and 30% steam tests consistently indicated combustion and more closely resembled dry tests than did the higher steam fraction tests.

The nature of the test procedure led to a higher amount of condensed water droplets in the tests for which the steam fraction was greater than the 30%. Condensation rates in the vessel were relatively rapid in the 40 and 50% steam tests, but became progressively slower as the steam fraction dropped.

Consequently, the lower steam fraction tests were probably influenced less by the presence of suspended water.

CONDENSATION TESTS

A total of 14 tests was executed in an attempt to explain the two anomalous tests of the first LLNL experimental series. The results of these tests are tabulated in Table 4. At the completion of the second series, there was still no clear explanation for the anomalies. The following, however, was known with some certainty:

- In all of the tests the glow plug temperature was higher than that required for ignition.
- The location of the plug in tests #34 and #43, 3 in. above the pool of condensate in the vessel bottom, had no measurable influence on the inability to initiate combustion. Most of the second series tests were conducted with the plug at the center of the vessel.
- Observations of the tests verified that the plug was not submerged in condensate.
- The inability to initiate combustion was not a repeatable phenomena, based on our understanding at the time.
- Combustion was not indicated (by discrete pressure rises) in most of the tests executed with the glow plug continuously activated. The majority of these tests, however, showed a marked decrease (40-50%) in hydrogen within the test vessel. This may be a result of thermal recombination or limited combustion.
- Intermittent firing of the glow plug at 5% steam fraction intervals would periodically produce pressure rises, although not at every firing.
- Instrumentation failure or experimental error was ruled out, because of the number of tests conducted which showed the anomalous behavior.

It is our opinion that the cause of these "anomalies" is the presence of condensation water droplets in the vessel mixture. The high steam fraction tests provide favorable conditions for the formation of this fog, because repeated recharging of the vessel was required to heat it up and reduce the condensation rate. This process tends to generate fog, and the saturated or slightly super-saturated state of the vessel mixture does not readily revaporize the droplets.

TABLE 4. Condensation Test Series

		Glow Plug Data							
Test #	Test Conditions	Firing	Voltage	Location	Time on (min.)	Fan?	Burn?	$\%H_2$ Consumed	Comments
34	12% H_2 53% steam, to 23% steam	Cont.	14.4	bottom	23	off	no	------	
43	12% H_2 49% steam, to 32% steam	Interm.	14.4	bottom	3.3	off	no	------	
45	9.3% H_2 52% steam	Cont.	14.4	bottom	1.5	off	yes	44%	2 psi burn occurred when plug reached 1500° F
46	9.4% H_2 60% steam, to 37% steam	Cont.	14.4	bottom	17	off	no	7%	
47	9% H_2 57% steam, to 40% steam	Cont.	14.4	bottom	25	off	no	------	
50	9.6% H_2 52% steam, to 34% steam	Cont.	14.4	bottom	13	off	yes	55%	1 psi rise when plug reached 1500° F
51	9.3% H_2 52% steam, to 25% steam	Interm.	14.4	bottom	5	off	yes	57%	1 to 2 psi rise noted 4 out of 6 firings
52	10% H_2 53% steam, to 26% steam	Cont.	14.4	center	20	off	no	57%	
53	9.5% H_2 52% steam, to 26% steam	Interm.	14.4	center	3.3	off	yes	51%	1 psi rises noted 4 out of 6 firings
55	11.9% H_2 50% steam	Cont.	14.4	center	1	on	yes	100%	65 psi rise noted
56	13.5% H_2 52.8% steam to 43% steam	Cont.	14.4	center	6	on	no	------	
57	11.3% H_2 52% steam to 42% steam	Cont.	14.4	center	12	on	no	------	
58	10.8% H_2 51% steam to 34% steam	Cont.	14.4	center	24	on	no	40%	
59	9.2% H_2 49% steam	Cont.	14.4	center	2.5	on	yes	18%	14 psi pressure rise
60	8.6% H_2 53% steam to 39% steam	Cont.	14.4	center	26	on	no	43%	
61	9.6% H_2 53% steam to 40% steam	Cont.	14.4	center	25	on	no	33%	

Several of the tests in the second series were video-taped through a Storz lens. The lens is a long, small diameter tube (24.0-in.-long by 0.25-in.-diameter) containing specialized optics that allow a 60^0 angle of view from one end. The lens was inserted into the vessel through a pressure fitting attached to a Lexan flange, and coupled to a low-light-level television camera outside the vessel. A floodlight shining through the Lexan flange provided illumination (see Fig. 15). The camera view included the glow plug, the gas sampling flange, and the top flange of the vessel through which the glow plug holder and conductor passed.

Figure 16 is a sequence of images taken from the television monitor during test #52. The first image represents the point at which steam has been injected into the vessel, the conditions have reached the desired state of 53% steam and 10% hydrogen, and the glow plug has been activated. The glow plug is just noticeable through the swirling cloud of water droplets. As time progresses the fog slowly clears, and the glow plug is seen as a glaring

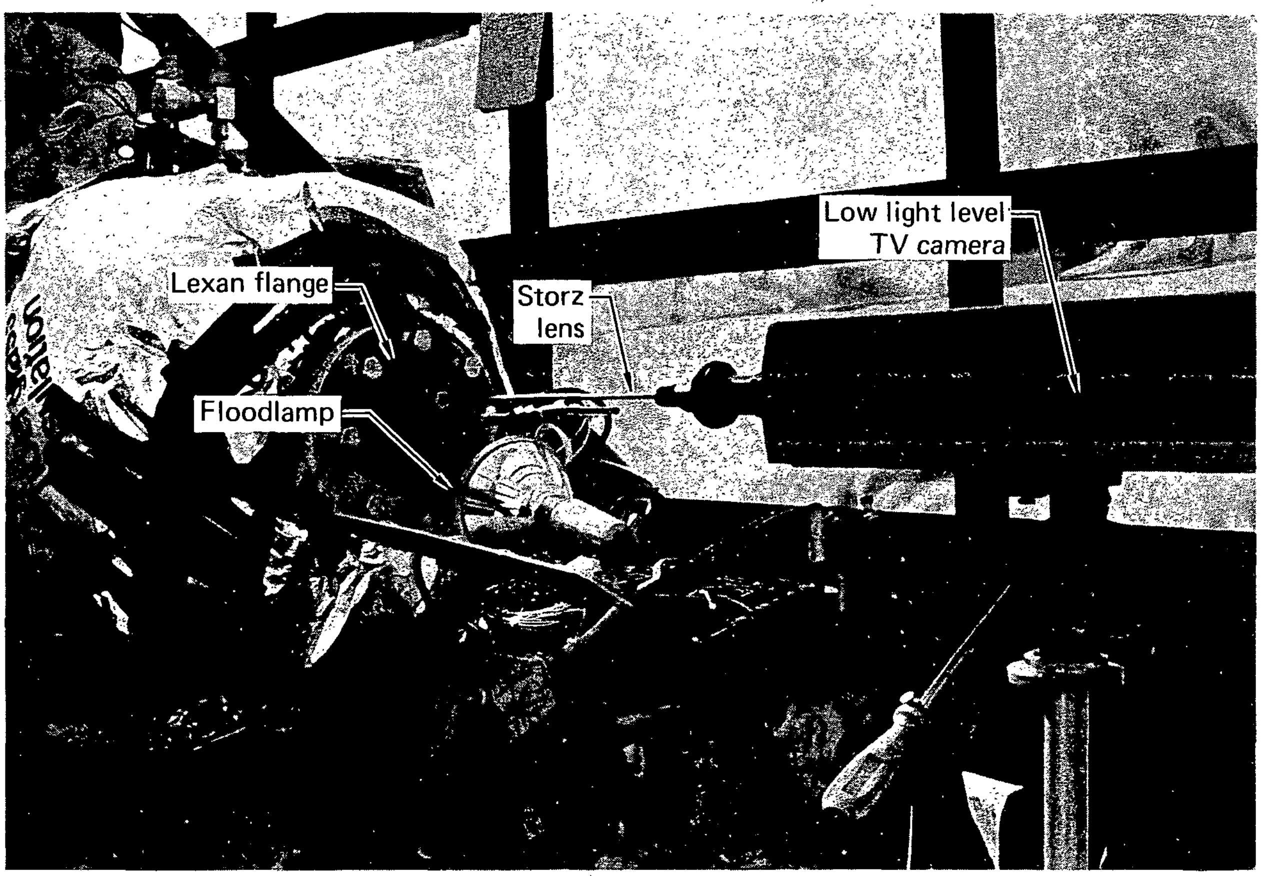
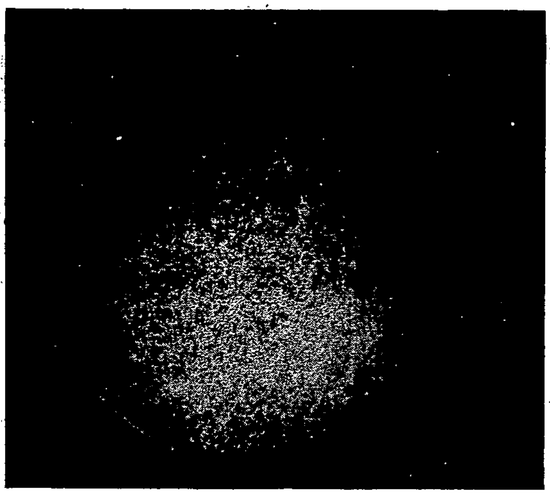
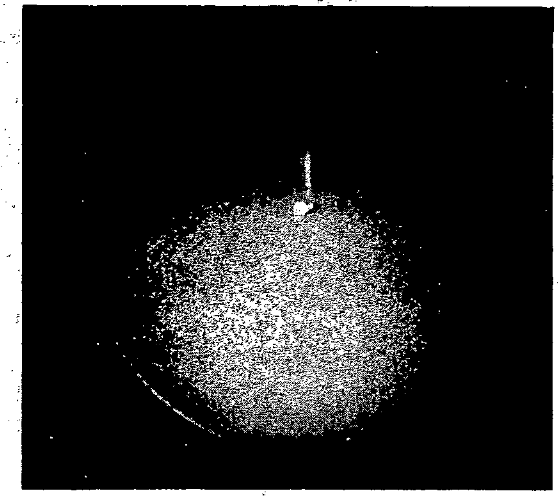


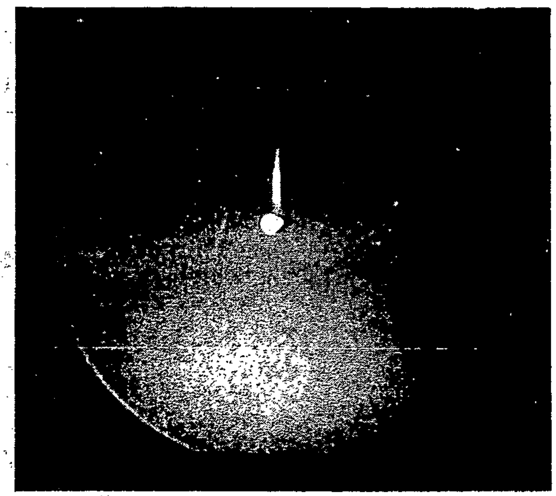
FIG. 15. A Storz lens in conjunction with a low light level television camera was used to film the condensation tests.



(a) $t = 0$ min. (plug activated)
$p = 27$ psig
$f_S = 53\%$ $f_{H2} = 10\%$

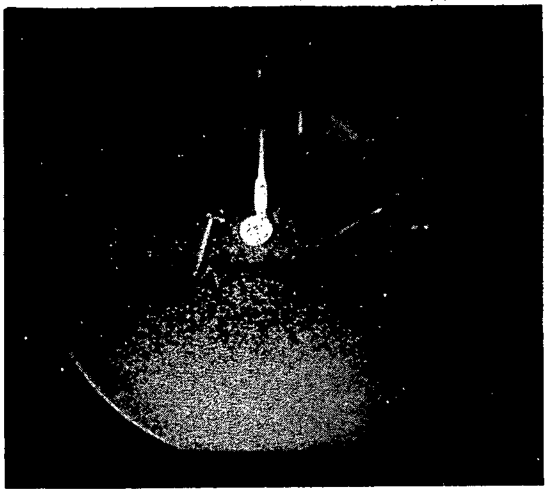


(b) $t = 1$ min.
$p = 25$ psig
$f_S = 51\%$

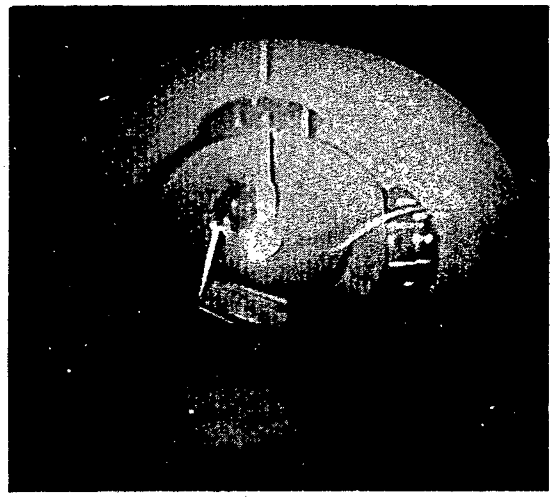


(c) $t = 2$ min.
$p = 23$ psig
$f_S = 49\%$

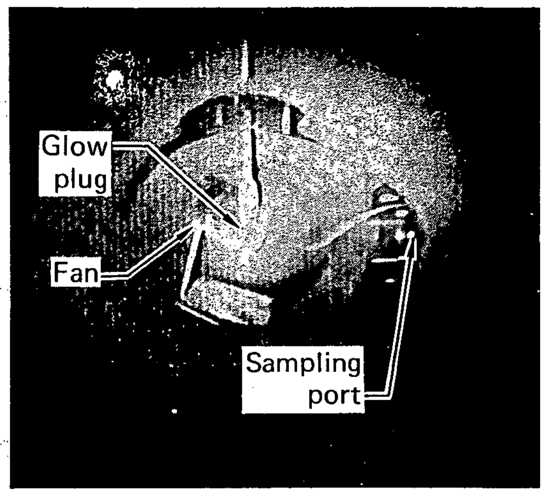
FIG. 16. This sequence of pictures was taken from a video tape of test #52. Note that the "fog" is clear four minutes into the test, but no burn was noticed.



(d) t = 3 min.
p = 21.5 psig
f_s = 47%



(e) t = 4
p = 20 psig
f_s = 45%



(f) t = 24
p = 10.5
f_s = 27%

FIG. 16. (Cont'd.)

bright spot. The vessel atmosphere soon becomes completely clear, and the condensate puddle on the bottom is visible. During this 20 minute test, no pressure rise was detected, although the gas analysis indicated that 57% of the original hydrogen was consumed.

A scoping study was conducted to analyze the conditions during these tests in an attempt to explain the anomalous results. Basic thermodynamic principles were utilized to evaluate condensate formation and the influence of suspended water droplets on the combustion process. A summary of this analysis is provided in Appendix B. The significant results are identified below:

- The total condensation rate inside the vessel can be accurately calculated using pressure histories.
- It is possible to estimate the amount of condensate present in the vessel atmosphere. This cannot be determined as accurately as the total condensation rate. A calculation for test #58 indicates that as much as 1.8 lbs of water could be suspended in the mixture at the start of the test.
- A very small amount of suspended liquid water will suppress the adiabatic flame temperature enough to prevent propagation of the flame front. Calculations estimate that as little as .05% by volume or .32 lbs of suspended liquid in the LLNL vessel is sufficient for this range of hydrogen fractions.
- If water droplets are present in the bulk mixture, a fuel lean zone around the glow plug may occur as a result of vaporization of the liquid water which increases the local steam fraction.

This scoping analysis only treated a few tests of the total igniter test program. A more extensive effort is required to refine the models used and to evaluate all of the condensation tests.

CHAPTER 4: CONCLUSIONS

This program evaluated the capability of thermal igniters to initiate combustion in a variety of hydrogen-air-steam environments to better understand the performance of the TVA Interim Distributed Ignition System. The conclusions drawn from these results are based on the current understanding of the data. An in-depth analytical program would improve the understanding of the influence of the steam environment on the igniter's performance characteristics. The following statements can be made with confidence:

- The glow plugs are capable of igniting any dry hydrogen-air mixture if the hydrogen concentration is greater than 6%. Concentrations of 5% hydrogen can be ignited if the mixture is circulated in a fashion similar to the LLNL tests. Complete combustion occurs in dry mixtures with hydrogen concentrations between 8 and 9%. This is consistent with other experimental results.
- The glow plug was not capable of initiating detonations in a stoichiometric hydrogen/air mixture.
- With the exception of three tests, combustion occurred consistently in mixtures with steam fractions as high as 40%. Mixtures with steam concentrations of 50% rarely could be ignited. It appears that failure of the mixture to ignite at these higher steam fractions was the result of the presence of suspended water droplets.
- Circulation of the mixture at approximately 1 ft/sec past the glow plug improved combustion in both the dry and steam tests.
- The glow plug consistently ignited the mixture at surface temperatures between 1300^{o}F and 1500^{o}F, with the higher temperatures required in steam environments. Decreasing the glow plug voltage from 14.4 VAC to 12.0 VAC had no discernible influence on the tests other than increasing the time to reach ignition temperature. Throughout the series of tests, the glow plug showed no appreciable deterioration in heat-up characteristics.
- The condensation tests showed that suspended water has a marked suppressive influence on combustion. A scoping study of the data indicated the possibility of enough suspended water to prevent combustion in some cases. Another effect noted from the scoping

study was that a local fuel lean zone might exist around the glow plug when condensation droplets are present in the vessel mixture.

An extended analytical effort is recommended to characterize the conditions in the vessel mixture during steam tests. This effort should be particularly directed to analyzing the effects of the presence of condensation-generated suspended water droplets. The models used in the scoping study require refinements to more accurately predict actual amounts of suspended water. Once the models are refined, they should be applied to the LLNL steam tests. An additional effort should concentrate on identifying the conditions expected during a Loss of Coolant Accident (LOCA) with respect to the presence of condensation fog.

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APPENDIX A

Pre- and Post-Test Calculations

Steam Fraction Determinations

Because the mass spectrometer can only analyze the gaseous water whose vapor pressure equals the operating pressure of the spectrometer sample chamber (which is very low), water concentrations obtained in the analysis are discarded and the remaining results for non-condensible gases normalized to represent a "dry" mixture. Consequently, steam fractions must be calculated as a function of both temperature and pressure to specify the conditions in the vessel at a given instant. This was done twice: first to predict the vessel pressure, after steam injection, at which the glow plug was fired, and again after the tests to verify the actual conditions from pressure and temperature data. If saturation conditions are assumed, it is possible to predict the steam fraction with a partial pressure calculation by the following procedure:

a) The total number of moles of gas in the vessel before steam injection, n_{gas}, is known from the previous fill bottle pressure calculation or can be inferred from the pressure and temperature inside the test vessel after hydrogen injection.

b) A temperature T_{bulk} is selected (iteratively) which provides a partial pressure ratio corresponding to the appropriate steam fraction. The gas partial pressure P_{gas} is first calculated as:

$$P_{gas} = \frac{n_{tot} \cdot R \cdot T_{bulk}}{V}$$

c) The steam saturation pressure (P_{sat}) at T_{bulk} is obtained from the steam tables.

d) The steam fraction f_{steam} is calculated from the partial pressure ratios:

$$f_{steam} = \frac{P_{sat}}{P_{gas} + P_{sat}}$$

e) Once the correct T_{bulk} is found so conditions yield the appropriate steam fraction, the total pressure (P_{sat} + P_{gas}) is the pressure at which the glow plug should be fired.

After the test is completed, conditions are reconstructed to determine how close to the desired state was the actual experiment. In the data table of the standard steam test results, the gas partial pressure (P_{gas}) is first calculated using the listed temperature at ignition (this is the average temperature measured by the thermocouples in the vessel). The steam fraction is then calculated from the ratio of P_{gas} to the measured total pressure:

$$f_{steam} = 1 - \frac{P_{gas}\ (\text{calc.})}{P_{tot}\ (\text{meas.})}$$

<u>$\%H_2$ Consumed</u>

Mass spectrometer analysis provides mole fraction figures for the non-condensible gases in the samples. Of primary interest, and comprising usually at least 99% of the sample, are the concentrations of hydrogen, nitrogen, and oxygen. The degree of combustion, or "$\%H_2$ consumed", calculation is detailed below, using the following notation:

f_{H_2}, f_{N_2}	pre-burn H_2 and N_2 mole fractions obtained from gas analysis
f'_{H_2}, f'_{N_2}	post-burn H_2 and N_2 mole fractions, also from gas analysis
n_{H_2}, n_{N_2}	pre-burn number of moles H_2 and N_2 in vessel
n'_{H_2}, n'_{N_2}	post-burn number of moles of H_2 and N_2 in vessel
n_{tot}, n'_{tot}	total number of moles of dry gas in vessel before and after ignition

The following equations identify the total number of moles of each constituent inside the vessel.

Pre-burn

$$f_{H_2} \cdot n_{tot} = n_{H_2}$$

$$f_{N_2} \cdot n_{tot} = n_{N_2}$$

Post-burn

$$f'_{H_2} \cdot n'_{tot} = n'_{H_2}$$

$$f'_{N_2} \cdot n'_{tot} = n'_{N_2}$$

The value for "%H_2 Consumed" is defined as:

$$\%H_2 \text{ Consumed} = 1 - \frac{n'_{H_2}}{n_{H_2}}$$

This can be expanded, using the previous equations, to give:

$$\%H_2 \text{ Consumed} = 1 - \frac{f'_{H_2} \cdot n'_{tot}}{f_{H_2} \cdot n'_{tot}} \tag{1}$$

For this combustion process it is reasonable to assume that the number of moles of nitrogen remains constant throughout the experiment. So,

$$f_{N_2} \cdot n_{tot} = n_{N_2} = n'_{N_2} = f'_{N_2} \cdot n'_{tot}$$

The left and right hand sides of this equation can be combined to yield:

$$\frac{f_{N_2}}{f'_{N_2}} = \frac{n'_{tot}}{n_{tot}}$$

The "%H_2 Consumed" figure can be written in terms of only pre- and post-burn hydrogen and nitrogen concentrations by substituting this last equality into equation (1):

$$\%H_2 \text{ Consumed} = 1 - \frac{f'_{H_2} \cdot f_{N_2}}{f_{H_2} \cdot f'_{N_2}}$$

The same equation can be applied to the oxygen fraction. Knowing the "% of original" consumed for both oxygen and hydrogen, the actual amount (number of moles) of each consumed by the reaction can be determined. This provides one way of checking the reliability of the gas sampling system: if the ratio of H_2 moles consumed to O_2 moles is two to one, the gas analysis data tends to be believable. In most cases the ratio was what would be expected; if the ratio was obviously bad, the data was discarded.

APPENDIX B

Scoping Analysis of Condensation Test Conditions

Introduction

The "condensation" tests conducted in the LLNL Hydrogen Igniter Test Program produced results which could not be explained by first examination of the data. It had been suspected that the presence of small suspended water droplets from the steam condensation process inhibited the capability of the glow plug to initiate a self-propagating flame. Observations of these tests showed that a fog did indeed exist in the vessel during the early period of the test, but that this visible "cloud" dissipated as the pressure and temperature in the vessel dropped. Since the glow plug was still energized at this time, the presence of a visible fog did not appear to be the sole cause for this inability to ignite the mixture. The presence of very small amounts of condensed water suspended in the mixture might prevent combustion of the test vessel mixture. This conclusion was drawn from analysis of the data.

This brief summary treats two aspects of the LLNL analytical effort. First is the characterization of the fog formation rates during the Livermore tests, and the second is the influence of this condensation rate on glow plug performance.

Condensation Rate Determination and Fog Formation

The LLNL steam-type tests were executed in an unheated vessel. Consequently, after steam was injected into the vessel, the mixture pressure and temperature dropped as steam condensed. This condensation rate was controlled to some degree by preheating the vessel with repeated steam injections before the actual test sequence was started.

The total condensation rate in the vessel can be calculated very accurately ($\pm$ 5%) using pressure decay data. Dalton's Law, the Ideal Gas

Model, and Clapeyron's Equation can be combined to yield an expression for the total mass condensation rate in the mixture of steam, air, and hydrogen:

$$\dot{m}_{ct} = -\frac{18\ V}{\bar{R}\ T}\left\{1 - \frac{P_t/T}{C_1 + C_2 + (h_{fg}/T\nu_{fg})}\right\}\frac{dP_t}{d\tau} \quad (1)$$

where:

$\dot{m}_{ct}$ = total mass condensation rate
V = vessel volume
T = mixture temperature
$\bar{R}$ = universal gas constant
P_t = total vessel pressure
τ = time
h_{fg} = enthalpy of evaporated steam
ν_{fg} = specific volume of steam
n = number of moles of specified gas (air or H_2)

$$C_1 = \left(\frac{n\bar{R}}{V}\right)_{H_2}$$

$$C_2 = \left(\frac{n\bar{R}}{V}\right)_{Air}$$

A sampling of the LLNL test data indicates a possible correlation between this calculated condensation rate and burn/no-burn results. Two tests at initial conditions of approximately 10% H_2 and 30% steam (#33 and #25), and two at 10% H_2 and 50% steam (#58 and #59) are compared below. These condensation rates are calculated at the time the glow plug was energized.

Test #	% H_2	% Steam	ΔP (psi)	$\dot{m}_{ct}$ (lbm/s)
33	10.5	32.2	2.0	0.53×10^{-3}
25	10.7	30.2	0.5	0.82×10^{-3}
58	10.8	51.0	0	0.99×10^{-3}
59	9.2	49.0	14.0	0.57×10^{-3}

In both comparisons, the test with the highest total condensation rate (m_{ct}) yielded the lowest pressure rise.

While these condensation rates do not appear to be large, if one were to scale up to the volume of the Sequoyah containment, test #58 would represent 807 gallons of total condensate being formed per minute.

The condensation rate which affects the glow plug is that fraction of the total condensation which takes place in the mixture, producing fog. Condensation fog is formed by cooling of the bulk steam/air/H_2 mixture. This cooling is dominated by two mechanisms: radiation between the mixture and the walls, and natural convection cooling of the bulk mixture. It is possible to derive an equation for the droplet formation rate by combining the First Law of Thermodynamics and Clapeyron's Equation to yield:

$$\dot{m}_{cd} = \frac{1}{h_{fg}} \left\{ \dot{q}(H_2O)_\nu - m_\nu c_\nu \left[\frac{1}{C_1 + C_2 + \frac{h_{fg}}{T\nu_{fg}}} \right] \frac{dP_t}{d\tau} \right\} \quad (2)$$

where:

$\dot{m}_{cd}$ = droplet mass formation rate

$\dot{q}(H_2O)_\nu$ = heat transfer rate between H_2O vapor and walls (all other variables same as Eq. (1))

The large uncertainty in this model is due in part to the difficulty in determining the heat transfer from the vessel mixture to the walls. However, a preliminary calculation for test #58 indicates that two thirds of the total condensation could be occurring in the mixture itself to form fog.

It is also possible to determine the total instantaneous mass of condensed droplets suspended in the mixture by using the First Law. This calculation is subject to the same limitations on heat transfer rates from the mixture to the walls. A crude calculation for test #58 indicates that 1.79 lbs of water could be suspended in the vessel mixture at the time of glow plug activation.

Influence of Suspended Liquid Water on Flame Propagation

We have known for some time that the presence of suspended water droplets inhibits flame propagation. Adiabatic calculations yielding flame temperatures provide a useful means to determine whether a flame will propagate through a mixture of known constituents. If the calculations produce a flame temperature which is lower than the auto-ignition temperature required to initiate hydrogen combustion (which under these conditions is about 850^0 K), then the flame is not expected to propagate. Calculations show that while the presence of steam has relatively little influence on the adiabatic flame temperature, suspended liquid water has a dramatic effect. Consider three cases below:

Case I. Dry 12% mole fraction H_2
T_f = adiabatic flame temperature $= 1285^0$ K >> 850^0 K

Case II. 12% H_2, 33% steam
$T_f = 1228^0$ K, still much greater than 850^0 K

(both Case I and Case II would be expected to burn well)

Case III. 12% H_2, no steam, but a mass of liquid water suspended equal to the mass of steam in the previous case (0.24 lbm)
$T_f = 770^0 \text{ K} < 850^0$ K
(a flame would not be self-sustaining in this case)

Consequently, it takes very little liquid water to prevent flame propagation. The above calculation shows that as little as 0.24 lbm in the LLNL test vessel could inhibit combustion. The calculation for test #58 presented earlier yielded 1.79 lbm present in liquid form, a substantial amount by these standards.

This discussion has addressed only the capability of the flame to propagate through mixtures of steam, air, H_2, and suspended liquid water. The ability of the glow plug to locally initiate a flame is also of interest. A locally fuel-lean environment can exist around the glow plug if water droplets are suspended in the mixture. This is best described by an example.

A 10% H_2, 50% steam mixture theoretically can combust. If, however, 0.5 lbm of suspended water is distributed throughout the LLNL test chamber, a non-combustible environment will be sustained around the glow plug even though there are no locally suspended water droplets (they would be vaporized by the heat flux from the plug). Consider the local environment to be a swirling mixture flowing past the glow plug. As water droplets pass close to the plug, they will evaporate to increase the local steam fraction. For each mole of H_2 passing the plug, 5 moles of steam and 4 moles of air will accompany it. As the field approaches the plug, however, another 5 moles of steam can join the mixture via evaporation of the water droplets. This yields a local mixture of 6.7% H_2, 66.7% steam, and 26.7% air, which is theoretically non-combustible.

Conclusions

These results are preliminary and require further in-depth analysis to yield quantitative conclusions with high confidence levels. However, the following can be stated at this point:

1) Steam does not inhibit H_2 combustion enough to be the sole source of "anomalous" results in the LLNL tests. Suspended condensed water droplets, on the other hand, can effectively inhibit combustion.
2) An accurate model for total condensation rates has been developed. Preliminary results show a correlation between total condensation rates and burn/no-burn cases, as well as indicating that a significant quantity of suspended water droplets were present in the LLNL tests.
3) The analysis showed that a fuel-lean zone can engulf the ignition zone of the glow plug if suspended water droplets are present in the bulk mixture.

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Thermal igniters proposed by the Tennessee Valley Authority for intentional ignition of hydrogen in nuclear reactor containments have been tested in mixtures of air, hydrogen, and steam. The igniters, conventional diesel engine glow plugs, were tested in a 10.6 ft.^{3} pressure vessel with dry hydrogen concentrations from 4% to 29% hydrogen, and in steam fractions of up to 50%. Dry tests indicated complete combustion between 8% and 9% H_2, and no combustion for concentrations below 5%. Steam tests were done with hydrogen volume fractions of 8%, 10%, and 12%. Steam concentrations of up to 30% consistently resulted in ignition. Most of the 40% steam fraction tests resulted in combustion. In a few isolated cases the 50% steam fraction tests indicated a pressure rise. Circulation of the mixture improved combustion in both the dry and the steam tests, most notably at low H_2 concentrations. An analysis of the high steam fraction test data showed a high probability for the presence of small, suspended water droplets in the test mixture. The suppressive influence of this condensation-generated fog on combustion is evaluated.

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