DUKE POWER COMPANY

An Analysis Of Hydrogen Control Measures At McGuire Nuclear Station

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5. AN EVALUATION OF THE HYDROGEN MITIGATION SYSTEM IGNITER TESTING PROGRAM

5.1 Introduction

Duke Power Company, Tennessee Valley Authority (TVA), and American Electric Power Corporation (AEP) sponsored an experimental program to determine the effectiveness of the hydrogen igniters which have been installed at McGuire Nuclear Station Unit 1 and Sequoyah Nuclear Plant Unit 1. This experimental program was conducted by Fenwal, Incorporated in conjunction with Westinghouse and Combustion and Explosives Research Company. The test conditions were selected to present significant environmental challenges to the effectiveness of the igniter so that it could be evaluated.

The experimental program was divided into two phases. Phase 1 testing was conducted to determine if the hydrogen igniter would cause hydrogen to burn at volumetric hydrogen concentrations of 8, 10 and 12 percent for various environmental conditions of pressure, temperature, humidity (steam), and air flow across the igniter.

Phase 2 testing was divided into four parts. The Phase 2, Part 1 tests were conducted to determine if the igniter would initiate burning at low hydrogen concentrations for various environmental conditions. The Phase 2, Part 2 tests were conducted to determine igniter performance under the conditions of continuous hydrogen injection with the igniter preenergized. The Phase 2, Part 3 tests were conducted to determine the effect of a water spray on igniter performance at volumetric hydrogen concentrations of 6 and 10 percent and during a continuous injection of hydrogen. One of these tests included a direct water spray on the igniter. Phase 2, Part 4 tests were conducted to determine the effect of a single hydrogen burn on equipment typical of that located inside containment.

An igniter assembly identical to those installed at Sequoyah Nuclear Plant Unit 1 was used for the Phase 1 and Phase 2, Parts 1, 2 and 3 testing. An igniter assembly identical to those installed at McGuire Nuclear Station Unit 1 was used for the Phase 2, Part 4 testing.

The results of this Phase 1 and Phase 2 testing indicate the following:

1) Initial pressure in the range of 6-to-12 psig has no effect on the ability of the igniter to initiate burning at volumetric hydrogen concentrations in the range of 8-to-12 percent.
2) High initial temperatures, in the range of 350°F, have a very small effect on the ability of the igniter to initiate burning.
3) Volumetric steam concentrations up to and including 40 percent steam or environmental conditions of 100 percent humidity do not hinder the ability of the igniter to initiate hydrogen burning. However, volumetric steam concentrations of 40 percent do suppress the peak pressure generated by a hydrogen burn.
4) Air flow across the igniter in the range of 5-to-10 feet per second does not hinder the ability of the igniter to initiate hydrogen burning. In the higher hydrogen concentration ranges (10-to-12 percent hydrogen) air flow across the igniter has little or no effect. However, at low hydrogen concentrations (6-to-8 percent hydrogen) air flow across the igniter increases the ability of the igniter to burn greater percentages of the available hydrogen.
5) Water spray does not hinder the ability of the igniter to initiate hydrogen burning. At low hydrogen concentrations (6-to-8 percent hydrogen) water spray promotes more complete hydrogen combustion just as air flow across the igniter does.

6) The igniter can initiate hydrogen burning at low concentrations of hydrogen during a continuous injection of hydrogen. Continuous injection of hydrogen and steam produce multiple burns similar to those calculated by the CLASIX computer code.

7) The environment produced by a hydrogen burn does not severely affect equipment typical of that located inside containment.

The Fenwal reports describing the results of the Phase 1 and Phase 2 testing are provided in Sections 5.3 and 5.4.

This experimental program demonstrated that the hydrogen igniters which have been installed at McGuire Unit 1 and Sequoyah Unit 1 can effectively initiate a hydrogen burn at volumetric hydrogen concentrations of 5 percent and higher. In the event of an accident resulting in the release of hydrogen in excess of the amount specified in 10CFR §50.44 these igniters will burn the released hydrogen at low concentrations, thereby preventing the burning or detonation of a large concentration of hydrogen.

5.2 The Hydrogen Mitigation System Igniter Testing Program

5.2.1 Description of Test Equipment

A detailed description of the test equipment is contained in Sections 5.3 and 5.4. During the Phase 1 tests the test configuration was altered slightly after the second test. In test Nos. 1 and 2 the temperature recorded at T_3 (see Section 5.3) was sensed and recorded from a thermocouple which was silver soldered to a bracket similar to the igniter transformer bracket, and mounted inside the igniter box. This thermocouple was replaced with another which would sense the temperature of the air inside the igniter box. This replacement was completed prior to beginning the third test, and thereafter there were no other changes to the test equipment in Phase 1.

Phase 2 testing was divided into four parts. The instrumentation used in Phase 2, Part 1 was identical to that used in the Phase 1 tests Nos. 3 through 14. The test configuration for Phase 2, Part 2 was modified to allow determination of igniter performance under a continuous injection of hydrogen with the igniter preenergized. A ball check valve was added to the injection line and the hydrogen supply bottle was regulated by a rotameter. The output of the rotameter was then connected to the check valve and this completed the test setup. The only difference between Phase 2, Part 2, test No. 3 and Phase 2, Part 2, test No. 2 was that the hydrogen supply bottle and the steam came together in a "tee connection" which was then attached to the check valve.

The Phase 2, Part 3 tests involved determining the effect of a water spray on igniter performance. A spray nozzle was installed in the top of the test vessel. This nozzle was fed through flexible tubing by a small water pump. The flow from the pump to the nozzle was controlled by a needle valve at the discharge of the pump. The nozzle was designed to produce 700 micron droplets over a 45° half angle at the flow rate of 2 gpm when the pressure differential across the nozzle was 9 psi. A pressure gauge was located near the nozzle intake and the pressure and flow were confirmed by measurement prior to the igniter tests. The remainder of the test equipment of Phase 2, Part 3 was identical to that used in Phase 2, Part 1. However, one of the Phase 2, Part 3 tests was performed with a continuous injection of hydrogen using test equipment as modified for Phase 2, Part 2.

Four additional temperatures were measured for the Phase 2, Part 4 tests conducted to determine the effect of a single hydrogen burn on equipment typical of that located inside containment. In three tests three thermocouples were located inside and one outside of a Barton transmitter casing. In two other tests one thermocouple each was located inside and outside of both an Namco limit switch and an Asco solenoid valve. In addition, a Duke igniter was substituted for the TVA igniter. The major difference between the Duke and TVA igniters is that the Duke igniter has voltage taps which allow operation at 10v, 12v, 14v, 16v, or 18v if necessary or desired. The remainder of the test configuration was identical to that used in Phase 2, Part 1.

5.2.2 Description of Test Procedures

A detailed description of the Phase 1 and Phase 2 test procedure is provided in Sections 5.3 and 5.4.

5.2.3 Description of the Individual Tests

5.2.3.1 Phase 1 Tests

The Phase 1 testing program consisted of 14 tests. The igniter reliably initiated burning in all the tests and the results are tabulated in Section 5.3.

The following is a description of the distinguishing characteristics of each of the 14 tests.

Test No. 1 - This was a 12 v/o hydrogen test conducted at an initial temperature of 180°F. It was designed to be used as a bench mark against which the other 12 v/o hydrogen tests could be compared. The $\Delta P/\Delta P$ max (calculated) indicated that it was a relatively complete burn.

Test No. 2 - This was an 8 v/o hydrogen test which was als conducted at an initial temperature of 180°F. It was also designed to be used as a bench mark against which the other 8 v/o tests could be c..pared. However, this test produced a differential peak pressure of 33 psi which was not expected prior to the test. In retrospect this was the first confirmation that an 8 v/o hydrogen mixture is indeed a border concentration where hydrogen can begin to burn much more completely.

Test No. 3 - This test repeated the same conditions used in test No. 2. The results, however, differed dramatically. The differential peak pressure was only 3 psi in this test and the $\Delta P/\Delta P$ max (calculated) indicated that only partial burning occurred. This was the type of test result which was expected prior to test No. 2.

Test No. 4 - This test was a 12 v/o hydrogen test with steam added. The initial pressure of the test was 6 psig. It produced a relatively complete burn and a peak differential pressure of 66 psi.

Test No. 5 - This was an 8 percent hydrogen test with steam added. The initial pressure of the test was 6 psig. This test was unusual in that the pressure trace (see Figure 1) clearly indicates two distinct hydrogen burns. The pressure in the vessel rose approximately 3.5 psi and then began a smooth climb to a differential pressure of 22.6 psi. No external cause was found for the second or continuous rise to the peak differential pressure.

Test No 6 - This 12 v/o hydrogen test was similar to test No. 4 except that it was run at 12 psig rather than 6. Results from this test were very similar to those recorded for test No. 4.

Test No. 7 - This 8 v/o hydrogen test generated unusual results due to a breakdown in the test procedure. Normally after the hydrogen burn reached its peak pressure and began to descend the igniter was deenergized, and after a small c' .down time the mixing fan, located in the bottom of the test vessel, was started prior to taking the post-burn sample. However, in this test, the mixing fan was started approximately 30 seconds after the glow plug was deenergized and a second burn occurred (see Figure 2). Previous tests at Singleton Laboratories confirmed that the igniter temperature 30 seconds after being deenergized was still above the 1200°F temperature range, and therefore it was concluded that the igniter rather than the fan initiated the second burn. During the Phase 2 tests this conclusion was confirmed when the mixing fan was started repeatedly in a 6 v/o hydrogen mix but failed to initiate a burn. The results of test 7 were the first indication of the possible positive effects of turbulence in low hydrogen concentrations.

Test No. 8 - This test was designed to determine the effects of fan flow across the igniter. This test was identical to the test conditions of test No. 4 described above except the addition of a small shaded pole motor fan which was adjusted to move the vessel air at 5 fps past the igniter. The test results were almost identical to those seen in test No. 4 and showed no effect other than delaying the ignition time for approximately 3 seconds.

Test No. 9 - The test conditions for this test were identical to those in test No. 8 except that the air flow across the igniter was increased to 10 fps.

The test results for this test were likewise almost identical to those in test No. 8 except for the time it took to initiate the burn. This was the longest time that any test went without beginning to burn.

Test No. 10 - This test was very similar to test No. 9 except the hydrogen concentration was lowered to 10 v/o. The position of the fan relative to the igniter was not changed from the previous test and was again confirmed to be producing air flow past the igniter at 10 fps. This test did not show any extended delay in initiating the hydrogen burn as was experienced in test No. 9.

Test No. 11 - This test was identical to test No. 10 with the exception of the fan being relocated to reduce the air flow to 5 fps. The test results, however, were almost identical to those recorded in test No. 10.

Test No. 12 - This was a 12 v/o hydrogen test which was conducted at an elevated temperature of 350°F and an air flow across the igniter of 10 fps. The peak differential pressure seen in this test was almost identical to the peak pressure generated in test No. 11. This indicates that the higher temperature did not affect the completeness of the burn. The time to ignition for this test and test Nos. 10 and 11 were very close. This is another indication that the elevated temperature had very little effect.

Test No. 13 - This test was another 12 v/o, high initial temperature test identical to test No. 12, except that there was no air flow across the igniter. This test produced peak pressures which were less than both test Nos. 4 and 6 which were similar 12 v/o tests but whose initial test temperatures were 212°F and 160°F less, respectively, than this test.

Test No. 14 - This test was also conducted at a high initial temperature but with an 8 v/o hydrogen concentration. This test produced a fairly complete burn similar in many respects to test No. 2 and much more complete than the other 8 v/o tests (test Nos. 3, 5, and 7) conducted in Phase 1.

5.2.3.2 Phase 2 Tests

5.2.3.2.1 Phase 2, Part 1

This part of the Phase 2 testing consisted of nine tests. The first five of the nine tests were designed to determine the igniter combustible limits in the lower hydrogen concentration range. Test Nos. 6 and 7 were designed to determine whether a hydrogen burn is enhanced or hindered by mixture flow past the igniter. Finally, test Nos. 8 and 9 were designed to determine whether high steam concentration (40 percent) affects flammability in a 10 v/o hydrogen atmosphere. The results are tabulated in Section 5.4.

Test Nos. 1 through 5 - All five of these tests were conducted in an identical fashion except with decreasing hydrogen concentrations beginning at 9 v/o and ending with 5 v/o. The test procedures used in these tests were identical to those used in Phase 1. The peak differential pressure began to decrease significantly around 8 v/o hydrogen down to a low of .25 psi for the 5 v/o tests. The results obtained in these tests confirm that the igniter can effectively ignite hydrogen at low concentrations.

Test Nos. 6 and 7 - These tests were run in a similar fashion to test Nos. 1 through 5 with the exception that both tests also included fan induced air flow of 5 fps across the igniter. In the 8 v/o test the maximum differential pressure was approximately 11 times greater than the corresponding test No. 2 conducted without the fan. The effect of the fan was even more significant in the 6 v/o test where the maximum differential pressure generated by the burn was 14 times greater than the similar test No. 4, conducted without the fan.

Test Nos. 8 and 9 - These tests were run to determine whether high steam concentrations (40 percent steam) would affect flammability in both a 10 and 6 v/o hydrogen mixture. In both tests the peak differential pressures were less than those measured in test No. 4 and the equivalent static tests performed in Phase 2, Part 4. This indicates that the higher steam concentrations act as a pressure suppressant. The time to ignition of these tests did not differ by more than one or two seconds from the equivalent static tests with low steam concentrations.

Test No. 10 - In test No. 9, two burns were observed. The first burn occurred shortly after the plug was energized followed by a second burn when the fan was turned on. This result was similar to that of Phase 1, test No. 7. It was decided to try and repeat the phenomenon which caused the second burn to determine definitely whether a fan spark caused the burn or whether the fan merely brought new fuel in contact with the igniter allowing a second ignition. Initially the vessel was loaded as prescribed for test No. 9. At this point, instead of energizing the igniter, the fan was switched on and off several times. No burn resulted. After the plug was energized, a small burn (ΔP = 0.2 psi) resulted. After a period of time, the fan was turned on and a larger burn (ΔP = 3.2 psi) occurred.

5.2.3.2.2 Phase 2, Part 2

Experiments were run to determine igniter performance under continuous injection of hydrogen with the igniter preenergized. The results are tabulated in Section 5.4.

Test No. 1 - The first attempt to perform test No. 1 was not considered valid because after running this test, a leak was discovered in the hydrogen input line near its entrance into the vessel. There was no way to determine how much hydrogen had leaked out and therefore no way to know how much hydrogen was actually fed into the vessel during the test. Thus, there is no way to correlate the measured data to the initial conditions. The leak was repaired and the test repeated.

Test No. 2 - This was a repeat of test No. 1. It began with the vessel filled with air at 80°F and 14.7 psia. Prior to the test, the glow plug was energized and allowed to reach its steady state temperature. From the start of the test, hydrogen was added to the vessel at a rate of 4 scfm for the 15-minute duration of the test. This hydrogen addition rate was selected to approximately scale the rate of addition into the ice condenser containment lower compartment during an S_2D type transient.

Approximately 100 seconds after initiation of hydrogen flow into the vessel, the first of two burns occurred. The first burn was a continuous burn at low hydrogen concentration for about 8.5 minutes. The average concentration in the vessel at the initiation of this burn was about 5 v/o hydrogen based on the time and rate of hydrogen injection. The peak differential pressure of 7.8 psi occurred 11 seconds after ignition and was followed by a gradual decrease in the differential pressure to 3.8 psi 8 minutes later. The slow pressure decay rate indicates that hydrogen burning was still occurring, though at a decreasing rate. This pressure behavior indicates a quick burn of about 30 percent of the accumulated hydrogen followed by a continuous burn of a portion of the constant injection flow.

A second burn was indicated at about 11 minutes after ignition by a local differential pressure peak of 3.6 psi above the preburn pressure. This burn, unlike the first quickly terminated, thus representing only a minor source of heat. The pressure vs time curve for this test is given in Figure 3.

The air temperature showed a quick increase from its preignition value of 83°F to its maximum of 330°F approximately 1/2 minute after ignition. After peaking, the temperature showed a slow, nearly linear decrease of 300°F six minutes later. At this time a slight temperature increase of 20°F over the next 1-1/2 minutes occurred. Approximately 8.5 minutes after initiation of the first burn, the air temperature showed a rapid decrease, the result of hydrogen burning cessation. Assuming that all injected hydrogen had burned, 80 percent of the oxygen would have been used by 10 minutes. The air temperature vs time plot is illustrated in Figure 4.

The glow plug box interior air temperature showed a continuous increase from 103°F at the time of ignition to a maximum of 193°F at the end of the test. At the completion of the test , the temperature had peaked as seen in Figure 5. The glow plug box exterior temperature showed a continuous increase from 83°F at the time of ignition to a maximum of 220°F nine minutes after ignition. After the temperature peak, a rapid cooling of the glow plug box exterior occurred. This corresponded with the cooling of the air following cessation of hydrogen burning. The glow plug box exterior temperature vs time is illustrated in Figure 4.

Test No. 3 - This test started with the vessel filled with air at 160°F and an initial pressure of 14.7 psia. The test began with the igniter plug pre-energized and the initiation of hydrogen and steam flows of 4 scfm and .3 lbm/min (290°F), respectively, into the vessel. These flows were maintained for the 15 minute duration of the test. The hydrogen and steam were mixed immediately prior to input.

Nearly 1-1/2 minutes after the initiation of hydrogen and steam mixture flow, the first of a series of eight finite burns occurred. At this time the hydrogen concentration would have been 4.8 v/o. In these burns, a maximum differential pressure of 10.15 psi over the preburn pressure resulted. The maximum air temperature was 367°F. These low temperatures and pressures result from the burning of hydrogen at low concentrations and the dissipation of energy to heat sinks between the burns.

As shown on the pressure vs time plot, Figure 6, the pressure peaks had an initial period of 1 minute decreasing to a period of 1/2 minute between the seventh and eighth burns. The 7.1 psi pressure increase from the first burn corresponds to burning off about 30 percent of the hydrogen present at that time. Assuming this and no additional burn in between would lead to a concentration of 6.3 v/o hydrogen at the time of the second peak. Alternately, assuming some continuous burning (about 40 percent of the injection flow) would result in the same concentration being reached at the beginning of the second peak as for the first (4.8 v/o). The general cyclical pattern appears consistent with buildup to a level where a quick partial burn occurs and then burns at an insufficient rate to match the addition between burn peaks. This shortening of time between the peaks could result from either a reduction in burn completeness due to increased steam concentration or possibly to a reduction in the hydrogen concentration required for a quick burn due to the system temperature increase. The maximum total differential pressure of 10.15 psi above the preburn pressure occurred at the fifth peak. The highest pressure change for a pressure peak with respect to its preburn pressure also occurred at the fifth peak with a value of 7.35 psi.

The air temperature vs time curve, Figure 7, shows a net increase in air temperature throughout the series of burns with a local temperature peak corresponding to each of the burns. The air temperature increased from a preburn temperature of 165°F to a maximum of 367°F at the peaks of both the fifth and eighth burns. Following the eighth (last) burn, the temperature decreased for the remainder of the test.

The glow plug box interior temperature gradually increased from a preburn temperature of 167°F to a maximum value of 238°F at approximately 11 minutes into the experiment. Corresponding to each of the eight burns is a small local perturbation in the curve with a greater slope indicating higher exterior temperatures. The glow plug box interior temperature vs time curve is illustrated in Figure 8. The glow plug box exterior temperature increased from the preburn value of 150°F to a maximum value of 265°F at 11 minutes into the test. This curve is illustrated in Figure 7.

The temperature and pressure results of this test are very close to the expected values in comparison with the previous test when the initial temperatures are considered.

5.2.3.2.3 Phase 2, Part 3

A series of tests were run t determine the effect of spray upon igniter performance. The results are tabulated in Section 5.4.

Test No. 1 - The first attempt to perform test No. 1 was not considered valid because upon completion of the test, a leak was discovered in the vessel drain line, allowing the vessel to continually relieve pressure during the test. Correlation, between the initial conditions and measured results was therefore not possible. The leaking line was fixed and tested, and the test was then rerun.

Test No. 2 - This test was a repeat of test No. 1. It was a static test with a 10 v/o hydrogen concentration. Initially, the vessel was filled with air at 14.7 psia and 80°F. Hydrogen was added to the mixture until the desired concentration was attained and allowed to reach thermal equilibrium. The preburn temperature was 82°F. Ignition occurred 11.59 seconds after the igniter was energized. The resulting burn caused a differential pressure peak of 50.0 psi above the preburn pressure. The time from ignition to peak differential pressure was .56 seconds. The pressure curve was similar to other static tests.

Test No. 3 - This test was identical to test No. 1 except that the hydrogen concentration was reduced from 10 v/o to 6 v/o. A single burn occurred 22 seconds after the igniter was energized resulting in a peak differential pressure of 31.2 psi above the preburn value. The time from ignition to peak differential pressure was 1.5 seconds. The pressure curve was similar to those in other static tests.

Test No. 4 - This test was the transient hydrogen burn in this series. It began with an air filled vessel at 14.7 psia and 80°F. At 1 minute before the test began, spray water flow was initiated with a measured average flow rate of 1.9 gpm. Hydrogen flow into the vessel coincided with the beginning of the test and was input at the rate of 4 scfm. Both flows were maintained for the duration of the test. The glow plug was energized at the beginning of the test.

Approximately 89.5 seconds after initiation of hydrogen flow, the first of two burns occurred. At this time the average hydrogen concentration would be 4.8 percent. The first was a continuous burn at a low hydrogen concentration which resulted in a 3.12 psi difference between the peak and preburn pressures. The peak differential pressure occurred 6 seconds after ignition and was followed by a gradual decrease in differential pressure to 0.9 psi after 9 minutes.

A second burn is indicated 10.5 minutes after ignition by a local differential pressure peak of 4 psi over the preburn pressure. This burn was not a continuous burn and quickly terminated. The pressure vs time curve for this test is shown in Figure 9.

Test No. 5 - This test was identical to test No. 1 except that the igniter box was inverted to allow spray water to fall directly on the glow plug. It should be noted that this arrangement is much more severe than would be expected in containment with the rain shield present. This test was included to conservatively bound the possibility of spray drops impinging on the igniter heating element due to turbulence.

Approximately 15 seconds after the glow plug was energized the only burn occurred. A peak differential pressure of 42.2 psi above the preburn pressure resulted 1.1 seconds after ignition. The pressure curve was similar to those of other static tests.

5.2.3.2.4 Phase 2, Part 4

This series of static tests was performed for the following purposes:

1. Determine the effect of a hydrogen burn on certain equipment and typical materials inside the containment vessel.

2. Determine the temperature response of a Barton transmitter casing and a solenoid valve/limit switch to a hydrogen burn.

3. Determine the effect of reduced igniter voltage upon the glow plug's ability to ignite hydrogen.

The results are tabulated in Section 5.4.

Test No. 1 - This test involved the burning of an air-steam hydrogen mixture at 5.9 psig and 129^{o}F with a hydrogen concentration of 12 v/o. The igniter voltage was reduced from 14.6 to 12 volts. A Barton transmitter casing was placed inside the test vessel for this experiment with three thermocouples attached to different positions within the casing and one to the outside. The locations of the internal thermocouples were: Strain Guage (TC No. 2); Inside Wall (TC No. 4), and Circuit Board (TC No. 5).

The result of this burn was a differential pressure increase of 60 psi over the preburn pressure and a maximum air temperature of 710°F. The Barton transmitter casing reached maximum internal and external temperatures of 150°F and 230°F respectively. The temperature and pressure curves are similar to those of other static tests.

Test No. 2 - This test was identical to test No. 1 except that the Barton transmitter casing was enclosed in a space blanket. This space blanket failed during this test and therefore the test results were very similar to those of test No. 1.

Test No. 3 - This test was identical to test No. 1 except that an unshielded solenoid valve/limit switch combination was placed inside the test vessel in addition to the Barton transmitter casing. The four additional thermocouples were relocated from the transmitter casing to this new equipment. One thermocouple was attached on the inside and one on the outside of both the solenoid valve and the limit switch.

The result of this burn was a differential pressure increase of 63 psi over the preburn pressure and a maximum air temperature of 760°F. The solenoid valve reached maximum interior and exterior temperatures of 228°F and 240°F. The lmiit switch reached maximum interior and exterior temperatures of 170°F and 235°F, respectively. The temperature and pressure curves are similar to those of other static tests.

Test No. 4 - This test was identical to test No. 3 except that the solenoid valve/limit switch combination was loosely wrapped in a single layer of aluminum foil.

The result of this burn was a differential pressure increase of 58 psi over the preburn pressure and a maximum air temperature of 755°F. With the aluminum foil enclosure, the limit switch reached maximum internal and external temperatures of 138°F and 185°F, respectively. The solenoid valve, also enclosed in the aluminum foil, reached maximum internal and external temperatures of 183°F and 250°F, respectively. The pressure and temperature curves are similar to those of other static tests.

Test Nos. 5 and 6 - These tests involved the burning of an air-steam-hydrogen mixture at 6.4 psig and 146°F with a hydrogen concentration of 10 v/o. The igniter voltage was reduced from 12 volts in test No. 5 to 10 volts in test No. 6 to demonstrate the ability of the glow plug to ignite hydrogen at reduced voltages.

The result of the burn in test 5 was a differential pressure increase of 49 psi over the preburn pressure and a maximum air temperature of 790°F. For test No. 6 the corresponding values were 50 psi and 760°F. In both cases, the pressure and temperature curves are similar to those of other static tests.

Test No. 7 - This test was identical to test No. 3 except that the Barton transmitter casing was enclosed in a single layer of loosely wrapped aluminum foil and the thermocouples were relocated back to the transmitter casing as in test No. 1.

The result of this burn was a differential pressure increase of 61 psi over the preburn pressure and a maximum air temperature of 735°F. With the aluminum foil enclosure, the Barton transmitter casing reached maximum internal and external temperatures of 140°F and 143°F, respectively. The temperature and pressure curves are similar to those of other static tests.

5.2.4 Anomalous Data

In the course of performing both the Phase 1 and Phase 2 testing some of the recorded data was anomalous due to instrument error. The following describes the anomalous data and the reason why that data has not been factored into this evaluation report.

5.2.4.1 Phase 1 - Inconsistent Data

Two of the thermocouple readings recorded in Section 5.3 require some discussion. Test No. 2 seems to have experienced a large temperature rise inside the igniter box. This reading for an 8 v/o test is higher than the previous 12 v/o and is inconsistent with the rest of the recorded data. Therefore Fenwal replaced and recalibrated that particular thermocouple. Also, the thermocouple was silver soldered to a transformer mounting bracket and subsequently was moved to a new location where it was suspended in air inside the igniter box. There are two possible explanations for this abnormally high reading. The first is the possibility of burning hydrogen leaking into the igniter box. (The box was intentionally not sealed so that this concern could be conservatively bound.) However, the thermocouple measuring the outside of the igniter box measured only 330°F and it was definitely exposed to the hydrogen burn. The second possibility was that the thermocouple was indeed faulty. Because of this uncertainty this data point was not used.

In test No. 9 the thermocouple reading vessel air temperature recorded an abnormally low temperature. It was postulated that water from the condensing steam effectively shorted the thermocouple. Fenwal checked the thermocouple for damage and recalibrated the instrumentation before continuing. The thermocouple operated properly therafter. Also, in those tests where a substantial and rapid burn occurred (such as all 10 and 12 v/o hydrogen concentrations) the gas temperature increased many hundreds of degrees in a very short time (a fraction of a second in many cases). In these tests the vessel air thermocouple does not have sufficient response time to measure the true gas temperature and should be disregarded as an indicator of maximum gas temperature. In such cases the pressure measurement in conjunction with the ideal gas law provides an accurate indication of the actual temperature of the vessel gas.

The pressure traces for tests with a fast pressure rise, less than one second, exhibit a sharp narrow spike near the pressure peak. This is due to the pressure transducer being located offset from the vessel in a short pipe. The gas within the pipe is pressurized to near the peak vessel pressure by the time the flame front reaches the pipe inlet. Hence an overpressure results within the pipe as its contents burn and exhaust into the test vessel.

5.2.4.2 Phase 2 Testing

During the course of the Part 3 tests, it was noted that many of the temperature vs time plots were of a jagged and highly erratic nature as opposed to the generally smooth and rounded plots obtained in previous experiments. After this series of experiments was completed, it was noticed that much of the teflon insulation had been burned off the lead wires to the thermocouples, allowing them to short out in the spray. The thermocouple wires were replaced and wrapped in aluminum foil before any subsequent tests were performed. No erratic temperature plots were found in the test data for subsequent tests. For this reason, the temperature data for this series of tests cannot be relied upon as being accurate.

In Part 4, test No. 4 the thermocouple on the outside of the solenoid valve, unlike the other measured equipment temperatures, did not follow the trend of lower temperatures when insulation was used. Instead, a higher temperature was measured for the insulated case than the non-insulated case. It is suspected that in this instance, the aluminum insulation was in direct contact with the surface thermocouple, thereby allowing a local situation of heat transfer nearly identical to the uninsulated case. This is substantiated by two facts. First, the valve exterior temperature is nearly the same in both cases, 240°F vs 250°F. Second, the valve interior temperature showed a 45°F reduction from 228°F in the non-insulated case to 183°F for the insulated case. For these reasons, the solenoid valve exterior temperature for the insulated case is considered invalid.

5.2.4.3 Hydrogen Sampling

Throughout the Phase 1 and Phase 2 testing program both pre-burn and post-burn gas samples were taken. The purpose of these samples was to confirm the pre-burn hydrogen concentration inside the test vessel and to confirm the completeness of the burn after the test had been completed. Prior to the start of Phase 1 testing it was decided that the gas samples would be analyzed by an independent laboratory using gas chromatography.

In the majority of the pre-burn sample the gas chromatograph hydrogen analysis did not agree with the hydrogen concentration believed to be in the test vessel prior to testing. In an attempt to isolate the problem duplicate samples were sent to another laboratory. Both laboratories agreed that the post-burn samples contained less than 0.1 percent hydrogen. However, the second laboratory reported hydrogen concentrations in the pre-burn samples which differed from the original laboratory's analysis by more than 1.5 percent and neither laboratory was in agreement with the hydrogen concentration believed obtained by using the partial pressure method of loading the vessel.

Every effort was made to verify that neither the method of taking the samples nor the sample bombs themselves was the cause of the discrepancies. It is not known why the gas chromatograph laboratory reported close agreement (within 0.5 percent) for four of the 14 pre-burn samples in Phase 1 and yet also found one test to be a full 3 percent off the expected hydrogen concentration. Further suspicion of the gas chromatograph analysis was created when the TVA test representative brought a pre-burn sample to Singleton Laboratories for analysis using a hydrogen analyzer. This Singleton analysis reported that the sample was within 0.5 percent of the expected concentration.

Due to the uncertainty created by gas chromatograph hydrogen analysis the results obtained from the gas chromatograph laboratory are not being used.

5.2.5 Environmental Effects on Igniter Effectiveness and Hydrogen Combustion

The igniter testing program was conducted to determine how effectively the Duke and TVA igniters could initiate combustion of hydrogen under the environmental conditions expected to exist inside containment after a loss-of cooling accident. The program was also designed to determine how these environmental conditions would affect the hydrogen burn once initiated. These environmental conditions include temperature, pressure, humidity (steam), air flow across the igniter (atmospheric turbulence), and presence of water spray droplets in the atmosphere. The parameters of importance in determining the effects of these environmental conditions are burn initiation, burning completeness, peak pressure rise and peak temperature rise.

5.2.5.1 Effects of Temperature

The tests conducted at Fenwal covered a range of initial test temperatures from approximately 130 to 350°F. In previous tests conducted at Singleton Laboratories it was determined that approximately 18 seconds elapsed from the time the TVA igniter was energized to the time it reached approximately

1200^oF. Figure 10 is a graph of the time to ignite versus initial test temperature for the Phase 1 tests. As the graph indicates there is little or no correlation between initial test temperature and the time required for the igniter to initiate burning.

5.2.5.2 Effects of Pressure

The tests conducted at Fenwal ranged in pressure from approximately 17.9 psia to 26.7 psia. Figure 11 is a graph of the time to ignite versus initial test pressure for the Phase 1 tests. The graph indicates that there is no correlation between the initial test pressure and the time required for the igniter to initiate burning.

5.2.5.3 Effects of Humidity (Steam)

In 21 of the tests conducted at Fenwal steam was injected either prior to or during the test. The quantity of steam and/or saturated conditions inside the vessel was chosen to produce high humidity. The percentage of water inside the vessel in the form of steam ranged from approximately 6 percent to a high of 40 percent. The results of these tests indicate that high humidity or steam concentrations up to 40 percent have no effect on the ability of the igniter to initiate burning. The primary effect of humidity (up to 40 percent steam) on hydrogen combustion is to slightly increase the lower combustion limit as humidity increases. The primary effect of steam upon hydrogen burning once initiated is to supress the resulting pressure and temperature rises. For those tests with similar initial temperatures and hydrogen concentrations, the thermocouple responses indicate a general trend toward lower observed temperatures with increasing water vapor concentration.

5.2.5.4 Air Flow Across the Igniter

Five of the 14 tests in Phase 1 were designed to test the ability of the igniter to ignite hydrogen with air flows of 5 and 10 fps. In all five of those tests the time to ignition increased. In Phase 1, test No. 8 the air flow across the igniter was set at 5 fps. This marginally increased the time to ignition by 2-to-4 seconds. In the very next test, however, the air flow across the igniter was set at 10 fps and the time to ignition increased significantly, to approximately 49 seconds, over the average time to ignition of 18 seconds. This result, however, was not reproduced in the two other 10 fps tests where the time to ignition was 29 and 25.9 seconds, respectively. It appears that air flow across the igniter retards only the rate at which the igniter heats up but does not prevent the igniter from reaching ignition temperatures.

The introduction of fan induced turbulence in the test medium served to increase the burn completeness for those burns with initial hydrogen concentrations of 8 v/o and below. In these cases, the hydrogen immediately around the igniter burned in a brief burst. Then as the fan remixed the atmosphere, a flammable mixture was again introduced in the vicinity of the igniter and the mixture ignited. Hence for relatively low hydrogen concentrations (4-to-8 percent) fans increase the amounts of hydrogen burned.

5.2.5.5 Effects of Water Sprays

The Phase 2, Part 3, tests were designed to determine what effect water spray would have on the ability of the igniter to initiate burning. The test results indicate that rather than hinder the igniter's performance water spray actually increases the completeness of the hydrogen burn at low hydrogen concentrations. In addition, the time to ignition was not increased by the sprays. The last test in Part 3 involved turning the igniter box over and allowing the igniter to be sprayed direct' Even in this severe test the igniter initiated a 10 v/o hydrogen burn in 1ь seconds. This demonstrates conclusively that water sprays do not hinder the igniters' ability to initiate burning.

The introduction of water sprays tends to have two effects upon hydrogen burning. The subcooled water droplets absorb greater amounts of energy as opposed to merely water vapor and therefore reduce the peak pressures and temperatures which result from the hydrogen burn. The introduction of the sprays also tends to create turbulence which, in turn, increases the amount of hydrogen burned.

5.2.6 <u>Comparison of Tests with the Duke and TVA Igniters</u>

The Phase 1 and Phase 2, Parts 1, 2 and 3 tests were conducted using an igniter assembly identical to those installed at the Sequoyah Nuclear Plant. The Phase 2, Part 4 tests were conducted using an igniter assembly identical to those installed at McGuire Nuclear Station. The major difference between the two igniter assemblies is that the Duke igniter features voltage taps which would allow igniter operation at 10v, 12v, 14v, 16v, or 18v if necessary or desired. The TVA igniter used in these Fenwal tests was operated at 14.6 volts. The Duke igniter was operated at 12 volts except for Phase 2, Part 4, test No. 6 where it was operated at 10 volts.

Most of the static tests were performed with the igniter voltage at 14.6 volts. In these tests the igniter initiated burning after an average of 15 seconds. When the igniter voltage was reduced to 12 volts, the average time to ignition increased to about 27 seconds. For the 10 volt case, ignition time increased to 56 seconds. Thus, it is seen that reducing the igniter voltage increases the time to ignition. This is expected as reduced voltages will increase the time needed for the glow plug to reach high enough temperatures to ignite the hydrogen. It should be noted that in no case was ignition prevented, but was instead merely delayed. Both igniters reliably and repeatedly initiated hydrogen burning.

5.2.7 Evaluation of Hydrogen Burning on Equipment

5.2.7.1 Test Results

The Phase 2, Part 4 tests were conducted with equipment typical of that found inside containment placed inside the test vessel. In addition, the TVA igniter assembly was subjected to over 30 hydrogen burns while the Duke igniter assembly was subjected to 7 hydrogen burns. Both igniter assemblies survived repeated hydrogen burns and still functioned properly. Hydrogen ignition was achieved in every test of Phase 1 and Phase 2.

Section 5.3, page 8, lists the Phase 1 tests and the four temperatures which were recorded for each of the tests. The tests results indicate that the average temperature rise across the igniter box (T_3 - T_V) for the tests run at 12, 10 and 8 percent volumetric concentrations of hydrogen was 48°F, 38°F and 17°F respectively. In several of the Phase 1, 12 v/o tests the vessel air temperature was recorded at 1000°F or over. In all cases the vessel air temperature returned to within approximately 50°F of initial temperature in less than 5 minutes. The corresponding air temperature inside the igniter box for these same tests, however, never exceeded the initial test temperature of the vessel by more than 65°F.

In Phase 2 it is more difficult to draw comparisons as was done for Phase 1 because fewer identical tests were performed and a meaningful average could not be calculated. However, in the Phase 2, Part 1 tests the maximum temperature rise across the igniter box for any of the Part 1 tests was 59°F which occurred during a fan induced second burn of a 6 v/o hydrogen mixture. The Phase 2, Part 2 tests provide larger temperature rises across the box, 118°F for the continuous hydrogen injection/burn case and 78°F for the eight peak multiple burn which occurred with the continuous injection of hydrogen and steam. It was expected that these numbers would be higher due to the longer burn duration and the quantity of hydrogen burned. Due to the melting of the teflon insulation on the thermocouples the temperature data for Phase 2, Part 3 is suspect.

In the Part 4 tests the thermocouple located inside the igniter box was removed and relocated so that the temperatures measured were the inside and outside of the equipment placed in the vessel for equipment survivability testing. In those tests the maximum temperatures measured across the Barton transmitter casing, the solenoid valve, and the limit switch were 101, 99 and 41°F, respectively, for exposure to a 12 v/o hydrogen burn.

Table 1 is a list of all the equipment exposed to at least 12 v/o hydrogen burns during the Phase 2, Part 4 tests. These components are representative of the critical components needed following a TMI-type accident. The majority of the equipment did not experience any visible signs of degradation. The only exceptions were some paint samples on concrete blocks which showed slight discoloration on the corners and one piece of cable which showed a couple of small (1/2 x 2 inch) scorch spots on the black plastic coating. Table 2 is a list of miscellaneous equipment which was also included in the test vessel during the testing.

5.2.7.2 Effects of Insulation

Four of the tests performed in Part 4 were included for the purpose of determining the effect of insulation on equipment inside containment during a hydrogen burn.

In test No. 1, a Barton transmitter casing was used which had three interior thermocouples to measure interior air temperature and one thermocouple attached to the exterior to measure surface temperature. The casing was exposed uninsulated to a 12 v/o hydrogen burn. This resulted in maximum interior air and exterior surface temperatures of 150°F and 230°F, respectively.

Test No. 7 was identical to test No. 1 except that the Barton transmitter casing was loosely wrapped in a single layer of heavy duty aluminum foil (1.0-1.5 mils thick). The foil wrap had the shiny surface facing outward. This test resulted in maximum interior air and exterior surface temperatures of 140°F and 143°F, respectively.

In test No. 3, a solenoid valve and limit switch combination was used which had for each component one thermocouple to measure interior air temperature and one thermocouple attached to the exterior of the structure to measure surface temperature. The switch-valve combination was exposed uninsulated to a 12 v/o hydrogen burn as in test No. 1. The results of this burn were maximum solenoid valve interior air and exterior surface temperatures of 228°F and 240°F, respectively. For the limit switch, the maximum interior air and exterior surface temperatures were 170°F and 235°F.

Test No. 4 was identical to test No. 3 except that the solenoid valve and limit switch combination was wrapped in aluminum foil in the same manner as described earlier for the Barton transmitter casing. The resulting maximum solenoid valve interior and exterior temperatures were 183°F and 250°F, respectively. For the limit switch, the maximum interior air and exterior surface temperatures were 138°F and 183°F. The interior air temperatures dropped 45°F and 32°F for the solenoid valve and limit switch respectively when insulation was used. The Barton transmitter casing maximum interior air temperature dropped 1[illegible]°F when insulation was used. Likewise, the limit switch exterior surface temperature showed a reduction of 52°F when insulation was used. The Barton transmitter casing exterior surface temperature showed a reduction of 87°F.

The solenoid valve exterior temperature is an exception to the trend of reduced temperatures when insulation is used showing a higher temperature for the insulated case than the non-insulated case. It is suspected that in this instance, the aluminum insulation was in direct contact with the surface thermocouple, thereby allowing a local situation of heat transfer nearly identical to the uninsulated case. This is substantiated by two facts. First, the valve exterior temperature is nearly the same in both cases, 240°F vs 250°F. Second, the valve interior temperature showed a 45°F reduction from 228°F in the non-insulated case to 183°F for the insulated case. The solenoid valve exterior temperature for the insulated case is therefore considered invalid.

A loosely wrapped single sheet of aluminum foil 1.0 to 1.5 mils thick has little insulating ability, except when convective and/or radiative heat transfer predominates. It is expected, in this burn case, that radiative heat transfer represents a very significant mode of heat transfer due to the high temperatures which result from the burning of 12 v/o hydrogen concentrations. Radiative heat transfer would be expected to decrease in significance as a primary mode of heat transfer when the concentration at which the hydrogen burned is reduced (and thus the flame temperature reduced). For burns at lower hydrogen concentrations, a larger part of the overall heat which was transferred to equipment would be through the vehicles of conduction and convection. These would not be as greatly affected by a single layer of aluminum foil as radiative heat transfer.

TABLE 1
COMPONENTS PLACED IN FENWAL VESSEL
FOR THE EQUIPMENT SURVIVABILITY TESTS

Equipment	No. of Test Exposures	Effect of Tests
1. Paint samples (on concrete blocks)	1	Very light oxidation film over paint, deeper discoloration of excess paint on corners of concrete blocks
2. Paint samples (on metal slabs	1	Very light oxidation film over paint
3. BX-type metal conduit	1	No obvious degradation
4. Black plastic coated cable	1	Two scorch spots (2" by 1/2")
5. Namco limit switch	3	No obvious degradation
6. Asco solenoid valve	3	No obvious degradation
7. Barton transmitter casing	5	No obvious degradation
8. Miscellaneous wiring	1	No obvious degradation
9. TVA igniter assembly	30	Assembly still functions well. Transformer coating scorched. Transformer wires scorched. Wrap on transformer windings scorched. Glow plug connector scorched. Transformer laminations corroded. Cover gasket scorched and hardened. Assembly exterior lightly corroded.
10. Duke igniter assembly	7	Cover seal burned, but no other obvious degradation
11. Fischer Regulator	1	No obvious degradation

TABLE 2
MISSCELLANEOUS EQUIPMENT IN FENWAL
VESSEL DURING TESTING

	Equipment	No. of Test Exposures	Effects of Tests
1.	Wood block (4" x 4" 5-1/2")	20	Thin browning over much of wood surface
2.	Thermocouples	40	No obvious degradation
3.	Thermocouple lead wires (first set)	30	Teflon insulation burned off most of wires
4.	Thermocouple lead wires (second set)(wrapped in aluminum foil)	6	No obvious degradation
5.	Spray nozzle	5	No obvious degradation
6.	Fan motor (1st)(1/150 hp shaded pole motor)	20	Light oxidation over surface; soldered connections failed on last test
7.	Fan motor (3rd)(1/150 hp shaded pole motor)	1	Failed after high temperature transient burn test; soldered connections detached

Figure No. 1
Phase No. 1
Part No. ___
Test No. 5
Initial Pressure - 20.59 psia
Initial Temperature - 138.3° F
Volume % H_2 - 8.11
H_2 Flow Rate ____
Steam Flow Rate ____
Max. Burn Pressure - 22.6 psid
Max. Air Temperature - 222° F

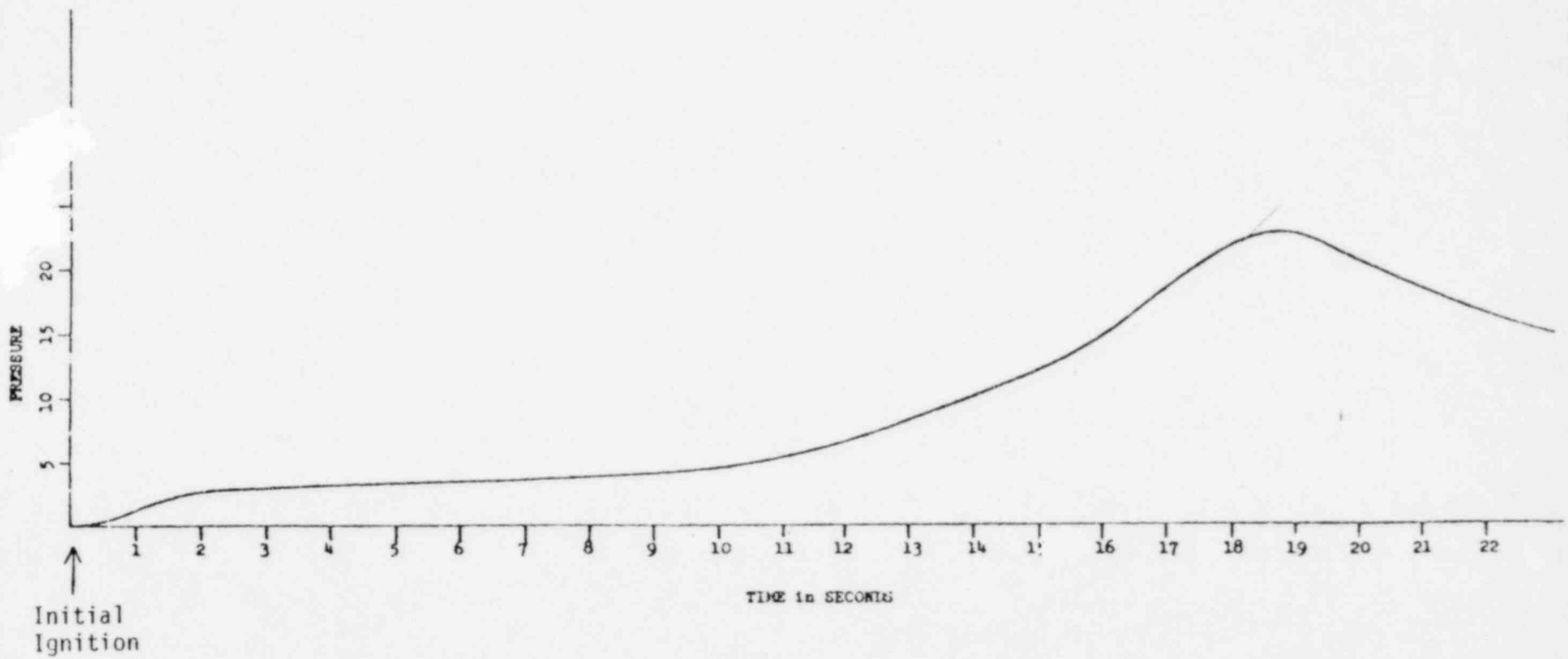

Figure 1

Figure No. 2
Phase No. 1
Part No. ___
Test No. 7
Initial Pressure - 26.671 psia
Initial Temperature - 190.3° F
Volume % H_2 - 8.0
H_2 Flow Rate _____
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 15.5 psid
Max. Air Temperature - 657° F

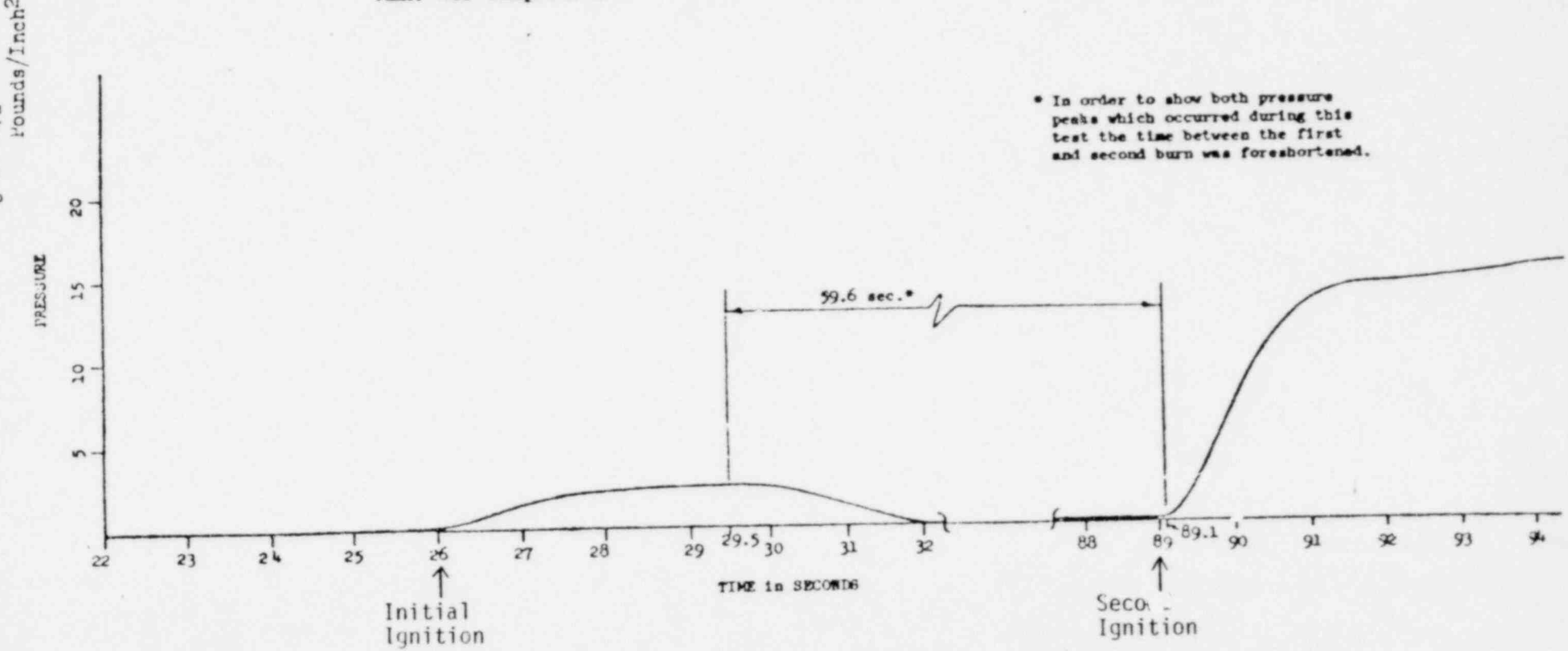

Figure 2

Figure No. 3
Phase No. 2
Part No. 2
Test No. 2
Initial Pressure - 14.67 psia
Initial Temperature - 80° F

Volume % H_2 ____
H_2 Flow Rate - 4 scfm
Steam Flow Rate ____
Spray Flow Rate ____
Max. Burn Pressure - 7.8 lb/in²g
Max. Burn Temperature - 330° F

TRANSIENT BURN IN DRY AIR

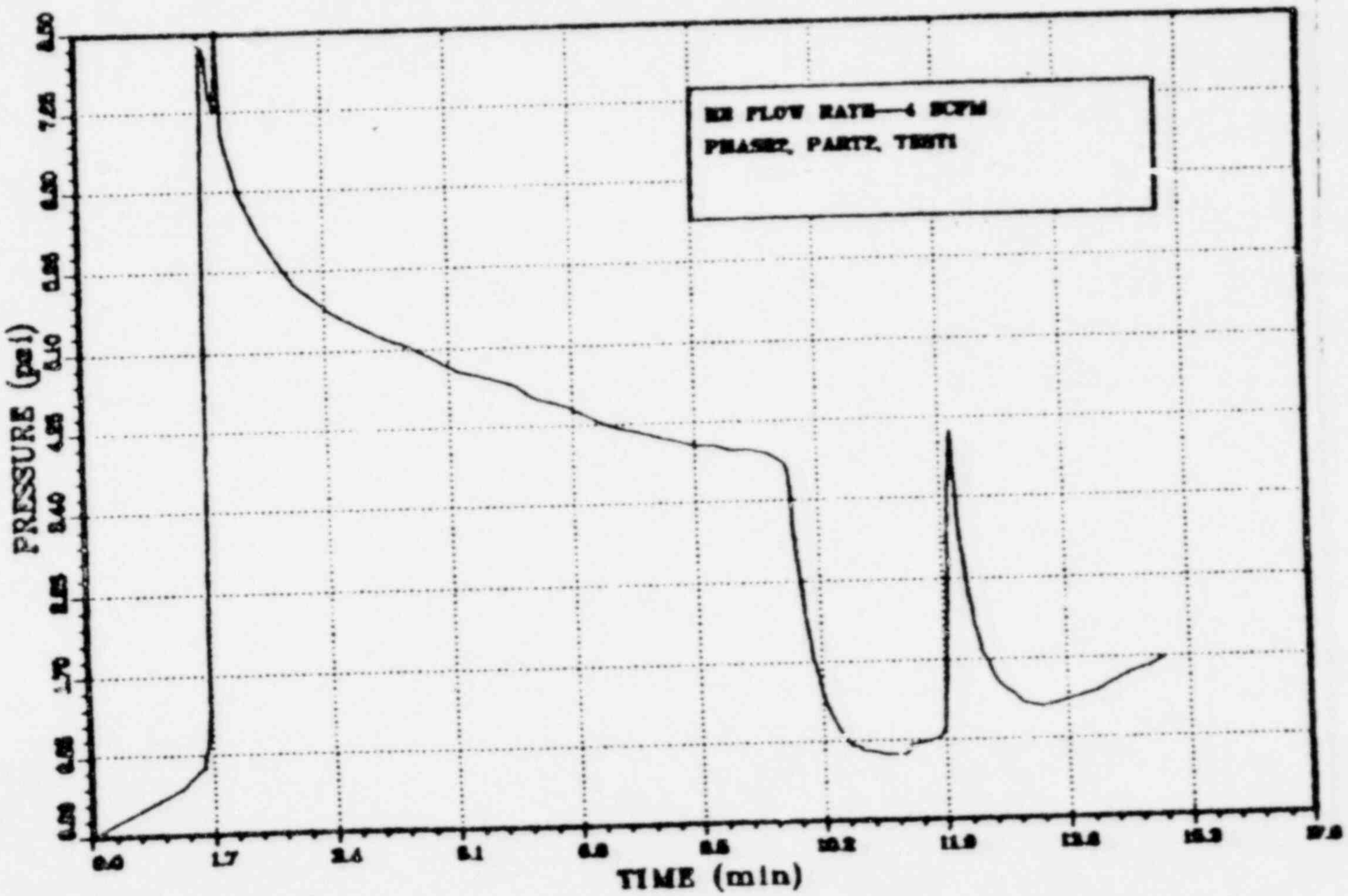

Figure 3

Figure No. 4
Phase No. 2
Part No. 2
Test No. 2
Initial Pressure - 14.67 psia
Initial Temperature - 80° F
Volume % H_2 _____
H_2 Flow Rate - 4 scfm
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 7.8 lb/in^{2}g
Max. Air Temperature - 330° F

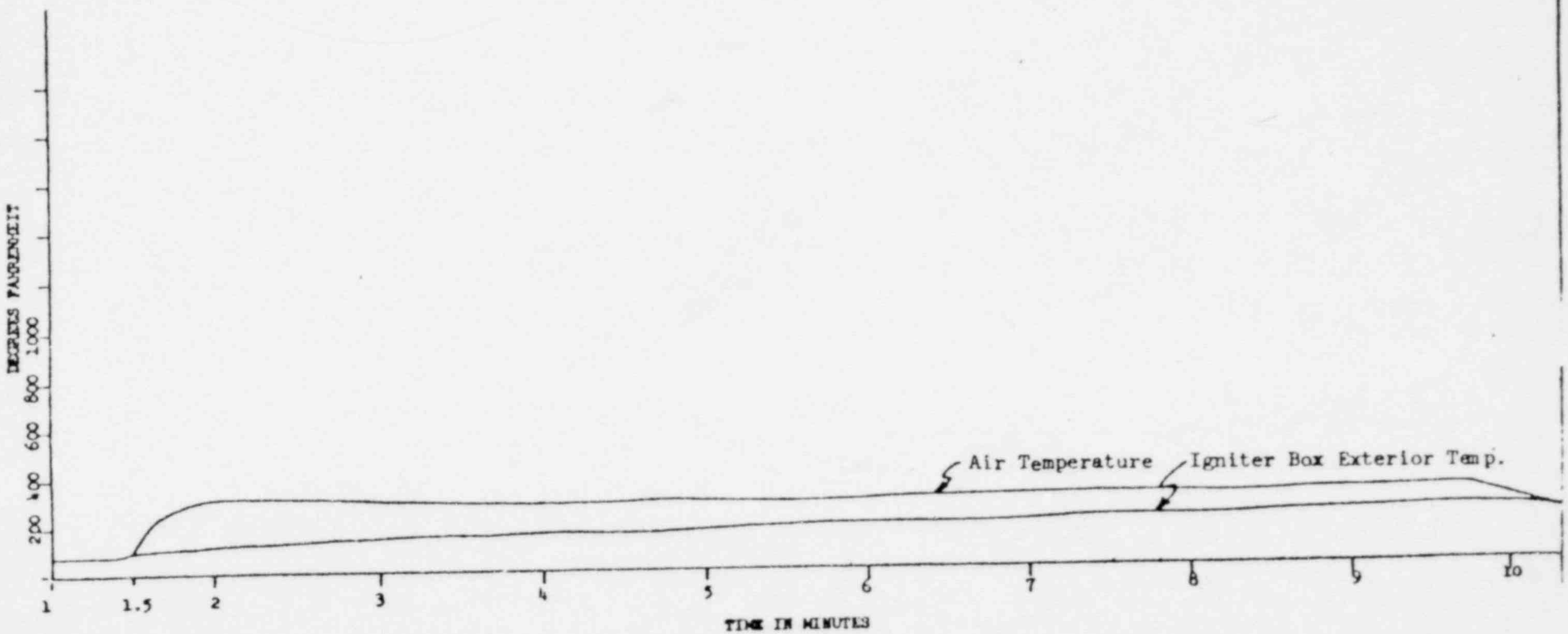

Figure 4

Figure No. 5
Phase No. 2
Part No. 2
Test No. 2
Initial Presaure - 14.67
Initial Temperature - 80° F
Volume % H_2 _____
H_2 Flow Rate - 4 scfm
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 7.8 lb/in²g
Max. Air Temperature - 330° F

Figure 5

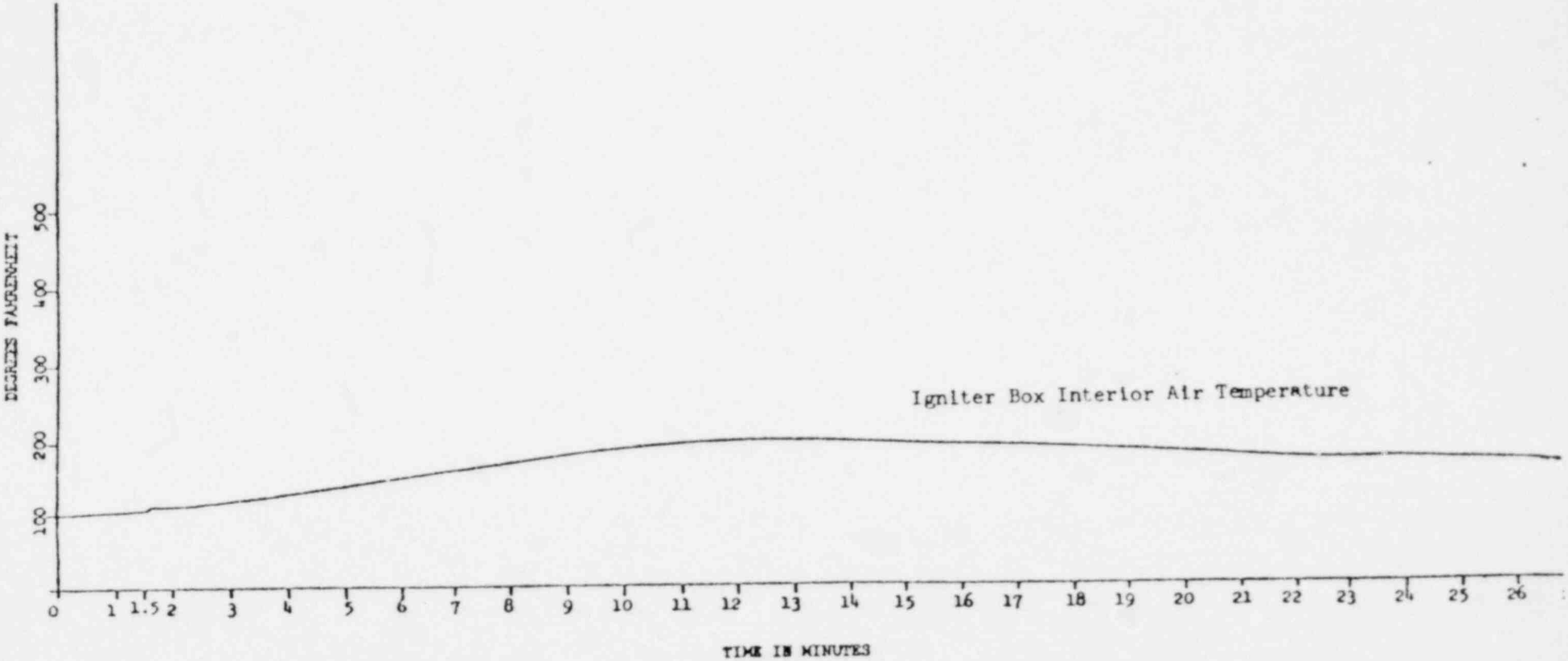

Figure No. 6
Phase No. 2
Part No. 2
Test No. 3
Initial Pressure - 14.85 psia
Initial Temperature - 160°F

Volume % H_2 ______
H_2 Flow Rate - 4 scfm
Steam Flow Rate - 0.3 lb/min
Spray Flow Rate ______
Max. Burn Pressure - 10.15 lb/in^{2}g
Max. Burn Temperature - 367°F

TRANSIENT BURN WITH STEAM INJECTION

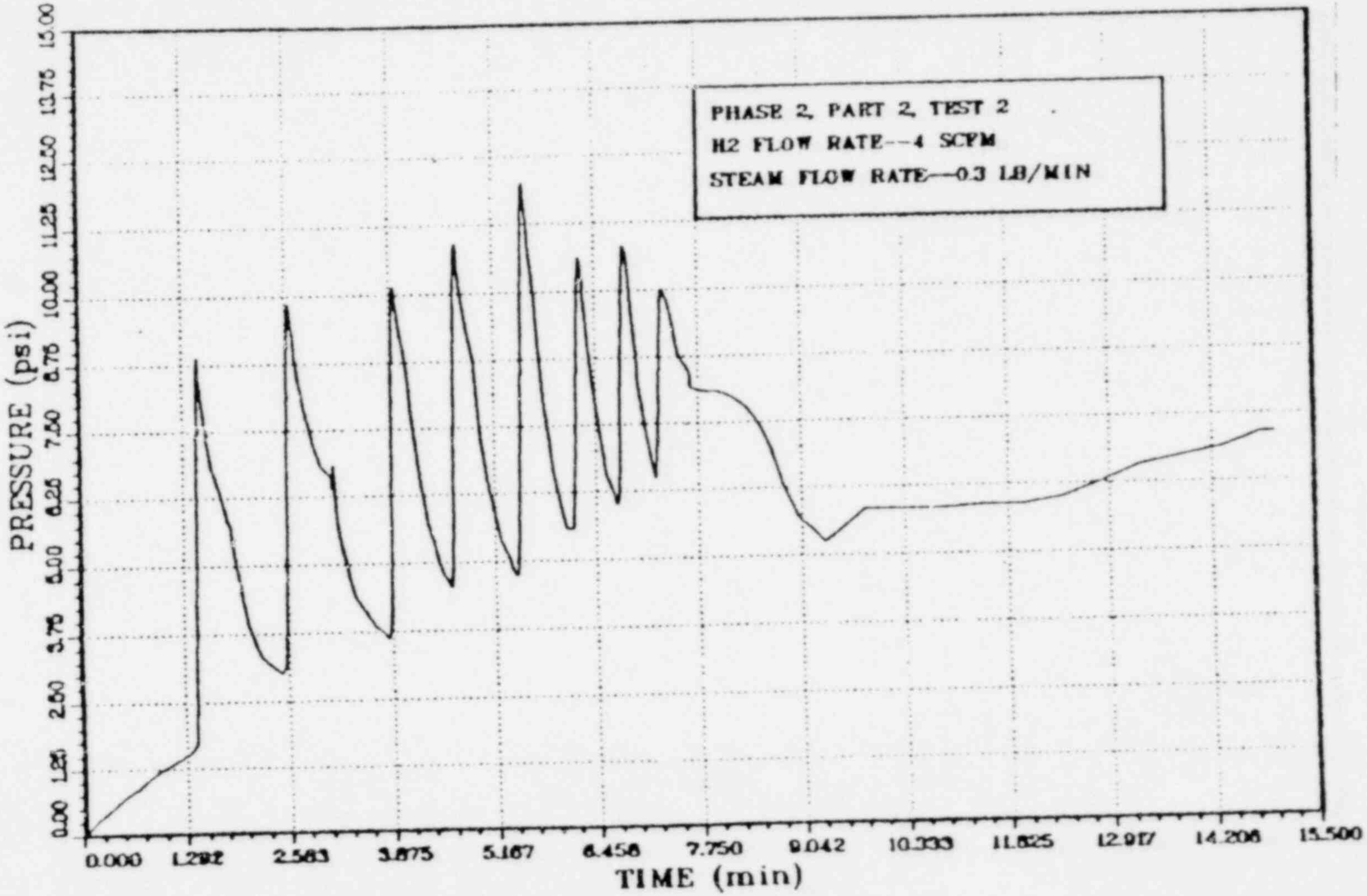

Figure 6

Figure 7

Figure No. 7
Phase No. 2
Part No. 2
Test No. 3
Initial Pressure - 14.85 psia
Initial Temperature - 160° F
Volume % H_2 _____
H_2 Flow Rate - 4 scfm
Steam Flow Rate - 0.3 lb/min
Spray Flow Rate _____
Max. Burn Pressure - 10.15 lb/in²g
Max. Air Temperature - 367° F

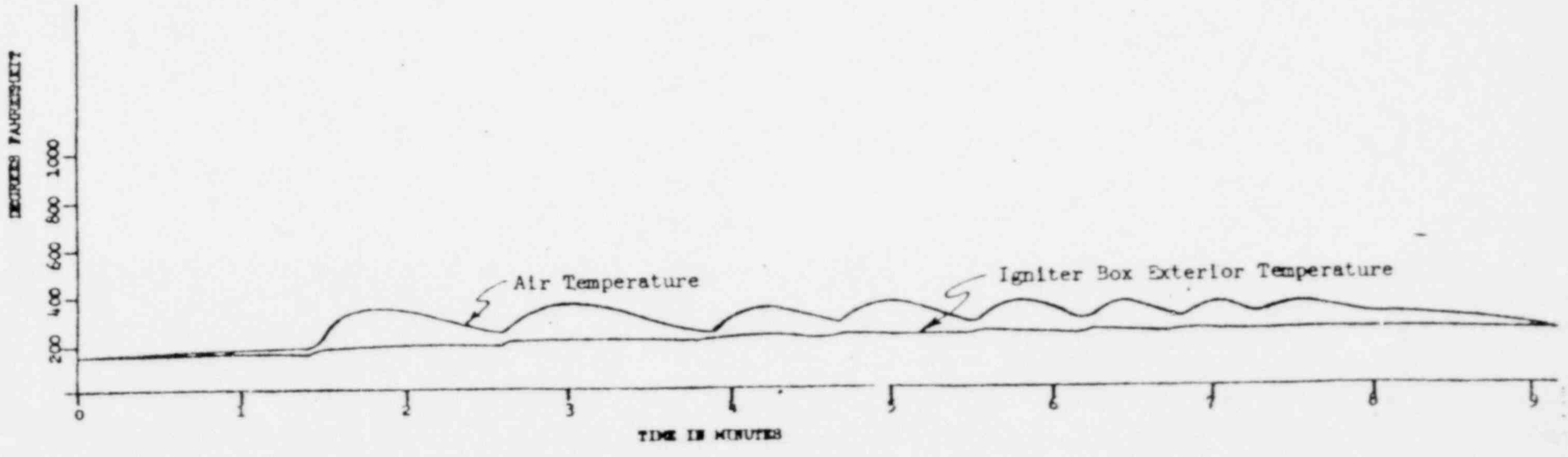

Figure No. 8
Phase No. 2
Part No. 2
Test No. 3
Initial Pressure - 14.85 psia
Initial Temperature - 160° F
Volume % H_2 ____
H_2 Flow Rate - 4 scfm
Steam Flow Rate - 0.3 lb/min
Spray Flow Rate ____
Max. Burn Pressure - 10.15 lb/in^2 g
Max. Air Temperature - 367° F

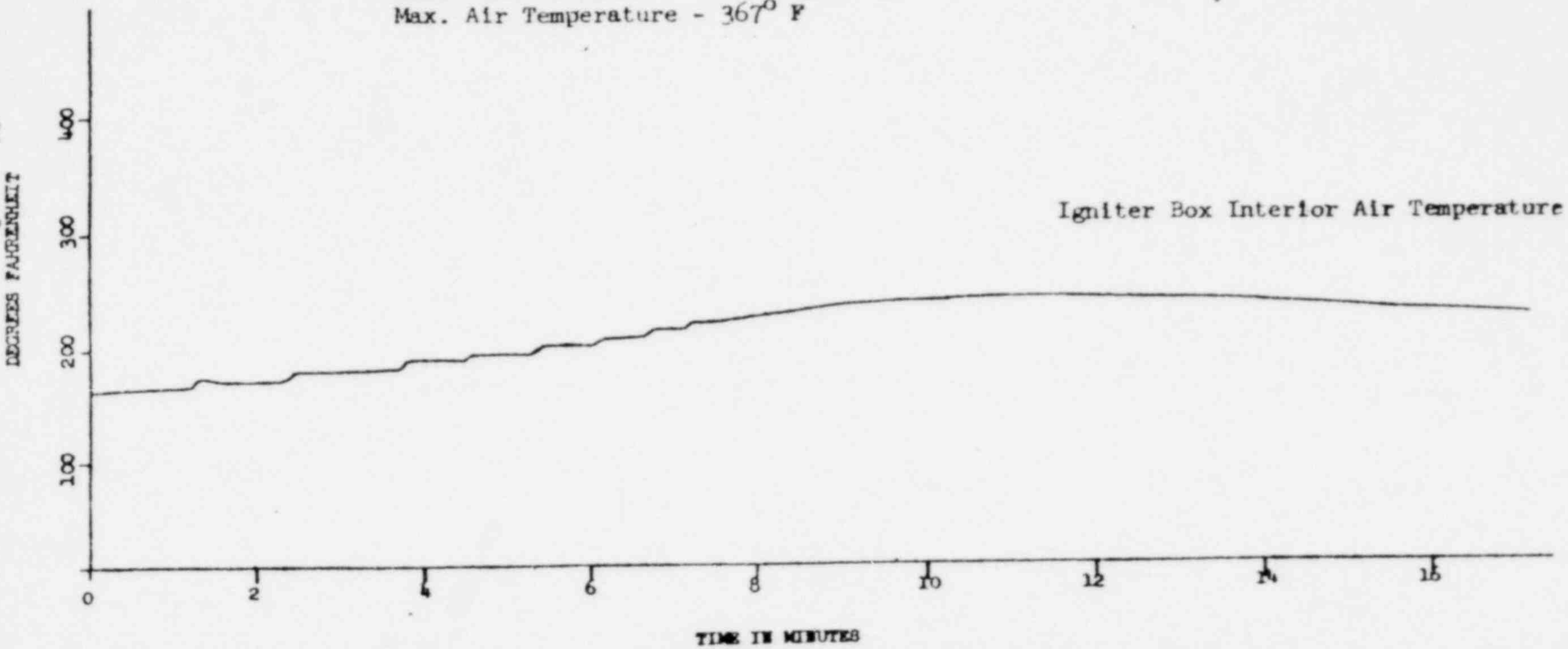

Figure 8

Figure No. 9
Phase No. 2
Part No. 3
Test No. 4
Initial Pressure - 14.60 psia
Initial Temperature - 80° F

Volume % H_2 ____
H_2 Flow Rate - 4 scfm
Steam Flow Rate ____
Spray Flow Rate - 1.9 gal/min
Max. Burn Pressure - 3.12 psid
Max. Air Temprrature - 502° F

TRANSIENT SPRAY TEST

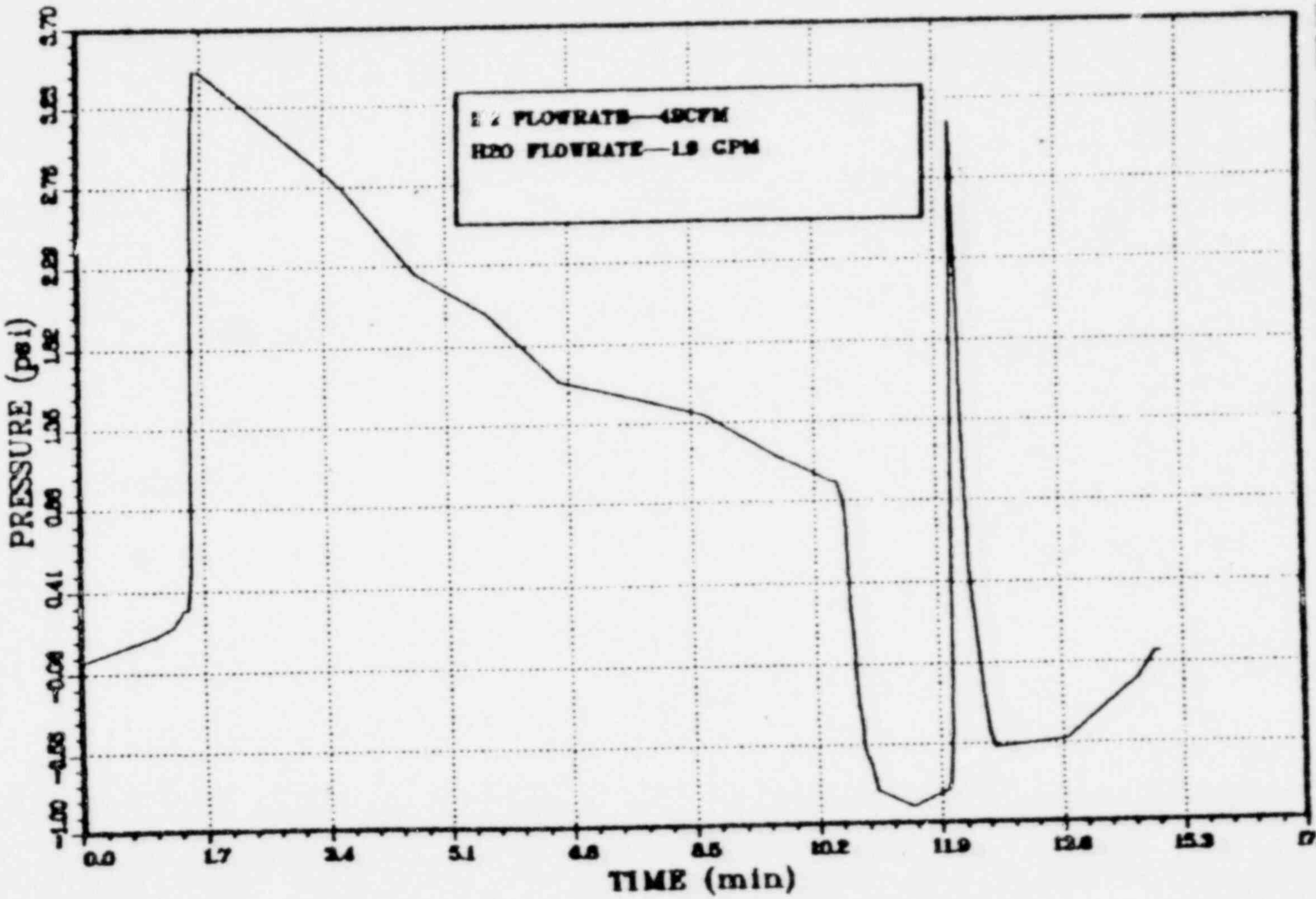

Figure 9

POOR ORIGINAL

Figure 10
Temperature vs. Time to Ignition

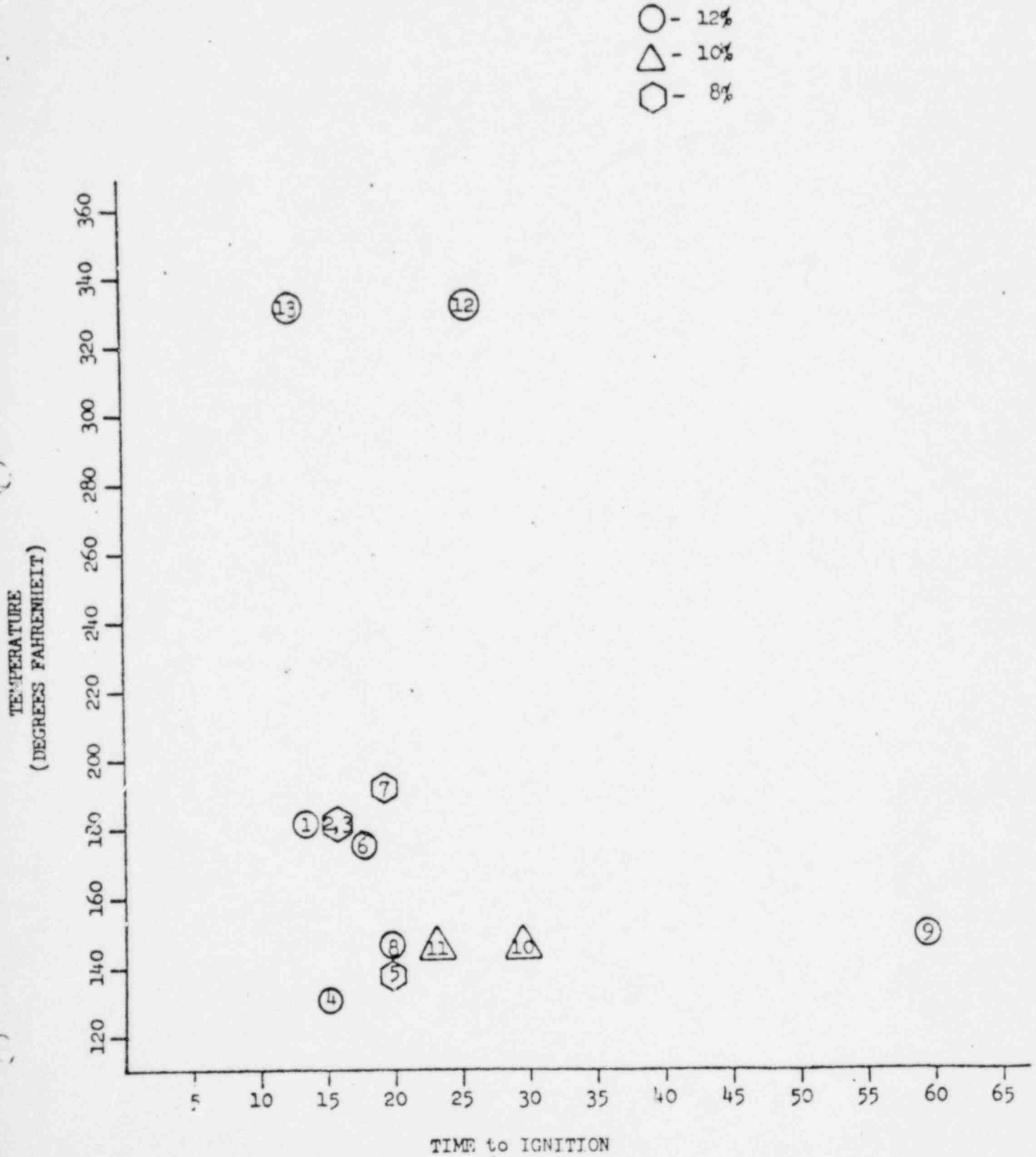

Figure 10

Figure 11
Pressure vs. Time to Ignition

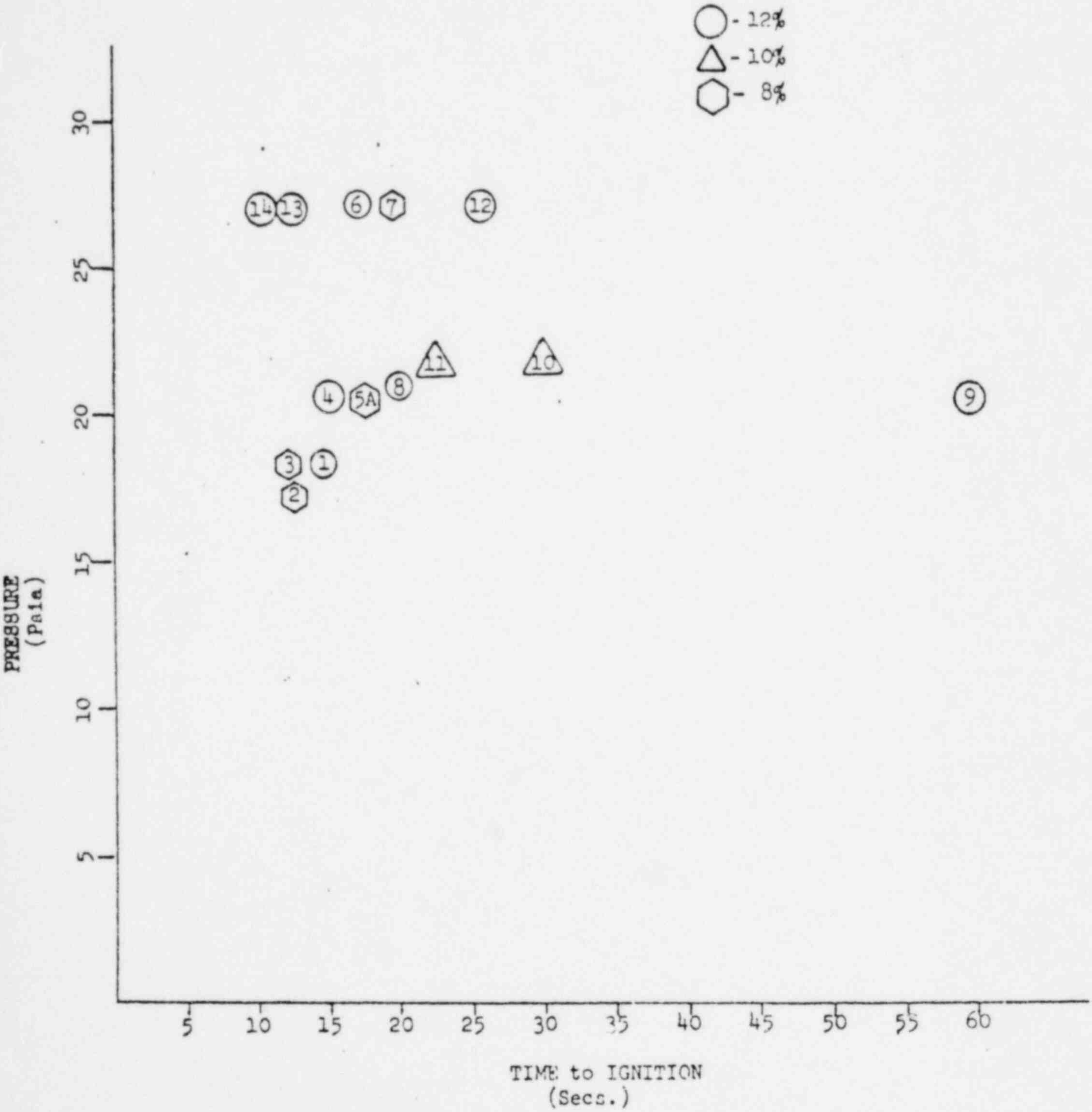

Figure 11

5.3 Fenwal Phase 1 Test Report

DETERMINATION OF IGNITION PERFORMANCE

CHARACTERISTICS OF GLOW PLUG

HYDROGEN IGNITOR

FOR

WESTINGHOUSE ELECTRIC CORPORATION

PITTSBURGH, PENNSYLVANIA

REPORT NO. PSR-914

Issued: November 10, 1980

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Division of Walter Kidde & Company, Inc.

SUMMARY

A series of tests have been conducted to ascertain the ignition capablity of a special glow plub ignitor in various mixtures of hydrogen, air and steam. Comparison of the test results, e.g. pressure and temperature transients due to combustion of hydrogen, with previously published information has shown good agreement. The performance of the glow plug ignitor in igniting hydrogen mixtures has been consistent with the literature and satisfactory in all respects.

RESULTS

Test No.	H_2 (%)	Steam Added	V (Ft/Sec)	ΔP (PSI)
1	12	No	0	53.00
2	8	No	0	33.00
3	8	No	0	3.00
4	12	Yes	0	66.00
5	8	Yes	0	22.60
6	12	Yes	0	72.00
7	8	Yes	0	16.25
8	12	Yes	5	67.50
9	12	Yes	10	65.00
10	10	Yes	10	53.70
11	10	Yes	5	52.70
12	12	Yes	10	58.75
13	12	Yes	0	60.00
14	8	Yes	0	30.00

H_2 - Hydrogen Test Concentration (%)

H_2O - Steam Added (Yes - No)

V - Air Velocity at Glow Plug (Ft/Sec)

ΔP - Maximum Pressure Increase (PSI)

Detailed Results are Shown in Table No. 1.

APPARATUS

Tests were conducted in a 1000 gallon spherical test vessel having a pressure rating of 500 psig with the capability of being heated to 350^{O}F. The vessel is constructed of carbon steel with a stainless steel liner.

The outside surface of the vessel was insulated with 3 inch thick fiberglass insulation. This insulation had an aluminum foil face which oriented away from vessel.

Mixing of the various gaseous components was accomplished by means of a small shaded pole electric motor fan. This fan had a 4 inch diameter blade with an air moving capacity of 200 CFM.

Steam was supplied to the test vessel from an electrically heated boiler which was self-regulated to maintain a pressure of 40-50 psig. A manually operated ball valve was positioned between the boiler and the test vessel.

The temperature of the test vessel was controlled by a thermocouple controller which had its sensing element in a well inside the vessel and approximately 18 inches from the vessel wall.

The temperature of the test vessel was sensed and recorded from a thermocouple which was approximately 12 inches below the geometric center of the vessel.

APPARATUS (Cont'd)

The temperature of the test vessel wall was sensed and recorded from a thermocouple which was silver soldered to the vessel inside wall at a point approximately 12 inches below the equator.

Transient pressures were monitored by means of two strain guage-type pressure transducers, the output of which are fed to a Consolidated Electrodynamics Corporation recording oscillograph. Timing markers were electronically superimposed on the oscillograph chart, providing a time base to facilitate the determination of the rate of pressure rise. One transducer was calibrated to read relatively low pressures resulting from marginal pressure transients and the other was calibrated to read higher pressures resulting from more complete combustion.

A mercury manometer was used to measure pressures during the loading of gaseous components by the partial pressure method.

Samples for gas chromatograph analysis were taken from the test vessel, through a cooling/condensing chamber into a 500 ML glass sample bulb. A vacuum pump and various valves were used so as to be able to draw the sample first into the cooling/ condensing chamber and then into the glass sample bulb.

Air flow across the glow plug (when specified) was provided by a small shaded pole motor electric fan placed on an adjustable horizontal mount.

APPARATUS (Cont'd)

Precise positioning of the fan was done each time air flow was specified by measuring the air flow at the glow plug with an Alnor Series 6000-P Velometer and moving the fan accordingly. This fan had a 4 inch diameter blade with an air moving capacity of 200 CFM.

The temperature of the outside wall of the glow plug box was sensed and recorded from a thermocouple silver soldered centrally on one of the vertical box walls.

The temperature that might be experienced by the glow plug transformer was sensed and recorded from a thermocouple which was silver soldered to a bracket which was similar to the transformer bracket and mounted inside the glow plug box in a similar location. (Used in tests No. 1 and No. 2).

The gas temperature of the interior of the glow plug box was sensed and recorded from a thermocouple suspended inside the box. (Used in tests No. 3 through No. 14).

All thermocouples were 24 gauge iron constantan welded junction with teflon insulation.

This apparatus is shown diagramatically in Figure No. 1.

PROCEDURE

Vessel temperature was stabilized at the specified test temperature.

Barometric pressure, relative humidity and ambient temperature were read and recorded.

Air, hydrogen and steam (when specified) were added according to the appropriate partial pressure.

The vessel contents were mixed for approximately five minutes.

The gas sampling apparatus was evacuated and the pre-burn gas sample was drawn into the cooling/condensing changer and held for 2-3 minutes. The gas sample was then transferred to the glass sample bulb.

The mixing fan was stopped for approximately two minutes.

The glow plug was energized.

The post-burn gas was sampled in the same manner as previously described.

The pre-burn and post-burn gas samples were analized by laboratories having gas chromotography capability. Gases from

PROCEDURE (Cont'd)

tests No. 1 through test No. 5 were analized by:

Arnold Green Testing Labs Inc.
6 Huron Drive
Natick, Massachusetts

Gases from tests No. 6 through test No. 14 were analized by:

Dynatech R/D Company
99 Erie Street
Cambridge, Massachusetts

TABLE NO. 1
TABULATED RESULTS

Test No.	H_2	Tv (°F)	V (Ft/Sec)	Baro (mmHg)	R/H (%)	T amb (°F)	P air (mmHg)	PH_2 (mmHg)	PH_2 (mmHg)	T_1 (°F)	T_2 (°F)	T_3 (°F)	T_4 (°F)	Tign. (Sec)	TF (Sec)	ΔP (psi)	Hp	Np	Op	Ha	Na	Oa	Su (Cm/Sec)
1	12	180	0	763.7	53	70	830.6	113.3	0	230	395	220	1050	14.50	0.50	53.00	14.0	70.00	18.0	0.0	82.6	17.1	65.51
2	8	180	0	763.7	46	76	830.6	72.2	0	310	330	500	710	14.00	4.00	33.00	5.80	76.0	20.0	0.0	80.7	18.8	17.33
3	8	180	0	757.3	78	61	897.5	78.1	0	245	140	205	190	14.25	4.70	3.00	7.3	74.2	10.4	4.9	76.3	19.1	26.08
4	12	129	0	763.9	82	55	833.1	128.9	101.6	280	205	178	748	15.75	0.55	66.00	8.5	71.8	18.7	0.0	83.3	15.6	64.38
5	8	138	0	763.9	68	50	846.0	85.9	141.7	129	150	150	222	18.25	18.25	22.60	6.5	74.1	19.5	1.6	80.7	17.6	-
6	12	176	0	759.4	95	67	888.7	165.4	324.2	270	250	228	1000	17.8	0.656	72.00	15.1	62.6	17.9	0.0	82.6	14.4	51.60
7	8	190	0	761.9	65	72	900.2	110.6	371.2	218	195	200	657	18.5	68.125	16.25	9.5	73.1	16.9	4.9	79.5	14.4	-
8	12	145	5	767.2	88	56	836.8	129.3	111.7	255	200	200	1000	19.06	0.375	67.50	14.7	61.1	18.9	0.0	85.4	12.6	71.43
9	12	130	10	767.2	63	75	836.8	129.3	111.7	212	195	175	1000	59.25	0.500	65.00	11.6	62.0	18.0	0.0	76.9	13.9	98.38
10	10	146	10	761.1	85	71	841.6	109.0	142.0	247	200	190	-	29.0	0.875	53.7	9.6	61.1	18.6	0.0	76.5	15.2	36.77
11	10	146	5	761.1	60	83	841.6	109.0	142.0	242	196	178	800	23.90	0.781	52.7	10.2	62.6	18.9	0.0	74.7	15.0	47.56
12	12	350	10	757.0	85	78	1135.5	165.1	75.0	478	403	395	1000	25.90	0.400	58.75	11.1	68.8	18.0	0.0	83.4	14.0	144.22
13	12	350	0	756.4	47	88	1135.5	165.1	75.0	450	402	400	495	12.06	0.406	60.00	12.0	63.9	16.7	0.0	90.6	12.5	101.65
14	8	350	0	752.5	76	78	1128.8	109.4	129.8	408	360	370	390	12.00	9.000	30.00	9.3	68.0	18.7	0.0	73.8	17.9	4.09

Legend for Table No. 1

% H_2	-	Hydrogen Test Concentration (%)
Tv	-	Vessel Test Temperature (^{o}F)
V	-	Air Velocity At Glow Pub (Ft/Sec)
Baro	-	Barometric Pressure (mmHg)
R/H	-	Relative Humidity (%)
T amb	-	Ambient Temperature (^{o}F)
P air	-	Partial Pressure (mmHg) Of Air Loaded
P H_2	-	Partial Pressure (mmHg) of Hydrogen Loaded
P H_2O	-	Partial Pressure (mmHg) of Steam Loaded
T_1	-	Glow Plug Box External Wall Maximum Temperature (^{o}F)
T_2	-	Vessel Internal Wall Maximum Temperature (^{o}F)
T_3	-	Glow Plug Box Internal Maximum Temperature (^{o}F)
T_4	-	Vessel Air Maximum Temperature (^{o}F)
Tign	-	Time From Energizing Glow Plug to Ignition (Sec)
Tp	-	Time From Ignition to Maximum Pressure (Sec)
Δ P	-	Maximum Pressure Increase (psi)
Hp	-	Pre-burn Hydrogen Concentration (%)
Np	-	Pre-burn Nitrogen Concentration (%)
Op	-	Pre-burn Oxygen Concentration (%)
Ha	-	Post-burn Hydrogen Concentration (%)
Na	-	Post-burn Nitrogen Concentration (%)
Oa	-	Post-burn Oxygen Concentration (%)
Su	-	Burning Velocity (Cm/Sec)

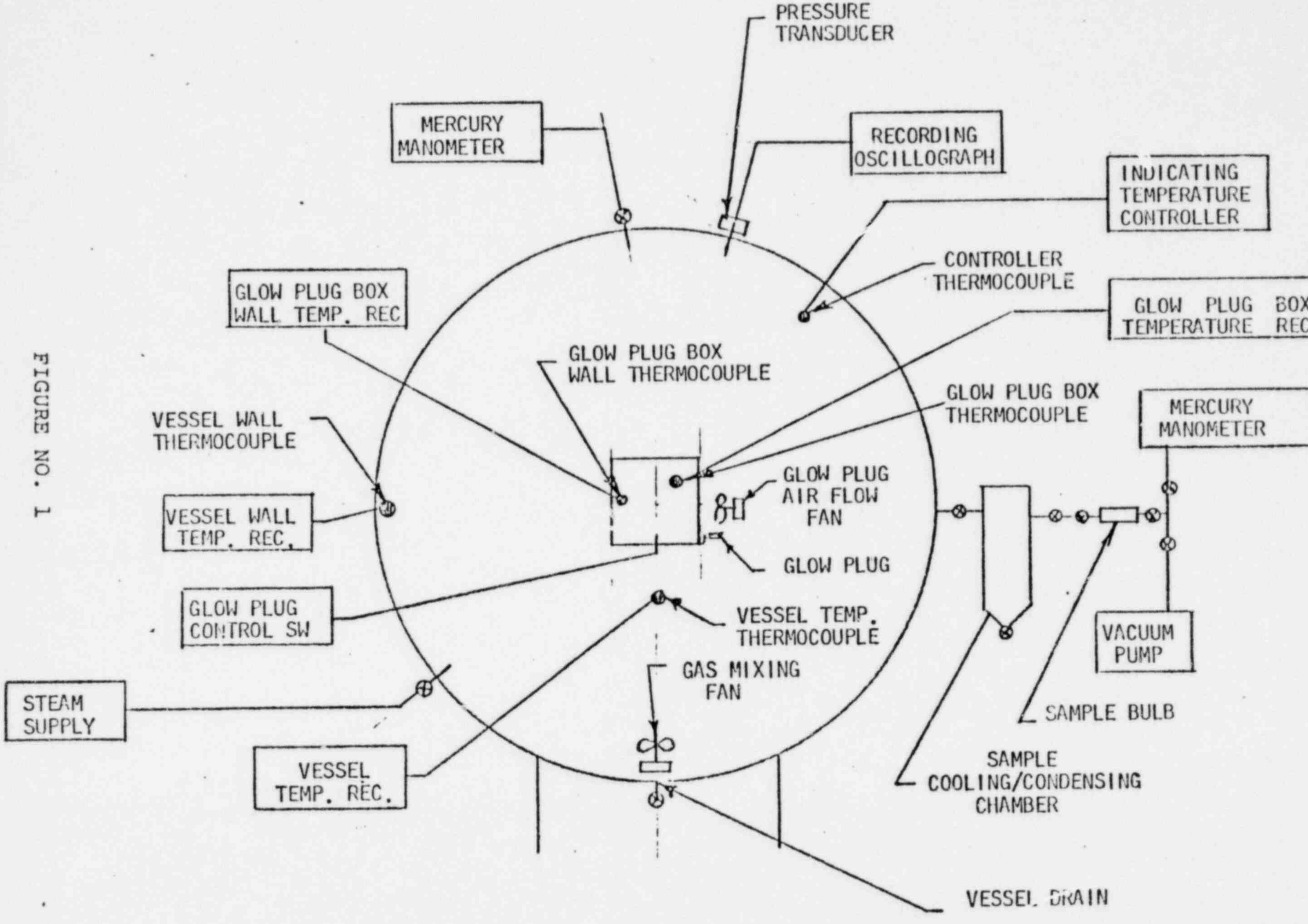
PRESSURE TRANSDUCER
MERCURY MANOMETER
RECORDING OSCILLOGRAPH
INDICATING TEMPERATURE CONTROLLER
CONTROLLER THERMOCOUPLE
GLOW PLUG BOX WALL TEMP. REC
GLOW PLUG BOX TEMPERATURE RECORDER
GLOW PLUG BOX WALL THERMOCOUPLE
GLOW PLUG BOX THERMOCOUPLE
VESSEL WALL THERMOCOUPLE
MERCURY MANOMETER
GLOW PLUG AIR FLOW FAN
VESSEL WALL TEMP. REC.
GLOW PLUG
GLOW PLUG CONTROL SW
VESSEL TEMP. THERMOCOUPLE
VACUUM PUMP
GAS MIXING FAN
STEAM SUPPLY
SAMPLE BULB
SAMPLE COOLING/CONDENSING CHAMBER
VESSEL TEMP. REC.
VESSEL DRAIN

FIGURE NO. 1

DETERMINATION OF IGNITION PERFORMANCE CHARACTERISTICS OF A GLOW PLUG HYDROGEN IGNITOR AND THE EFFECT OF EXPOSURE OF EQUIPMENT TO HYDROGEN BURNS

FOR

WESTINGHOUSE ELECTRIC CORPORATION

PITTSBURGH, PENNSYLVANIA

REPORT NO. PSR-918

Issued: December 3, 1980

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FENWAL INCORPORATED : ASHLAND, MASSACHUSETTS

Division of Walter Kidde & Company, Inc.

Report No.
PSR-918

SUMMARY

Part 1:

A series of tests was conducted to determine the burning characteristics of various mixtures of hydrogen, air and steam when ignited by a special glow plug ignitor. These tests were directed to low hydrogen mixtures, and mixtures with 40% steam.

Part 2:

A series of tests was conducted to determine the characteristics of the burning which occurs when hydrogen is introduced into a test vessel at a constant rate and when both hydrogen and steam are simultaneously introduced into the test vessel at a constant rate in the presence of an activated glow plug ignitor.

Part 3:

A series of tests was conducted to determine the effect of water spray on glow plug ignitor performance under various conditions.

Part 4:

A series of tests was conducted to determine the ability of various pieces of equipment to withstand exposure to a hydrogen burn.

RESULTS

Part 1:

Test No.	H_2 (%)	V (Ft/Sec)	ΔP (Psi)
1	9	0	38
2	8	0	3.1
3	7	0	1.5
4	6	0	1.0
5	5	0	0.2
6	8	5	36
7	6	5	15
8	10	0	30
9	6	0/5*	.75/2.7
10	6	0/5*	.2/3.2

Detailed results are shown in Table No. 1.

* In tests 9 and 10 the draft fan was energized after a period of time.

RESULTS

Part 2:

Test No.	Hydrogen Added	Steam Added	ΔP (Psi)
1	Yes	No	6.1
2*	Yes	No	7.8
3**	Yes	Yes	10.1

Test 2 was a repeat of test 1 in which a leak in the hydrogen supply line occurred.

Detailed results are shown in Table No. 2.

* During the 15 minute test period there were two burns. One peaked approximately 100 seconds after flow was initiated and the other 618 seconds later. The first peak reached a ΔP = 7.8 psi and the second a ΔP = 3.6 psi.

** During the 15 minute test period, there were 8 burns. The first peaked approximately 88 seconds after flow was initiated and the last 350 seconds later. The first peak reached a ΔP = 8.9 psi and the last a ΔP = 10.0 psi. The greatest pressure peak was 12.0 psi at the 5th peak. (333 sec.).

RESULTS

Part 3:

Test No.	H_2 (%) (Initial)	Hydrogen Flow (SCFM)	Water Flow (GPM)	Ignitor Orientation	Tign (Sec)	ΔP (Psi)
1	10	0	2	Normal	14.8	60
2	10	0	2	Normal	11.4	50
3	6	0	2	Normal	22.0	32
4	0	4	2	Normal	90.0	3.1
5	10	0	2	Rotated	14.0	42.5

Detailed results are shown in Table No. 3.

Test 2 was a repeat of test 1 in which a leak in the vessel drain valve occurred.

RESULTS

Part 4:

Test No.	H_2 (%)	Igniter Voltage	Tign (Sec)	ΔP (Psi)
1	12	12 VAC	27.1	60
2	12	12 VAC	26.8	58
3	12	12 VAC	25.8	63
4	12	12 VAC	26.3	58
5	10	12 VAC	27.6	49
6	10	10 VAC	56.0	50
7	12	12 VAC	27.2	61

Detailed results are shown in Table No. 4.

These tests included typical equipment present in a containment. In test 2 a space blanket was used as a component insulator and failed. The test was repeated in Test 7 using aluminium foil as an insulator.

APPARATUS

Tests were conducted in a 1000 gallon spherical test vessel having a pressure rating of 500 psig with the capability of being heated to 350^{o}F. The vessel is constructed of carbon steel with a stainless steel liner.

The outside surface of the vessel was insulated with 3 inch thick fiberglass insulation. This insulation had an aluminum foil face which oriented away from vessel.

Mixing of the various gaseous components was accomplished by means of a small shaded pole electric motor fan. This fan had a 4 inch diameter blade with an air moving capacity of 200 CFM.

Steam was supplied to the test vessel from an electrically heated boiler which was self-requlated to maintain a pressure of 40-50 psig. A manually operated ball valve was positioned between the boiler and the test vessel.

The temperature of the test vessel was controlled by a thermocouple controller which had its sensing element in a well inside the vessel and approximately 18 inches from the vessel wall.

The temperature of the test vessel was sensed and recorded from a thermocouple which was approximately 12 inches below the geometric center of the vessel.

Hydrogen for the transient tests was supplied from a high pressure supply cylinder, through a regulator, control valve, flowmeter, check valve and then to the bottom of the vessel through a length of 1/4 inch copper tube.

APPARATUS (Cont'd)

Steam for the transient tests was supplied from the boiler described, through a check valve then to a pipe "tee" where it was mixed with the hydrogen flow. The mixture of hydrogen and steam was directed to the bottom of the vessel through a length of 1/4 inch copper tube inside the vessel. A calibration test of this steam supply indicated the rate to be approximately 0.3 pounds per minute.

Water for the spray tests was supplied from a positive displacement pump which produced the required volume of water through the nozzle.

A sketch of the test apparatus is shown in Figure No. 1.

PROCEDURE

Part 1:

Vessel temperature was stabilized at the specified test temperature.

Barometric pressure, relative humidity and ambient temperature were read and recorded.

Air, hydrogen and steam (when specified) were added according to the appropriate partial pressure.

The gas sampling apparatus was evacuated and the pre-burn gas sample was drawn into the cooling/condensing changer and held for 2-3 minutes. The gas sample was then transferred to the glass sample bulb which also had been evacuated.

The mixing fan was stopped for approximately two minutes.

The glow plug was energized.

The post-burn gas was sampled in the same manner as previously described.

The pre-burn and post-burn gas samples were analized by:

Dynatech R/D Company
99 Erie Street
Cambridge, Massachusetts

PROCEDURE

Part 2:

Vessel temperature was stabilized at the specified test temperature.

Barometric pressure, relative humidity and ambient temperature were read and recorded.

The glow plug was energized and allowed to come to a stable temperature.

Hydrogen or steam and hydrogen flow was initiated at the specified flow rate and continued for 15 minutes.

The gas sampling apparatus was evacuated and the gas sample was drawn into the cooling/condensing changer and held for 2-3 minutes. The gas sample was then transferred to the glass sample bulb which also had been evacuated.

The gas sample was analized by:

Dynatech R/D Company
99 Erie Street
Cambridge, Massachusetts

PROCEDURE

Part 3:

Vessel temperature was stabilized at the specified test temperature.

Barometric pressure, relative humidity and ambient temperature were read and recorded.

Hydrogen, when specified, was added according to the appropriate partial pressure. The vessel contents were mixed for approximately five minutes.

The gas sampling apparatus was evacuated and the pre-burn gas sample was drawn into the cooling/condensing changer and held for 2-3 minutes. The gas sample was then transferred to the glass sample bulb.

The mixing fan was stopped for approximately two minutes.

Spray water flow, as specified, was initiated.

Hydrogen flow, when specified, was initiated and continued for 15 minutes.

The glow plug was energized.

The post-burn gas was sampled in the same manner as previously described.

The pre-burn and post-burn gas samples were analized by:

Dynatech R/D Company
99 Erie Street
Cambridge, Massachusetts

PROCEDURE

Part 4:

The "Duke" ignitor box was substituted for the "TVA" ignitor box.

The appropriate pieces of equipment to be exposed to the hydrogen burn (see listing) were placed in the vessel and instrumented w.th thermocouples as directed.

Vessel temperature was stabilized at the specified test temperature.

Barometric pressure, relative humidity and ambient temperature were read and recorded.

Air, hydrogen and steam (when specified) were added according to the appropriate partial pressure.

The vessel contents were mixed for approximately five minutes.

The gas sampling apparatus was evacuated and the pre-burn gas sample was drawn into the cooling/condensing changer and held for 2-3 minutes. The gas sample was then transferred to the glass sample bulb.

The mixing fan was stopped for approximately two minutes.

The glow plug was energized.

The post-burn gas was sampled in the same manner as previously described.

The pre-burn and post-burn gas samples were analized by:

Dynatech R/D Company
99 Erie Street
Cambridge, Massachusetts .

LISTING OF EXPOSED MATERIALS

Description	Exposure Test No.
Barton Transmitter	2-4-1
	2-4-2
	2-4-3
	2-4-4
	2-4-7
ASCO Valve	2-4-3
	2-4-4
	2-4-7
Namco Switch	2-4-3
	2-4-4
	2-4-7
Sample Blocks - All	2-4-1
Sample Slabs - All	2-4-2
Fisher Regulator	2-4-7

LISTING OF EXPOSED MATERIALS (Cont'd)

Wire Description	Exposure Test No.
WVA 2/C #16 87232 XPS	2-4-2
Type SIS WJH	2-4-2
WVC	2-4-2
WRO SROJJ	2-4-2
WVA-1 2/C #18 87232 XPS	2-4-3
WPA - SROAJ	2-4-2
WPD - SROAJ	2-4-2
WPF - 1/C #6 SROAJ	2-4-3
WUB-1 Type TX	2-4-2
WNB - 8KV	2-4-1
Duke - BX	2-4-1
Type CPJ - WDB	2-4-3
RTD	2-4-2

TABLE NO. 1
SERIES 2 - PART 1

Test No.		2-1-1	2-1-2	2-1-3	2-1-4	2-1-5	2-1-6	2-1-7	2-1-8	2-1-9	2-1-10
Date		10/10	10/14	10/14	10/15	10/15	10/15	10/16	10/17	10/17	10/27
% H_2		9	8	7	6	5	8	6	10	6	6
TV	^oF	136	138	140	142	144	138	142	212	212	212
V	ft/sec	0	0	0	0	0	5	5	0	0/5	0/5
Baro	mmHg	765.3	761.4	761.4	767.7	767.7	767.7	768	767	767	762
R.H.	%	36	76	35	80	43	34	60	74	55	52
Tamb	^oF	56	41	55	44	51	49	67	65	65	50
Air	mmHg	839	843	846	856	858	850	856	535	578	578
H_2	mmHg	96	86	75	65	54	86	65	107	64	64
H_2O	mmHg	134	142	147	157	165	142	157	428	428	428
T_1	^oF	210	141	140	142	144	230	190	280	210/225	212/225
T_2	^oF	175	130	135	142	144	183	152	242	200/220	210/247
T_3	^oF	142	140	140	142	144	N.O.	N.O.	240	N.O.	227/289
T_4	^oF	960	165	N.O.	142	144	685	335	700	245	205/208
Tign	sec	15.8	15.9	15.4	17	17	15	17	17	17/1.0*	19/6.1*
Tp	sec	6.6	5.4	5.3	11	3	4	9	9.6	13/10	1.9/4.8
$\triangle$ P	psig	38	3.1	1.5	1.0	0.2	36	15	30	.75/2.7	0.2/3.2
H_2(P)	%	9.2	8.8	9.0	8.0	6.4	9.6	6.8	17.9	11.5	6.1
N_2(P)	%	69.6	69.9	69.3	68.6	74.5	72.2	72.9	66.4	71.7	73.7
O_2(P)	%	21.9	21.9	21.8	21.8	22.6	21.6	19.0	16.9	17.9	19.3
H_2(A)	%	0	3.3	4.5	6.2	5.1	0	3.6	0	9.2	6.1
N_2(A)	%	78.5	75.8	74.7	71.9	75.0	82.9	75.[illegible]	85.4	74.3	73.9
O_2(A)	%	18.9	20.3	20.6	21.8	22.5	19.6	18.0	12.6	17.8	18.3

N.O. - Not Obtained

* - Timed From Fan Start

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TABLE NO. 2
SERIES 2 - PART 2

Test No.		2-2-1	2-2-2	2-2-3
Date		10/28	10/29	10/30
TV	^{o}F	80	80	160
Baro	mmHg	759	762	769
R.H.	%	95	65	57
Tamb	^{o}F	34	34	37
H_2 *	SCFM	4	4	4
H_2O **	lb/min	0	0	$\approx$ .3
T_1	^{o}F	215	226	265
T_2	^{o}F	120	130	190
T_3	^{o}F	193	198	240
T_4	^{o}F	318	330	370
Tign***	sec	65	100	84
Tp	sec	12	12	4
ΔP_{max}	psig	6.1	7.8	10.1
H_2(A)	%	--	23.6	23.9
N_2(A)	%	--	72.2	71.0
O_2(A)	%	--	4.8	7.3

* Hydrogen Flow Rate
** Steam Flow Rate
*** Approximate Time From Hydrogen Flow Start To First Ignition

Fenwal
FENWAL INCORPORATED : ASHLAND, MASSACHUSETTS
Division of Walter Kidde & Company, Inc.

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TABLE NO. 3
SERIES 2 PART 3

Test No.		2-3-1	2-[illegible]	2-3-3	2-3-4	2-3-5
Date		10/23	10/31	10/31	10/31	11/3
% H_2		10%	10%	6%	N.A	10%
TV	(^{o}F)	39	80	80	80	80
Baro	(mmHg)	772	760	756	756	771
R.H.	(%)	45	50	34	50	50
Tamb	(^{o}F)	39	47	48	50	40
H_2	(mmHg)	86	84	48	0	86
H_2 *	(SCFM)	0	0	0	4	0
H_2O**	(gal/min)	2	2	2	2	2
T_1	^{o}F	125	$\approx$135	80	135	120
T_2	^{o}F	110	130	120	100	120
T_3	^{o}F	40	N.G.	133	155	145
T_4	^{o}F	665	$\approx$650	407	505	360
Tign	sec	14.8	11.4	22.0	90	14.9
Tp	sec	.50	.65	1.50	6.0	1.1
$\triangle$ P	psig	60	50	32	3.1	42.5
Ignitor Orientation		Normal	Normal	Normal	Normal	Rotated
H_2(P)	%	N.O.	6.7	N.O.	N.O.	7.8
N_2(P)	%	N.O.	73.1	N.O.	N.O.	73.5
O_2(P)	%	N.O.	19.4	N.O.	N.O.	19.3
H_2(A)	%	N.O.	.8	N.O.	N.O.	0
N_2(A)	%	N.O.	79.4	N.O.	N.O.	82.5
O_2(A)	%	N.O.	16.6	N.O.	N.O.	17.5

* Hydrogen Flow Rate

** Water Spray Flow Rate

N.O. Not Obtained

FENWAL INCORPORATED : ASHLAND, MASSACHUSETTS

Division of Walter Kidde & Company, Inc.

TABLE NO. 4

SERIES 2 - PART 4

Date		11/12	11/13	11/14	11/17	11/16	11/07	11/18
Test No.		2-4-1	2-4-2	2-4-3	2-4-4	2-4-5	2-4-6	2-4-7
% H_2		12%	12%	12%	12%	10%	10%	12%
TV	^oF	129^o	129^o	129^o	129^o	146^o	146^o	129^o
Baro	mmHg	756.6	762.3	755.0	771.0	760.0	754.1	751.6
R.H.	%	55%	42%	30%	57%	60%	55%	93%
Tamb	^oF	40^o	37^o	55^o	29^o	39^o	65^o	26^o
Air	mmHg	830.3	830.3	830.3	830.3	841.6	841.6	830.3
Hg	mmHg	124.1	124.1	124.1	124.1	109.0	109.0	124.1
M_2O	mmHg	111.7	111.7	111.7	111.7	147.0	142.0	111.7
T_1	^oF	--	--	--	--	380	510	--
T_2	^oF	255	395	365	395	432	510	357
T_3	^oF	--	---	--	--	202	195	--
T_4	^oF	710	760	760	755	790	760	735
T_5	^oF	140	140	--	--	--	--	130
T_6	^oF	150	155	--	--	--	--	140
T_7	^oF	135	140	--	--	--	--	133
T_8	^oF	230	250	--	--	--	--	143
T_9	^oF	--	--	240	250	--	--	--
T_{10}	^oF	--	--	170	138	--	--	--
T_{11}	^oF	--	--	240	250	--	--	--
T_{12}	^oF	--	--	228	183	--	--	--

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TABLE NO. 4 (Cont'd)
SERIES 2 - PART 4 (Cont'd)

Date		11/12	11/13	11/14	11/17	11/16	11/07	11/18
Test No.		2-4-1	2-4-2	2-4-3	2-4-4	2-4-5	2-4-6	2-4-7
Volts		12	12	12	12	12	10	12
INS		None	Space Wrap	None	.0010 Aluminium	None	None	.0010 Aluminium
Tign	Sec	27.1	26.8	25.8	26.3	27.6	56.0	27.2
Tp	sec	.64	.70	.55	.65	1.750	1.500	.60
△ P	psig	60 psig	58 psig	63 psig	58 psig	49 psig	50 psig	61 psig
H_2(P)	%	13.1	12.8	14.1	13.6	9.3	9.8	10.6
N_2(P)	%	68.8	69.4	68.1	69.0	74.4	70.9	73.3
O_2(P)	%	18.0	18.0	17.7	18.2	18.7	18.4	18.8
H_2(A)	%	0	0	C	0	0	0	0
N_2(A)	%	83.7	83.7	83.1	84.9	82.9	81.0	83.7
O_2(A)	%	15.0	14.5	14.8	15.6	15.8	15.4	14.9

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Legend For Table No. 1, No. 2, No. 3 and No. 4

% H_2	-	Hydrogen Test Concentration (%)
TV	-	Vessel Test Temperature (^oF)
V	-	Air Velocity At Glow Plug (ft/sec)
Baro	-	Barometric Pressure (mmHg)
R. H.	-	Relative Humidity (%)
T amb	-	Ambient Temperature (^oF)
P air	-	Partial Pressure (mmHg) Of Air Loaded
P H_2	-	Partial Pressure (mmHg) Of Hydrogen Loaded
P H_2O	-	Partial Pressure (mmHg) Of Steam Loaded
T_1	-	Glow Plug Box External Wall Maxiumu Temperature (^oF)
T_2	-	Vessel Internal Wall Maximum Temperature (^oF)
T_3	-	Glow Plug Box Internal Gas Maximum Temperature (^oF)
T_4	-	Vessel Air Maximum Temperature (^oF)
T_5	-	Barton Transmitter # 2 (^oF)
T_6	-	Barton Transmitter # 4 (^oF)
T_7	-	Barton Transmitter # 5 (^oF)
T_8	-	Barton Transmitter - Outside Surface Maximum Temperature (^oF)
T_9	-	Limit Switch - Outside Surface Maximum Temperature (^oF)
T_{10}	-	Limit Switch - Internal Maximum Temperature (^oF)
T_{11}	-	Solenoid Valve - Outside Surface Maximum Temperature (^oF)
T_{12}	-	Solenoid Valve - Internal Maximum Temperature (^oF)
Volts	-	Voltage At Glow Plug (VAC)
INS	-	Insulating Wrap Type

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Legend (Cont'd)

Tign	-	Time From Energizing Glow Plug To Ignition (sec)
Tp	-	Time From Ignition To Maximum Pressure (sec)
Δ P	-	Maximum Explosion Pressure Increase (psi)
Hp	-	Pre-burn Hydrogen Concentration (%)
Np	-	Pre-burn Nitrogen Concentration (%)
Op	-	Pre-burn Oxygen Concentration (%)
Ha	-	Post-burn Hydrogen Concentration (%)
Na	-	Post-burn Nitrogen Concentration (%)
Oa	-	Post-burn Oxygen Concentration (%)

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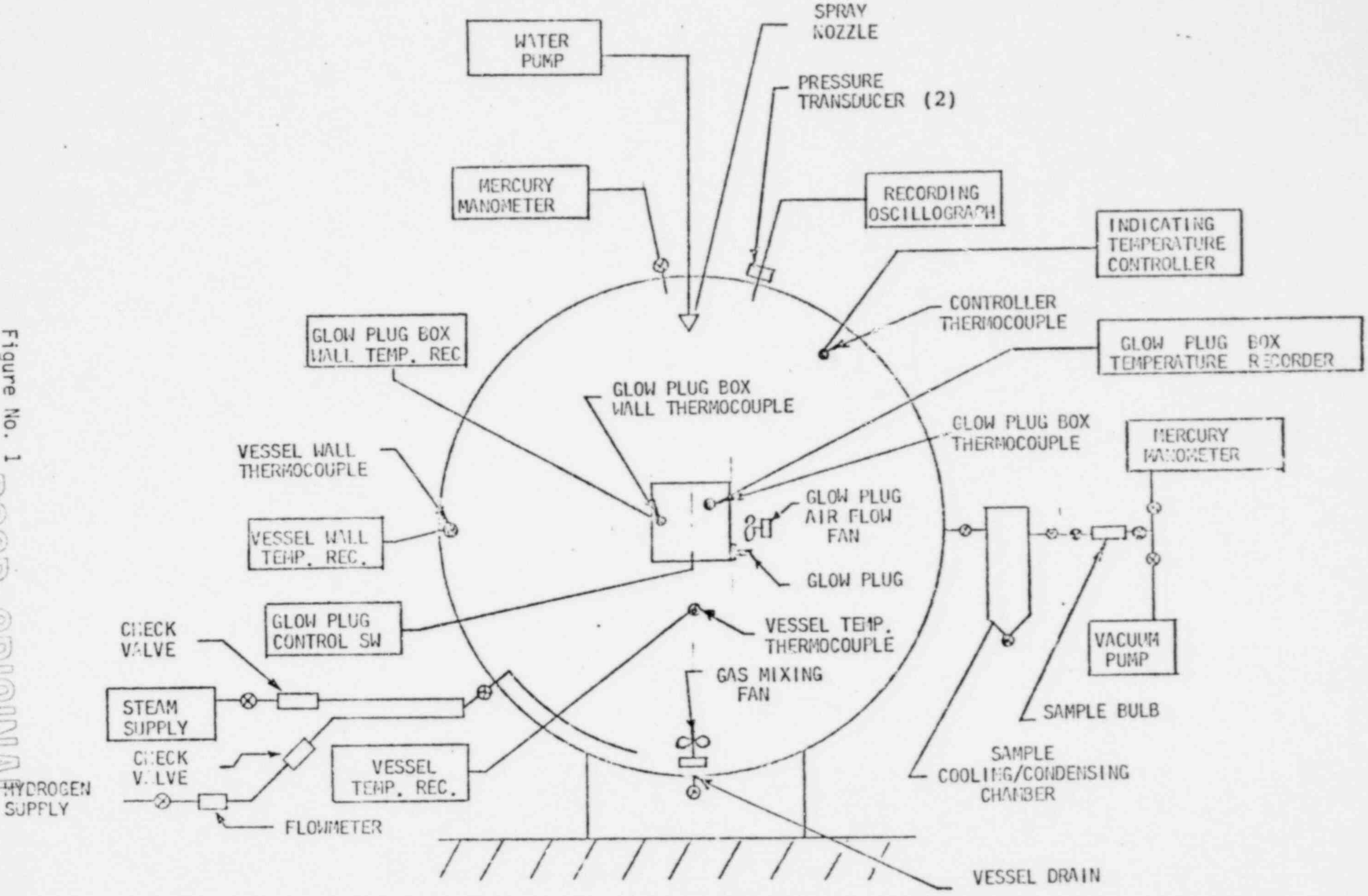

Figure No. 1