SEQUOYAH NUCLEAR PLANT

UNIT 1

An Evaluation of the Phase 1 and 2

Tests Performed with the IDIS

Igniter at Fenwal, Incorporated, Laboratories

November 26, 1980

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AEP - American Electric Power

Duke - Duke Power Company

fps - feet per second

gpm - gallons per minute

IDIS - Interim Distributed Ignition System

psi - pounds per square inch

psia - pounds per square inch absolute

psid - pounds per square inch differential

psig - pounds per square inch gauge

scfm - standard cubic feet per minute

SQN - Sequoyah Nuclear Plant

TMI - Three Mile Island Nuclear Plant

TVA - Tennessee Valley Authority

v/o - volume percent

Abstract

TVA, Duke, and American Electric Power in cooperation with Westinghouse devised a two-phase testing program that, in general, was designed to determine the relative effectiveness of a hydrogen ignition system.

This report is an evaluation of the test results generated by those tests at Fenwal, Incorporated, laboratories in Ashland, Massachusetts. It contains a detailed description of the two phases of testing, a discussion of the effects of steam, spray, and fan flow on the ability to burn hydrogen, a comparison of the measured test results with the theory of hydrogen burning, an evaluation of the igniter effectiveness, and an evaluation of hydrogen burning on equipment.

This report does not claim that the test conditions directly model or represent the worst environmental conditions that might exist inside Sequoyah containment after an accident. However, based on the results of these tests and the information gained, it is our general conclusion that this system will contribute to the reduction in risk of a TMI-type event.

1.0 Introduction

TVA designed and installed at Sequoyah Nuclear Plant unit 1 an Interim Distributed Ignition System (IDIS) to protect the primary containment from deflagration of large volumetric quantities of hydrogen which would be generated in a severe degraded core event. This system is a temporary modification and is intended to provide an additional margin of safety until a permanent hydrogen control system can be designed.

TVA in cooperation with Duke Power, American Electric Power (AEP), and Westinghouse devised a two-phase testing program that, in general, was designed to determine the relative effectiveness and worth of the IDIS igniter. This report is an evaluation of the test results generated in that testing program.

The test conditions which were chosen for these tests do not directly model the worst environmental conditions which might exist inside Sequoyah containment after an accident. The test conditions were instead selected to present significant environmental challenges to the effectiveness of the igniter by which it could be evaluated.

1.1 Purpose

The testing program was divided into two phases. The first phase was designed to test the igniter's capability in various mixtures of hydrogen, air, and steam. The second phase was designed to provide further empirical data and to test the igniter under dynamic conditions of continuous injection of hydrogen and steam.

1.1.1 Phase 1

The purpose of the phase 1 testing was to determine if the igniter would burn hydrogen at volumetric hydrogen concentrations of 8, 10, and 12 v/o for various environmental conditions of pressure, temperature, air flow across the igniter, and humidity. The phase 1 tests were also to determine the durability of the commercially available igniter we had selected.

1.1.2 Phase 2

The purpose of the phase 2 tests was to:

a. Establish the lowest hydrogen concentration at which the igniter would initiate burning

b. Determine the igniter's ability to function in a spray environment

c. Measure the gross effects of a hydrogen burn on a representative sample of equipment

d. Confirm multiple burns due to continuous addition of hydrogen

e. Provide more empirical data for support of igniter licensing

1.2 Conclusions/Recommendations

The test results obtained from the phase 1 and 2 tests indicate the following:

a. Initial pressure in the 6 to 12 psig range had no effect on the ability of the igniter to initiate a volumetric hydrogen burn in the 8 to 12 percent range.

b. High initial temperatures, in the $350^{\circ}F$ range, may help the igniter initiate burning but the effect is very small and of no real consequence.

c. 100 percent humidity or steam concentrations up to and including 40 percent steam do not hinder the ability of the igniter to initiate hydrogen burning. High steam concentrations (40%) however, do suppress the peak pressure generated by a hydrogen burn to some extent.

d. Air flow (5 to 10 feet per second) across the igniter did not hinder the ability of the igniter to initiate hydrogen burning. In the higher hydrogen concentration tests (10 to 12 v/o) the air flow induced by the fan had little or no effect. However, at low concentrations (6 percent through 8 v/o) the fan flow actually increased the ability of the igniter to burn greater percentages of the available hydrogen.

e. Likewise with the spray tests, the water spray did not affect the ability of the igniter to successfully burn hydrogen (even direct spraying of the igniter). However, at low hydrogen concentrations the sprays, by agitating the mixture, promoted much more complete hydrogen combustion.

f. The tests involving continuous injection of hydrogen showed that hydrogen would begin burning at low concentrations and that continuous injection of hydrogen and steam produced multiple burns very similar to results predicted by the Westinghouse CLASIX code, and

g. The hydrogen burn environment while it does produce extreme temperatures, is of such a short duration that the effect on equipment is not any more severe than the accident conditions for which the equipment is presently qualified.

Based on the positive results obtained in these tests TVA can claim with greater assurance that the IDIS can, in fact, operate reliably in even the most extreme conditions, burn hydrogen at low concentrations, limit the peak pressure to within allowable structural capabilities and in general reduce the overall risk of an accident similar to that which occurred at Three Mile Island.

2.0 Description of Tests

Westinghouse, under authorization from TVA, Duke, and AEP, subcontracted Fenwal, Incorporated, of Ashland, Massachusetts, to perform the phase 1 and 2 testing program. Fenwal has submitted to Westinghouse their report for the phase 1 testing and it is included in this report as attachment 1. Fenwal is currently preparing the phase 2 report but it is not expected to be ready in time for the submittal of this evaluation report. When this report becomes available it will be included as attachment 2. The following is an individual description of the phase 1 and 2 tests and a discussion of the procedures, parameters, and results.

2.1 Description of Test Equipment

A detailed description of the test equipment is contained in attachment 1, Fenwal test report No. PSR-914 (page 3). During the phase 1 tests the test configuration was altered slightly after the second test. In tests No. 1 and 2 the temperature recorded at T_3 (see Attachment 1, page 8) 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 in a similar location. It was decided to replace this thermocouple with another which would sense the temperature of the air inside the igniter box. This was done beginning with 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, parts 1, 2, and 3, was identical to that used in the phase 1 tests, 3 through 14, described above. The part 1, phase 2, tests were performed to determine the igniter combustible limit in the lower hydrogen concentration range.

The part 2, phase 2, tests were performed to determine the igniter performance under a continuous injection of hydrogen with the igniter preenergized. To accomplish this the test configuration was modified in the following fashion. A ball check valve was added to the injection line identified in attachment 1, page 10, as the "steam supply" 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 second (part 2) test was similar to the first (part 2) test with the only difference being that the hydrogen supply bottle and the steam came together in a "tee connection" which was then attached to the check valve.

The part 3, phase 2, tests involved determining the effect of a water spray on igniter performance in a 10 volume percent hydrogen mix, 6 volume percent hydrogen mix, and a continuous injection of hydrogen. In addition a 10 percent hydrogen test was run where the igniter was directly sprayed with water. 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 for the two 10-percent mixture tests and the one 6-percent test was identical to that used in phase 2, part 1. The test equipment for the continuous injection test was identical to the phase 2, part 2, test described above.

The part 4, phase 2, tests were conducted to determine the effect of a single hydrogen burn on typical equipment and to determine their temperature response. These tests were conducted with the same test equipment configuration as was used in part 1 of this phase of testing with one exception. During the two tests where, one, the Barton transmitter casing, and two, the Asco solenoid valve and Namco limit switch, were tested, four additional temperatures were measured. In the test with the Barton transmitter casing, three thermocouples were located inside and one outside of the casing. In the other exception, one thermocouple each was located inside and outside of both the limit switch and the solenoid valve.

2.2 Description of Test Procedures

A detailed description of the test procedure used in the phase 1 testing is contained in Attachment 1, page 6. This same procedure was used for the phase 2, part 1, tests and the non-transient test of parts 3 and 4.

Transient test procedure is as follows:

Vessel temperature was stabilized at the specified pre-test temperature and pressure.

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

The glow plug was energized.

Hydrogen, steam (when specified) and spray (when specified), were added according to the appropriate flow rate.

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

The pre-burn and post-burn gas samples were analyzed using gas chromatography by:

Dynatech R/C Company
99 Erie Street
Cambridge, Massachusetts

2.3 Description of the Individual Tests

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 attachment 1, page 8, and Table 1. 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 $180^{o}F$. 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.

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 No. 9 above.

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

Test No. 12 - This was a 12 v/o hydrogen test which was conducted at an elevated temperature of $350^{\circ}F$ 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 above. This indicates that the higher temperature did not effect the completeness of the burn. As seen in Table 1 the time to ignition for this test and tests 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 above, except that there was no air flow across the igniter. This test produced peak pressures which were less than both tests 4 and 6 which were similar and the f ~~as~~ started repeatedly but failed to initiate a burn. ..is also served to alert us to 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 No. 4 described above except with 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 above 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 No. 8 above 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 tne fan relative to the igniter was not changed from the previous test a hydrogen burns. The burn began approximatel, 18 seconds after the igniter was energized. The pressure in the vessel rose approximately 3.5 psid and then began a smooth climb to 22.6 psid. We could find no external cause for the r ond 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 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 cooldown 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). At Singleton Laboratories we confirmed that the igniter temperature 30 seconds after being deenergized was still above 1200°F temperature range and therefore we felt that the igniter rather than the fan initiated the second burn. During phase 2 tests this was confirmed when a 10 v/o hydrogen mix was prepared

Test No. 2 - This was a 8 v/o hydrogen test which was also 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 compared. However, this test produced a differential peak pressure of 33 psid which was not expected prior to the test. In retrospect this was our first confirmation that an 8 v/o hydrogen mixture was indeed a border concentration where hydrogen can begin to burn much more completely.

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

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 psid.

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 concentrations beginning at 9 v/o and ending with 5 percent. The test procedure used in these tests were identical to that used in Phase 1. As seen in Table 2 the peak differential pressure decreases significantly around 8 v/o down to a low figure of .25 psid for the 5 v/o test. This corresponds directly with the Bureau of Mines curve included in this report as Figure 3. The results obtained in these tests confirm that the igniter can ignite hydrogen at low concentrations just as effectively as the spark or squib igniter used in the GE report NEDO-10812 "Hydrogen Flammability and Burning Characteristics in BWR Containments."

Tests No. 6 and 7 - These tests were run in a similar fashion to tests No. 1 through 5 above with the exception that both tests also included fan induced flow speeds across the igniter of 5 fps. In the 8 /o tests the maximum differential pressure was approximately 11 times greater than the corresponding static test, No. 2. As seen in Table 2 the effect of the fan was even more significant in the 6 v/o test where the maximum differential pressure generated

12 v/o tests but whose initial test temperatures were 212^{o}F and 160^{o}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 but much more complete than the other 8 v/o tests (tests No. 3, 5, and 7) conducted in phase 1.

2.3.2 Phase 2 Testing

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. Tests No. 6 and 7 were designed to determine whether a hydrogen burn is enhanced or hindered by mixture flow past the igniter. Finally, tests 8 and 9 were designed to determine whether high steam concentration (40 percent) affects flammability in a 10 v/o hydrogen atmosphere.

Tests No. 1 through 5 - All five of these tests were conducted in an identical fashion except with decreasing hydrogen by the burn was 14 times greater than the similar test, No. 4, conducted without the fan.

Tests No. 8 and 9 - These tests were run to determine whether high steam concentrations (40 percent steam) would effect flammability in a 10 and 6 v/o hydrogen mixture. In both tests the peak differential pressures were less than those measured in the equivalent static tests performed in Part 4 and No. 4 in this part of the Phase 2 tests. This indicates that the higher steam concentrations act a pressure suppressant. It is interesting to note that the time to ignition of these tests does 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. It was decided to try and repeat the phenomenon which caused the second burn to determine definitely whether the fan sparked when it was turned on which 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 psig) resulted. After a period of time, the fan was turned on and a larger burn (ΔP = 3.2 psig) occurred.

2.3.2.2 Phase 2, Part 2

Two experiments were run to determine igniter performance under continuous injection of H_2 with the igniter preenergized.

Test No. 1 - This test was performed twice. The first attempt to perform Test 1 is listed in Table 3 as "Extra." The reason for this is that after running this test the first time, 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. For this reason, the data is considered unreliable and is included for reference only in Table 3.

The first of these transient tests began with the vessel filled with air at $80^{\circ}F$ 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 this time a slight temperature increase of $20^{\circ}F$ 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 This is 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 5.

The glow plug box interior air temperature showed a continuous increase from $103^{\circ}F$ at the time of ignition to a maximum of $193^{\circ}F$ at the end of the test. At the completion of the test, the temperature had peaked as seen in Figure 6.

The glow plug box exterior temperature showed a continuous increase from $83^{\circ}F$ at the time of ignition to a maximum of $226^{\circ}F$ 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 5.

Selected data for this test are listed in Table 3.

For continuous hydrogen addition at a sufficiently high rate, a continuous hydrogen burn at a low concentration as seen in this test, is not unexpected.

Relatively low temperatures and pressures result from this burn as the heat is added over a long period of time allowing dissipation of the heat energy to heat sinks.

Test No. 2 -The second test started having the vessel filled with air at 160°F and an an initial pressure of 14.7 psia. The test began with the igniter plug preenergized 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 pressure of 10.15 psid 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 7, 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 psid pressure increase from the first burn corresponds to burning off about 30 percent of the hydrogen present at that time (4.8 v/o). 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. 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 pressure of 10.15 psid 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 psid.

The air temperature vs. time curve, Figure 9, 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) bur . the temperature decreased for the r..ainder 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 indicatin.. higher exterior temperatures. The glow plug box interior temperature vs. time curve is illustrated in Figure 10.

The glow plug box exterior temperature curve is very similar to the previous curve. The box surface 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 9.

Data for this test is recorded in Table 3.

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.

2.3.2.3 Phase 2, Part 3

A series of tests, one transient and three static, were run to determine the effect of spray upon igniter performance. Spray parameters in this equipment were selected so as to model the spray conditions seen in the SQN containment post-LOCA (i.e., the flow was scaled to the flow per unit volume in the upper compartment). One exception to this was that the spray water temperature during these tests which was $50^{\circ}F$.

An unnumbered test appears in Table 4. This was the first attempt to perform Test 1. The test 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, tested, and the test was then rerun.

Test No. 1 -The first experiment was a static test with a 10 v/o hydrogen concentration. Initially, the vessel was filled with air at 1 atmosphere 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 pressure peak of 50.0 psid above the preburn pressure in 0.56 seconds. The pressure curve was similar to other static tests. Data describing the curve and other data concerning this test are given in Table 4.

Test No. 2 -This test was identical to Test 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 pressure of 31.2 psid above the preburn value. The time from ignition to peak pressure was 1.5 seconds. The pressure curve was similar to those in other static tests. Data describing this test are listed in Table 4.

Test No. 3 -The third experiment was the transient hydrogen burn in this series. This test 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 pressure occurred 6 seconds after ignition and was followed by a gradual pressure decrease to 0.9 psid after 9 minutes.

A second burn is indicated 10.5 minutes after ignition by a local pressure peak of 4 psid 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 11. Additional data concerning this test are given in Table 3.

Test No. 1A -This test was identical to Test 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 pressure peak of 42.2 psid above the preburn pressure resulted 1.1 seconds after ignition. The pressure curve was similar to those of other static tests. Data describing this curve and other data concerning this test is given in Table 4.

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 radiative heat transfer on the temperature obtained in the previous part and hence on instruments inside containment during a hydrogen burn.
4. Determine the effect of reduced igniter voltage upon the glow plug's ability to ignite hydrogen.

Test No. 1 -The first test involved the burning of an air-steam-hydrogen mixture at 5.9 psig and 129°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 Gauge (TC #2); Inside wall (TC #4), and Circuit Board (TC #5).

The result of this burn was a pressure increase of 60 psid over the preburn pressure and a maximum air temperature of 710°F. The temperature and pressure curves were similar to those of other static tests. Details of these curves and other data concerning the test are given in Table 5.

The Barton transmitter casing reached maximum internal and external temperatures of 150°F and 230°F respectively.

Test No. 1A - This test was identical to Test 1 except that the Barton transmitter casing was enclosed in a single layer of loosely wrapped aluminum foil.

The result of this burn was a pressure increase of 61 psid over the preburn pressure and a maximum air temperature of 735°F. The temperature and pressure curves are similar to those of other static tests. Details of these curves and other data concerning the test are given in Table 5.

With the aluminum foil enclosure, the Barton transmitter casing reached maximum internal and external temperatures of 140°F and 143° F, respectively.

Test No. 2 - This test was identical to the first test except that an unshielded solenoid valve/limit switch combination was placed inside the test vessel in place of the Barton transmitter casing. 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 pressure increase of 63 psid over the preburn pressure and a maximum air temperature of 760°F. The temperature and pressure curves were similar to those of other static tests. Details of these curves and other data concerning the test are given in table 5.

The solenoid valve reached maximum interior and exterior temperatures of 228°F and 240° F.

The limit switch reached maximum interior and exterior temperatures of 170°F and 235° F, respectively.

Test 2A - This test was identical to test 2 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 pressure increase of 58 psid over the preburn pressure and a maximum air temperature of 755°F. The pressure and temperature curves are similar to those of other static tests. Details of these curves and other data concerning the test are given in table 5.

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.

Tests No. 5 and 6 -Tests 5 and 6 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 14.6 volts to 12 volts in test 5 and to 10 volts in test 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 pressure increase of 49 psid over the preburn pressure and a maximum air temperature of 790°F. For test 6 the corresponding values were 50 psid and 760° F. In both cases, the temperature curves were similar to those of other static tests. Details of these curves and other data concerning these tests are given in Table 5.

2.4 Anomalous Data

In the course of performing both the phase 1 and phase 2 testing some of the data we recorded 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.

2.4.1 **Phase 1 -Inconsistent Data.** Two of the thermocouple readings recorded in attachment 1, page 8, 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 inconsistent with the rest of the recorded data. This caused Fenwal to replace and recalibrate 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 we are not using this data point.

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 thereafter. 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 (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.

2.4.2 Phase 2 Testing

The phase 2 testing was broken into 4 parts. Part 1 further defined the IDIS combustible limits by testing in the lower hydrogen concentration range. Part 2 determined igniter performance under a continuous injection of hydrogen with the igniter preenergized. Part 3 determined the effect of spray on igniter performance in a rich and lean mix of hydrogen and in a transient hydrogen addition. Part 4 determined the effect of a single hydrogen burn on typical equipment and to determine temperature response.

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 above reason the temperature data for this series of tests cannot be relied upon as being accurate.

In part 4, Test No. 2A 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.

2.4.3 Hydrogen Sampling

Throughout the phase 1 and 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 samples the gas chromatograph hydrogen analysis did not agree with the hydrogen concentration we 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 sample contained less than 0.1 percent hydrogen. However, the second laboratory reported hydrogen concentrations in the pre-burn sample which differed from the original laboratory's analysis by more than 1.5 percent and neither laboratory was in agreement with the hydrogen concentration we believed we 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. We are at a loss to know why the gas chromatograph laboratory reported close agreement (within 0.5 percent) for four of the 14 pre-burn samples in phase 1 and vet 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 back to Knoxville for analysis using a hydrogen analyzer at TVA's Singleton Laboratories. Our laboratories reported the sample was within 0.5 percent of the expected concentration.

Due to the uncertainty created by this type of hydrogen analysis TVA is not using results obtained from the gas chromatograph laboratory although they have been included in the tables of this report as test data.

3.0 Burning Characteristics

Following ignition, knowledge of the manner in which hydrogen burns is of paramount importance in determining, with accuracy, the bounding limits associated with a particular mixture of hydrogen and air. These limits must be established within the realm of atmospheric conditions postulated in containment structures for the various accident scenarios resulting in hydrogen generation. These conditions include the effects of hydrogen concentration, water vapor concentration, presence of spray droplets in the atmosphere, and atmospheric turbulence. The parameters of importance in establishing these hazard limits include peak pressure rise, burning completeness, and peak temperature rise. The igniter testing program was initiated to determine the effects of the various atmospheric conditions in relation to these important parameters.

3.1 Test Results

In general, the results observed follow those established by previous investigators. For instance, the downward flame propagation limit of approximately 8-9 v/o hydrogen is exemplified by burning completeness. This is due to the placement of the igniter in the approximate center of the test vessel. Burning completeness is shown in Figure 14 by the observed pressure rise for a particular initial H_2 concentration over the theoretical maximum pressure rise, $\Delta P/\Delta P$ max, possible assuming an adiabatic burn. This figure depicts a great range of yields for those burns initiating from an initial H_2concentration of 8 percent.

A summary of the test results is presented in Table 1. This table presents the temperature, pressure, hydrogen concentration fan velocity, and burn data. This data was analyzed to estimate the amount of hydrogen consumed based on the observed pressure rise using an adiabatic burn model. These calculations are summarized in Table 1.

3.2 Discussion of Results

As previously stated, the effects of expected containment environmental conditions on hydrogen combustion are of primary interest. The effects specifically investigated in this test series include steam, sprays, and fan flow. Each of these effects will be discussed below.

3.2.1 Effects of Steam

The effect of steam on the combustion of hydrogen is small. The primary effect is to alter the combustion limits. In the region of interest, water vapor tends to slightly increase the lower combustion limit with increasing water vapor concentration. In addition, due to the high specific heat of water vapor relative to the gas constituents, the result is a suppression of the temperature and pressure response. For those tests with similar initial temperatures and H_2 concentrations, the thermocouple responses indicate a general trend toward lower observed temperatures with increasing water vapor concentration (see Table 1).

3.2.2 Effects of Spray

The introduction of sprays tends to have offsetting effects. The subcooled sprays absorb greater amounts of energy as opposed to merely vapor. However, the introduction of the sprays tends to create turbulence which, in turn, increases the amount of H_2 consumed. Table 1 indicates lower observed temperatures as opposed to the static tests.

3.2.3 Effects of Fan Flow

The introduction of turbulence in the test medium serves to increase the burn completeness for those burns with initial hydrogen concentrations below the downward flame propagation limit. In these cases, the hydrogen immediately around the igniter burns in a brief burst. Then as the fan remixes the atmosphere, a flammable mixture is again introduced in the vicinity of the igniter and the mixture ignited. Figure 14 shows a typical pressure response curve for the situation previously described. Hence for relatively low H_2 concentrations (4-8%), fans increase the response of the ignitors.

3.3 Comparison of Results with Theory

Hydrogen flammability limits are considered to be 4 v/o for upward propagation, 6 v/o for horizontal propagation, and 9 v/o for downward propagation in hydrogen air mixtures at standard conditions. Experiments with increasing hydrogen concentration exhibit an S-shaped curve such as shown in figure 3 based on the data of Furno where a very low ΔP is seen to result for concentrations in the 4 to 8 v/o range and a sharp transition to substantially complete burn ΔP's occurs in the 8 to 9 v/o hydrogen concentration range. The above data was based on spark type ignition source.

The data presented here with the glow plug igniter has been substantially consistent with this behavior, i.e., relatively complete burning at 10 and 12 v/o and variable completeness for burns at 8 percent, the steep rise portion of the curve. The one exception has been that partial burns have resulted with the glow plug at lower concentrations. This is attributed to convection continually driving hydrogen mixtures to the heated vicinity of the glow plug where burning can take place without need for flame propagation. This belief is reinforced by the observation that substantial burning was observed for low hydrogen cases where either fan or spray were present to force turbulent mixing, e.g., pressure increases of 15 and 32 psid resulted for 6 v/o hydrogen mixtures with the draft fan and spray, respectively.

Flammability limits are affected by the environmental conditions. For example, it is known that the lower flammability limit decreases with increasing temperature, increases with increasing steam concentration, and is relatively insensitive to pressure. A similar affect may well be anticipated for the transition to a burn which essentially propagates spherically throughout the chamber. It is expected that flame temperature is a critical parameter for such propagation. Since reaction rates are an exponential function of temperature a threshold between flames which can propagate or be extinguished by heat loss is logically dependent on the flame temperature. On this basis the S-shaped Furno type curve would shift left (lower concentration) for increasing initial temperature or shift right (higher concentration) for increasing steam concentration due to its higher heat capacity relative to air. In addition to the above affects, steam inerts hydrogen mixtures from burning in the range of 50 to 60 volume percent steam. Similarly, suspended fine water droplets (~100μ diameter) can effectively quench flame propagation when present in sufficient concentration, i.e., distance between droplets less than the flame quench distance of 0.165 cm for 10 v/o H_2-air mixtures. Large spray droplets can promote turbulence and provide a heat sink during a burn, but would not prevent flame propagation.

Tests run with steam concentrations up to about 30 percent exhibited no difference compared with similar tests without steam. A 40 percent steam concentration and a 9 v/o hydrogen mixture exhibited a lower yield in terms of pressure rise (~60 percent of theoretical) than did other 10 v/o mixtures though the post-burn hydrogen analysis sample indicated a complete burn. The lower pressure rise may well be due to some shifting of the burn curve toward higher hydrogen concentration at this high steam content. A simi'ar reduction in yield was noted in tests with 6 v/o hy ogen when 40 percent steam was present.

The continuous hydrogen addition transients exhibit interesting behavior in that burning initiated at low hydrogen concentration, about 5 v/o. These initial burns were partial, based on the magnitude of the pressure rise, and reasonably quick (10 sec). It is possible that the hydrogen or hydrogen and steam introductions established convection patterns such that good mixing flow past the igniter existed when the lower flammability limit was exceeded thus promoting burning. An alternate possibility is that the mixture was not uniform in hydrogen concentration and that at a higher (than average) concentration an upward and horizontal propagation occurred burning a significant portion of the mixture in the upper vessel.

4.0 Evaluation of Igniter Effectiveness

The IDIS igniter functioned consistently and reliably ignited hydrogen in every test of both phase 1 and phase 2. The igniter has survived over 30 tests under all the various environmental conditions described earlier in this report. The completeness which the mixture was burned as expressed by the ratio of the differential pressure generated to the calculated maximum differential pressure is also an indicator of igniter effectiveness but this is more strongly influenced by other factors, such as the hydrogen concentration and fan flow, therefore it is not useful in this discussion.

4.1 Effects of Environmental Conditions

The following discusses the effect that the various environmental conditions of temperature, pressure, humidity, air flow across the igniter, and sprays had on the igniter's effectiveness.

4.1.1 Temperature

Tests were conducted over a range of temperatures ranging from approximately 130 to 350^{o}F. In tests conducted at TVA's Singleton Laboratories we determined that from the time the igniter was energized to the time it reached approximately 1200^{o}F was on the order of 18 seconds. Figure 12 is a graph of the time to ignite versus initial test temperature. As the graph indicates there is little or no correlation between initial test temperature and the relative speed by which the igniter initiates burning.

4.1.2 Pressure

The testing at Fenwal did not cover a wide range of initial test pressures because all of the accident scenarios considered up until now have not exceeded pressures of 26.7 psia. The tests conducted at Fenwal therefore ranged in pressure from approximately 17.9 psia to 26.7 psia. Again, we graphed our test results (figure 13) to indicate that there is no correlation between the effectiveness of the igniter and initial pressure.

4.1.3 Humidity (Steam)

In 21 of the tests conducted at Fenwal we injected steam 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 as seen in Tables 1 and 2 indicate that humidity or steam concentrations up to 40 percent have no effect on the ability of the igniter to initiate burning.

4.1.4 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 feet per second (fps). In all five of those tests the time to ignition increased. In test No. 8 (phase 1) 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, by approximately 42 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.

All of these tests were conducted with an igniter powered by 14.6 volts ac. The tests of Part 4 were conducted using a similar igniter arrangement which was built by Duke Power and operated at 12.0 volts ac except for test 6 which used the Duke igniter set at 10 volts ac.

Most of the static tests which were performed with the igniter voltage at 14.6 volts ac ignited the mixture after an average of 15 seconds. When the igniter voltage was reduced to 12 volts ac, 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.

4.1.5 Sprays

TVA was concerned that water sprays from the containment spray system would prevent igniter operation. We therefore designed a spray shield which is located on top of the igniter box to protect it from direct spray impingement.

The part 3, phase 2, tests were designed to determine what effect the 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 the sprays by agitating the mixture actually increased 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 directly. Even in this severe test the igniter initiated a 10 v/o hydrogen burn in 15 seconds which demonstrates conclusively that water sprays do not hinder igniter performance.

5.0 Evaluation of Hydrogen Burning on Equipment

One of the most serious questions raised by the presence of large quantities of hydrogen inside containment is its effect, through burning or detonation, on critical components. Through the use of the Interim Distributed Ignition System (IDIS) TVA plans to burn the hydrogen at low concentrations, thus limiting the pressures and temperatures which could be generated by burning of large volume percents of hydrogen.

5.1 Test Results

The phase 1 testing was conducted to prove the igniter's ability to burn hydrogen under various environmental conditions. The phase 2 testing was conducted to further test the ability of the igniter as well as to observe the effect of hydrogen burning on a representative sample of equipment. The temperatures recorded in these tests indicate that burning of hydrogen should not endanger equipment inside of containment previously qualified for a loss-of-coolant accident.

5.1.1 Phase 1 Testing

Although it was not the purpose of this group of tests to demonstrate equipment survivability, the test results provide useful data. In addition, the IDIS igniter box demonstrated that it could survive repeated hydrogen burn tests and still function. Attachment 1, page 8, lists the phase 1 tests and the four temperatures which were recorded for each of the tests. The test results indicate that the temperature rise across the igniter box ($T_3 - T_V$) for the 12 volume percent hydrogen tests averaged 48°F, and for the ten volume percent tests averaged 38°F and for the eight volume percent tests averaged 17°F.

In several of the phase 1, 12 volume percent 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 the comparisons as we did in phase 1 above because we did not perform as many identical tests so that an average could be taken. 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 (test 1) and 78°F for the eight peak multiple burn which occurred with the continuous injection of hydrogen and steam (test 2), but this is still quite reasonable considering the duration of the burn and the quantity of hydrogen burned.

In phase 2, part 3, as mentioned earlier, due to the melting of the teflon insulation on the thermocouples the temperature data is suspect. Neglecting this the temperature rise across the igniter box according to the data colected is still no larger than the part 2 continuous injection tests mentioned above.

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 $41^{\circ}F$, respectively, for exposure to a 12 v/o hydrogen burn.

Table 6 is a list of all the equipment we exposed to at least 12 v/o hydrogen burns during the 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 peice of cable showed a couple of small (1/2 x 2 inch) scorch spots on the black plastic coating. Table 7 is a list of miscellaneous equipment which was also included in the test vessel during the testing. This list is provided to demonstrate the minor effect of the hydrogen burn environment on completely unqualified equipment.

5.2 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 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 inte··:r air and exterior surface temperatures of 150°F and 230°F, respectively.

Test 1A was identical to Test 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 2, 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 the previous case. 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 2A was identical to Test 2 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 temperature data presented herein is also listed in table 5. As can be seen from this data, in general, the temperatures were lower for the cases where the equipment was insulated than the cases in which the instrument was uninsulated.

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 10°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

$45^{o}F$ reduction from $228^{o}F$ in the noninsulated case to $183^{o}F$ for the insulated case. For these reasons, the solenoid valve exterior temperature for the insulated case is considered invalid.

It is thus seen from experiments 1, 1A, 2, and 2A that when the Barton transmitter casing, solenoid valve and limit switch were each enclosed in the aluminum foil, significantly lower interior temperatures resulted.

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.

percent steam do not hinder the ability of the igniter to initiate hydrogen burning. High steam concentrations (40%) however, do suppress the peak pressure generated by a hydrogen burn to some extent.

d. Air flow (5 to 10 feet per second) across the igniter did not hinder the ability of the igniter to initiate hyrogen burning. In the higher hydrogen concentration tests (10 to 12 percent) the air flow induced by the fan had little or no effect. However, at low concentrations (6 percent through 8 v/o) the fan flow actually increased the ability of the igniter to burn greater percentages of the available hydrogen.

e. Likewise with the spray tests, the water spray did not affect the ability of the igniter to successfully burn hydrogen (even direct spraying of the igniter). However, at low hydrogen concentrations the sprays, by agitating the mixture, promoted much more complete hydrogen combustion.

f. The tests involving continuous injection of hydrogen showed that hydrogen would begin burning at low concentrations and that continuous injection of hydrogen and steam produced multiple burns very similar to results predicted by the Westinghouse CLASIX code, and

g. The hydrogen burn environment while it does produce extreme temperatures, is of such a short duration that the effect on equipment is not any more severe than the accident conditions for which the equipment is presently qualified.

This can be illustrated in the continuous transient burn tests of Parts 2 and 3. Aluminum foil would not have as great of an effect in these cases as in the static burns of tests 1A and 2A, because in the transient cases when the vessel air is heated to a high temperature for a long period of time, it becomes an important convective and conductive heat transfer medium, especially late in the transient experiments. This fact is evidenced by the continual rise of the glow plug box interior temperature in the transient cases even after the burns had ceased. Noteworthy also at this time is the point that in the transient tests, hydrogen ignition occurred and maintained itself at approximately an 8 v/o hydrogen concentration and not the 12 v/o used in the part 4 tests 1, 1A, 2, and 2A.

6.0 Conclusions

The Fenwal tests have generally provided very favorable results for the IDIS system. Many of the tests confirmed published data on hydrogen burning while others provided us with a better understanding of hydrogen burning phenomena. The following is a summary of the significant results obtained from the Fenwal Tests.

a. Initial pressure in the 6 to 12 psig range had no effect on the ability of the igniter to initiate a volumetric hydrogen burn in the 8 to 12 v/o range.

b. High initial temperatures, in the 350°F range, may help the igniter initiate burning but the effect is very small and of no real consequence.

c. High humidity or steam concentrations up to and including 40

Based on the positive results obtained in these tests TVA can claim with greater assurance that the IDIS can, in fact, operate reliably in even the most extreme conditions, burn hydrogen at low concentrations, limit the peak pressure to within allowable structural capabilities and in general reduce the overall risk of an accident similar to that which occurred at Three Mile Island.

FENWAL

LEGEND FOR TABLES 1 AND 2

T_i = initial test temperature
T_1 = igniter box exterior temperature
T_2 = vessel wall temperature
T_3 = igniter box internal temperature
T_4 = vessel air temperature
P_h, P_{air}, P_{H_2O} = partial pressure in mm of Hg
H_p = % hydrogen (preburn) chromatagraphic analysis
H_a = %hydrogen (post-burn) via chromatagraphic analysis
S_u = burn velocity
$\%H_2$ is % hydrogen g[illegible] in test condition
V = air velocity ac[illegible] glow plugs
R/H = relative humi[illegible]
Amb. Temp - ambient [illegible] temperature prior to test
Bar. Press - barometric pressure in mm of Hg

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TABLE 2
PHASE 2, PART 1

Test No.	T_1	T_1 °F	T_2 °F	T_3 °F	T_4 °F	P_{H_2} mmHg	P_{air} mmHg	P_{H_2O} mmHg	P lb/in²	Time to P max sec	Time to Ign sec	R/H %	Amb Temp °F
1	136	210	175	-	960	96.16	838.57	134.42	38.75	6.85	15.8	36	56
2	138	141	130	140	165	85.64	843.18	141.65	3.1	5.4	15.9	76	41
2a	-	185	143	148	330	-	-	-	16.0	-	-	-	-
3	140	140	135	145	-	74.77	846.0	147.39	1.5	5.5	15.5	35	55
4	142	142	142	142	142	64.67	856.0	157.17	1	11	17	80	44
5	144	144	144	144	144	53.9	858.69	165.44	.25	3	17	-	51
6	138	230	183	140	685	86.25	850.16	141.66	36.0	4	15	34	49
7	142	190	152	-	335	64.68	856.18	157.17	14.0	9	17	85	45
8	212	280	242	240	700	107.02	535.1	428.08	30.0	9.6	17	74	62
9	212	212/225	200/200	212/217	235/245	64.21	577.9	428.08	.78/2.66	-	16.5	55	65
10	210/210	212/225	210/247	227/269	205/208	64.21	577.9	428.08	.20/3.2	1.88/5.88	19.75/25.7	52	50

H_p	H_a	S_u	V	% H_2	Bar. Press mm Hg
-	-	-	-	9	765.3
-	-	-	-	8	761.4
-	-	-	-	-	-
-	-	-	-	7	761.4
-	-	-	-	6	767.7
-	-	-	-	5	767.7
-	-	-	5	8	767.7
-	-	-	5	6	768.0
-	-	-	-	10	767.4
-	-	-	0/5	6	767.4
-	-	-	0/5	6	762.3

Note: 1) For Test 10, T_2 is the maximum vessel air temperature and T_4 is the maximum vessel wall temperature.

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TABLE 1
PHASE 1

Test	H_2 %	H_2O %	Temp °R	Press psia	Fan Vel ft/sec	P psi	$\Delta P/\Delta P_{max}$ (calc.) %	Time Ignite	Time P max
	Initial Conditions[1]					Results			
1	11.97	1.35	640.0	18.218	0	53.0	92.4	14.5	0.5
2	7.97	1.44	640.0	17.424	0	33.0	85.1	14.0	4.0
3	7.98	1.36	640.0	18.828	0	3.0	7.2	14.25	4.7
4	12.04	10.57	589.0	20.509	0	66.0	95.5	15.75	0.55
5A[2]	8.11	12.78	598.0	20.598	0	22.6	46.6	18.25	18.75
5B	8.11	12.78	598.0	10.598	0	3.5	7.2	-	-
6	12.0	24.69	636.0	26.586	0	72.0	91.2	17.8	0.66
7A[3]	8.0	27.81	650.0	26.671	0	16.25	29.8	18.5	68.13
7B	8.0	27.81	650.0	26 671	0	2.7	4.9	-	-
7C	7.54	28.36	742.5	20.395	0	15.5	37.2	-	-
8	12.01	11.29	605.0	20.802	5	67.5	99.4	19.06	0.375
9	12.12	10.79	590.0	20.60	10	65.0	92.0	59.25	0.5
10	9.98	14.51	606.0	21.07	10	53.7	92.4	29.0	0.875
11	9.98	14.6	606.0	21.09	5	52.7	90.6	23.9	0.781
12	12.01	6.98	810.0	26.55	10	58.75	92.1	25.9	0.40
13	12.01	6.61	810.0	26.55	0	60.0	94.2	12.06	0.406
14	8.00	10.85	810.0	26.40	0	30.0	68.3	12.0	9.0

[1] The initial conditions (%H_2 and %H_2O) were adjusted, in some cases, to account for the effects of loading the test vessel. The test vessel was initially sealed at ambient conditions, then dry compressed air was added to achieve a precalculated air pressure such that the subsequent addition of a measured partial pressure of H_2 resulted in the desired percentage of hydrogen. Then, in those cases requiring vapor, steam was added to again achieve a desired precalculated pressure. Hence, due to the initial enclosure of ambient air, the initial condition values were adjusted to account for this initial vapor present.

[2] Test 5 experienced two burns: 5A represents the assumption of one burn, 5B represents the initial burn data only from the pressure traces.

[3] Test 7 experienced two burns also; 7A represents the assumption of one burn, 7B represents the initial burn, and 7C the second burn. These two burns were distinct and separate; therefore 7C utilized the initial conditions as calculated by HYFIRE for 7B.

TABLE 3
Phase 2, Part 2

Test No.	T_1	T_1	T_2	T_3	T_4	P_{H_2}	P_{air}	P_{H_2O}	P	Time to P_{max}	Time to Ign*	R/H	Amb Temp
1	80 ^oF	226 ^oF	330 ^oF	198 ^oF	163 ^oF	4 scfm	759.1 mm Hg	-	7.8 lb/in^2	11 sec.	1.5 min.	95%	34 ^oF
Extra***	84 ^oF	218 ^oF	338 ^oF	193 ^oF	120 ^oF	4 scfm	759.1 mm Hg	-	6.09 lb/in^2	12 sec.	1 min.	95%	34 ^oF
2	160 ^oF	265 ^oF	367 ^oF	238 ^oF	185 ^oF	4 scfm	**768.5 mm Hg	-	10.15 lb/in^2	4.5 sec.	1.4 min.	57%	37 ^oF

H_p	H_a	S_u	V	$\%H_2$	Bar. Press
-	-	-	-	-	759.1 mm Hg
-	-	-	-	-	759.1 mm Hg
-	-	-	-	-	768.5 mm Hg

*From H_2 input initiation

**Initial conditions - 1 atmos., T=160^oF

***Test considered extra due to uncertainty in H_2 input

E50323.09

LEGEND FOR TABLES 3 AND 4

T_i = initial test temperature
T_1 = igniter box exterior temperature
T_2 = vessel air temperature
T_3 = igniter box internal temperature
T_4 = vessel wall temperature
P_{H_2}, P_{air}, P_{H_2O} = partial pressure in mm of Hg
H_p = % hydrogen (preburn) chromatagraphic analysis
H^p_a - %hydrogen (post-burn) via chromatagraphic analysis
S_u = burn velocity
$\% H_2$ is % hydrogen given in test condition
V = air velocity across glow plugs
R/H = relative humidity
Amb. Temp - ambient air temperature prior to test
Bar. Press - barometric pressure in mm of Hg

E50323.08

TABLE 4
PHASE 2, PART 3

Test No.	T_1 °F	T_1 °F	T_2 °F	T_3 °F	T_4 °F	P H	P Air	P H_2O	P psid	Time to Pmax sec	Time to Ign sec	R/H %	Amb Temp °F	H	H	S_p	V_s	% H_e	Bar. Press mm Hg
-	42	-[3]	665	135	108	85.72 mm Hg	771.5	-	56.25	-	-	45	39	-	-	-	-	10	771.5
1	82	137	650	157	130	84.47 mm Hg	760.2	-	50.0	.56	11.59	50	47	-	-	-	-	10	760.2
2	80	83	415	132	122	48.27 mm Hg	756.2	-	31.2	1.56	22.0	34	48	-	-	-	-	6	756.2
3	80	133	502	157	105	4 scfm	755.5	-	3.12	6	89.5	34	48	-	-	-	-	-	755.5
1A	73	118	358	142	118	85.67 mm Hg	771.0	-	42.2	1.125	15.0	50	40	-	-	-	-	10	772.5

Notes:

1. Average spray flow rate during test measured to be 1.9 gpm.
2. Temperature spray approx 50° F for all tests.
3. Igniter box exterior thermocouple fell off during the course of the experiment.
4. Legend for this table same as for Table 3.

Circled data are uncertain due to thermocouple insulation failure.

DE02:FENWAL.2

POOR ORIGINAL

TABLE 5
PHASE 2, PART 4

Test No.	T_1 °F	T_1* °F	T_2* °F	T_3* °F	T_4* °F	T_5* °F	T_6* °F	P H_2	P Air	P H_2O	P psid	Time to Pmax sec	Time to Ign sec	R/H %	Amb Temp °F	H_p	H_a	S_u	V
1	129	255	140	230	150	135	710	124.1	830.3	111.7	60	.64	27.1	55	40	-	-	-	-
1A	129	357	130	143	140	13[illegible]	735	124.1	830.3	111.7	61	.60	27.2	93	26	-	-	-	-

*Temperatures are as designated below:

T_1 = Maximum test vessel wall temperature
T_2 = Barton transmitter casing maximum interior air temperature (thermocouple #2)
T_3 = Barton transmitter casing maximum exterior surface temperature
T_4 = Barton transmitter casing maximum interior air temperature (thermocouple #4)
T_5 = Barton transmitter casing maximum interior air temperature (thermocouple #5)
T_6 = Maximum test vessel air temperature

% H_2	Bar Press	Vac Pulled	Pre-Burn Anal	Post-Burn Anal	Ign Voltage
12	756.6				12
12	751.6				12

PHASE 2, PART 4

Test No.	T_1 °F	T_1* °F	T_2* °F	T_3* °F	T_4* °F	T_5* °F	T_6* °F	P H_2	P Air	P H_2O	P psid	Time to Pmax sec	Time to Ign sec	R/H %	Amb Temp °F	H_p	H_a	S_u	V
2	129	365	240	228	235	170	760	124.1	830.3	111.7	63	.55	25.8	30	55	-	-	-	-
2A	129	395	250	183	185	138	755	124.1	830.3	111.7	58	.65	26.3	57	27	-	-	-	-

*Temperatures are as designated below:

T_1 = Maximum test vessel wall temperature
T_2 = Solenoid valve maximum exterior surface temperature
T_3 = Solenoid valve maximum interior air temperature
T_4 = Limit switch maximum exterior surface temperature
T_5 = Limit switch maximum interior air temperature
T_6 = Maximum test vessel air temperature

% H_2	Bar Press	Vac Pulled	Pre-Burn Anal	Post-Burn Anal	Ign Voltage
12	755.0				12
12	771.0				12

FENWAL.3

PHASE 2, PART 4

Test No.	T_1 °F	T_1 °F	T_2 °F	T_3 °F	T_4 °F	P_{H_2} mm Hg	P_{Air} mm Hg	P_{H_2O} mm Hg	P psid	Time to Pmax sec	Time to Ign sec	R/H %	Amb Temp °F	H_p	H_w	S_u	V	% H_e	Bar Press
5 [1]	146	379	790	203	432	109	841.6	142	49.0	1.7	27.8	60	30	-	-	-	-	10	760 mm Hg
6 [2]	146	510	760	195	510	109	841.6	142	50.0	1.5	56	55	65	-	-	-	-	10	-

Notes:
1. Test conducted with igniter at 12 volts, P = 21.1 psia; 6.4 psig.
2. Test conducted with igniter at 10 volts, P = 21.1 psia; 6.4 psig

from test 6: BI cable - no visible damage
black plastic cable - single spots (2)
approx 1/2"x2" spaces scorched

POOR ORIGINAL

LEGEND FOR TESTS 5 AND 6

T_i = initial test temperature
T_1 = igniter box exterior temperature
T_2 = vessel air temperature
T_3 = igniter box internal temperature
T_4 = vessel wall temperature
P_{H_2}, P_{air}, P_{H_2O} = partial pressure in mm of Hg
H_p = % hydrogen (preburn) chromatagraphic analysis
H_a = %hydrogen (post-burn) via chromatagraphic analysis
S_u = burn velocity
$\%H_2$ is % hydrogen given in test condition
V = air velocity across glow plugs
R/H = relative humidity
Amb. Temp - ambient air temperature prior to test
Bar. Press - barometric pressure in mm of Hg

E10339.01

TABLE 6
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	6	Cover seal burned, but no other obvious degradation
11. Fischer Regulator	1	No obvious degradation

E10331.01

TABLE 7
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

E10331.01

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

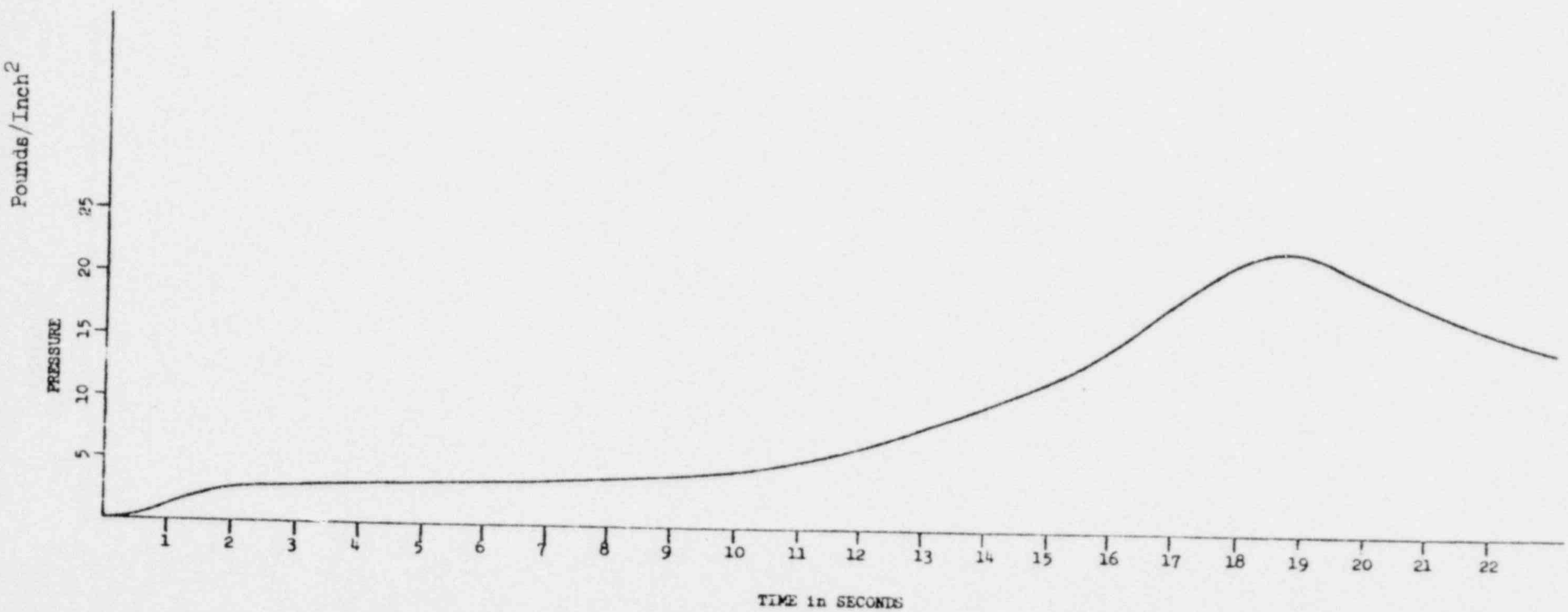
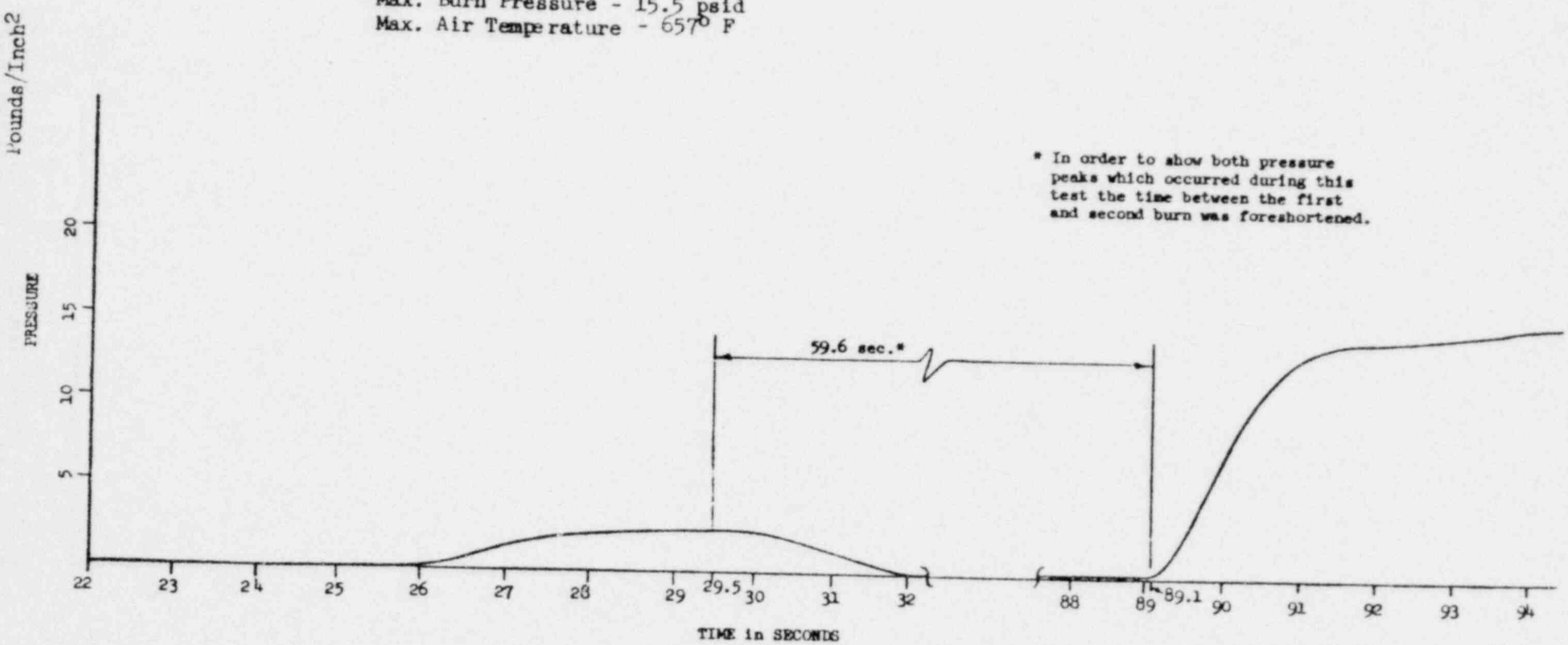


Figure No. 2
Phase No. 1
Part No. ___
Test No. 7
Initial Pressure - 26.671 psia
Initial Temperature - 190.3° F
Volume % H_2 - 8.0
H_2 Flow Rate _____
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 15.5 psid
Max. Air Temperature - 657° F



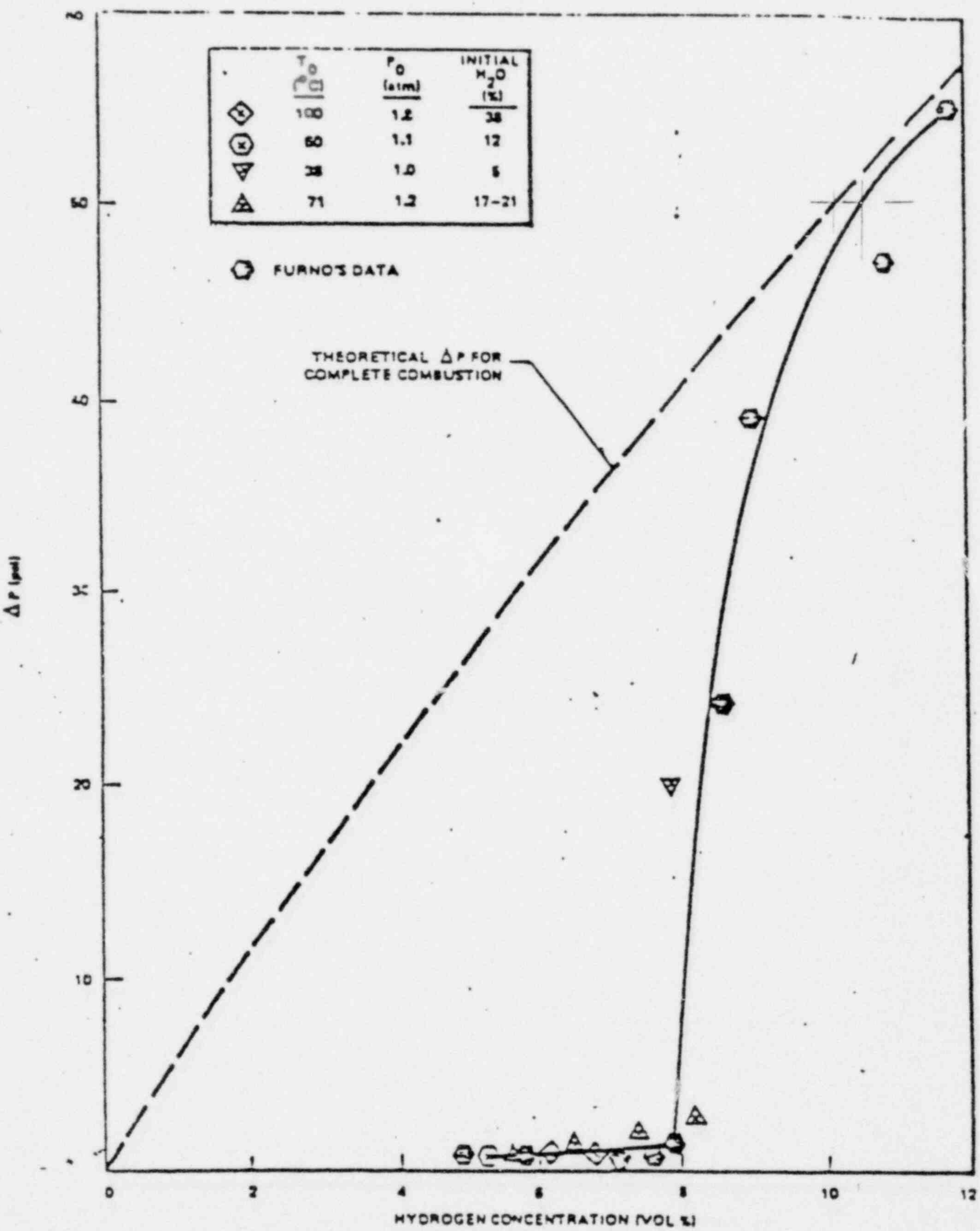


Figure 3

PRESSURE RISE VERSUS HYDROGEN CONCENTRATION SPARK IGNITOR

Figure No. 4
Phase No. 2
Part No. 2
Test No. 1
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. Burn Temperature - 330° F

TRANSIENT BURN IN DRY AIR

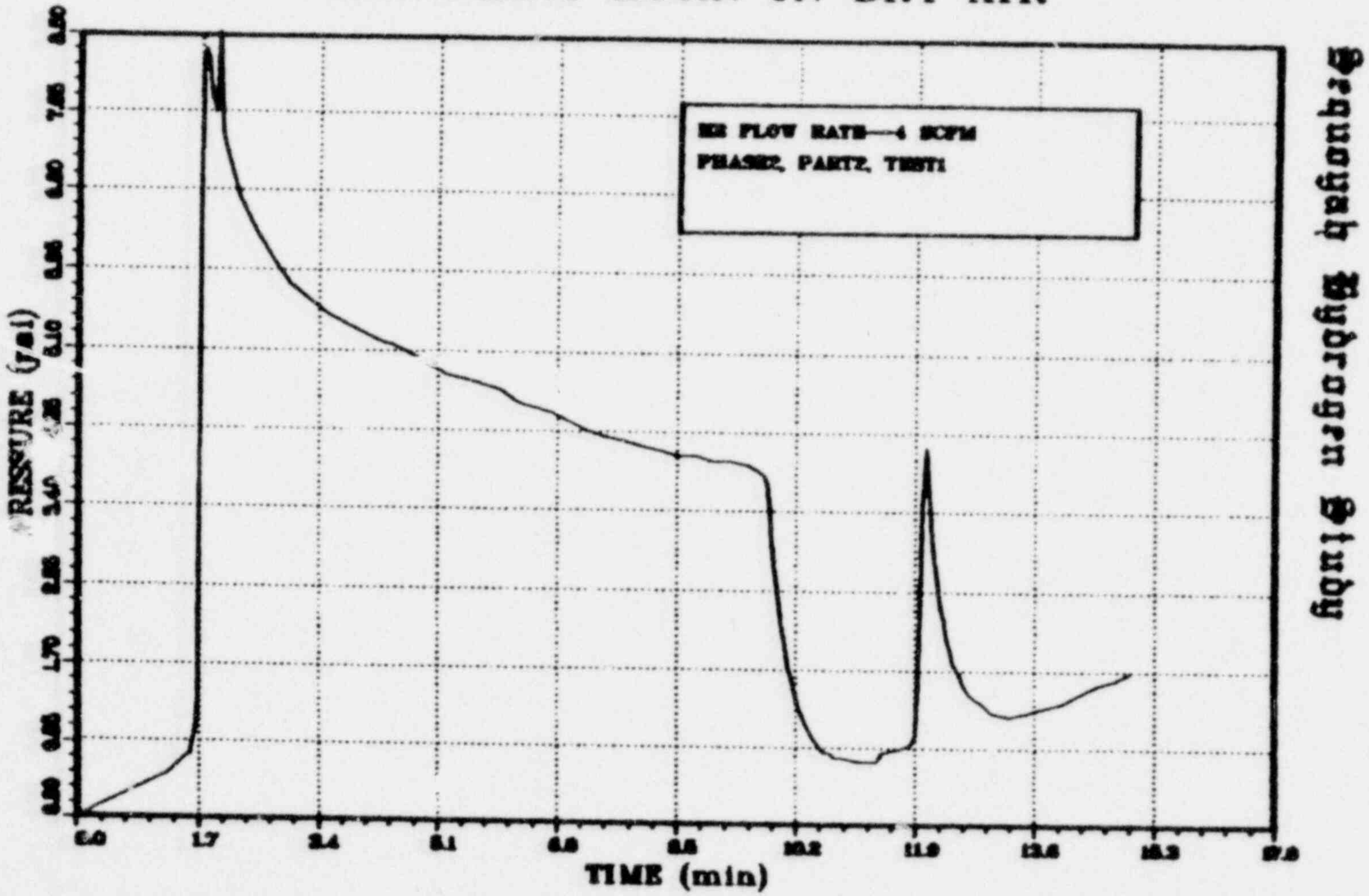


Figure No. 5
Phase No. 2
Part No. 2
Test No. 1
Initial Pressure - 14.67 psia
Initial Temperature - 80° F
Volume % H_2 _____
H_2 Flow Rate - 4 scfm
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 7.8 lb/in^{2}g
Max. Air Temperature - 330° F

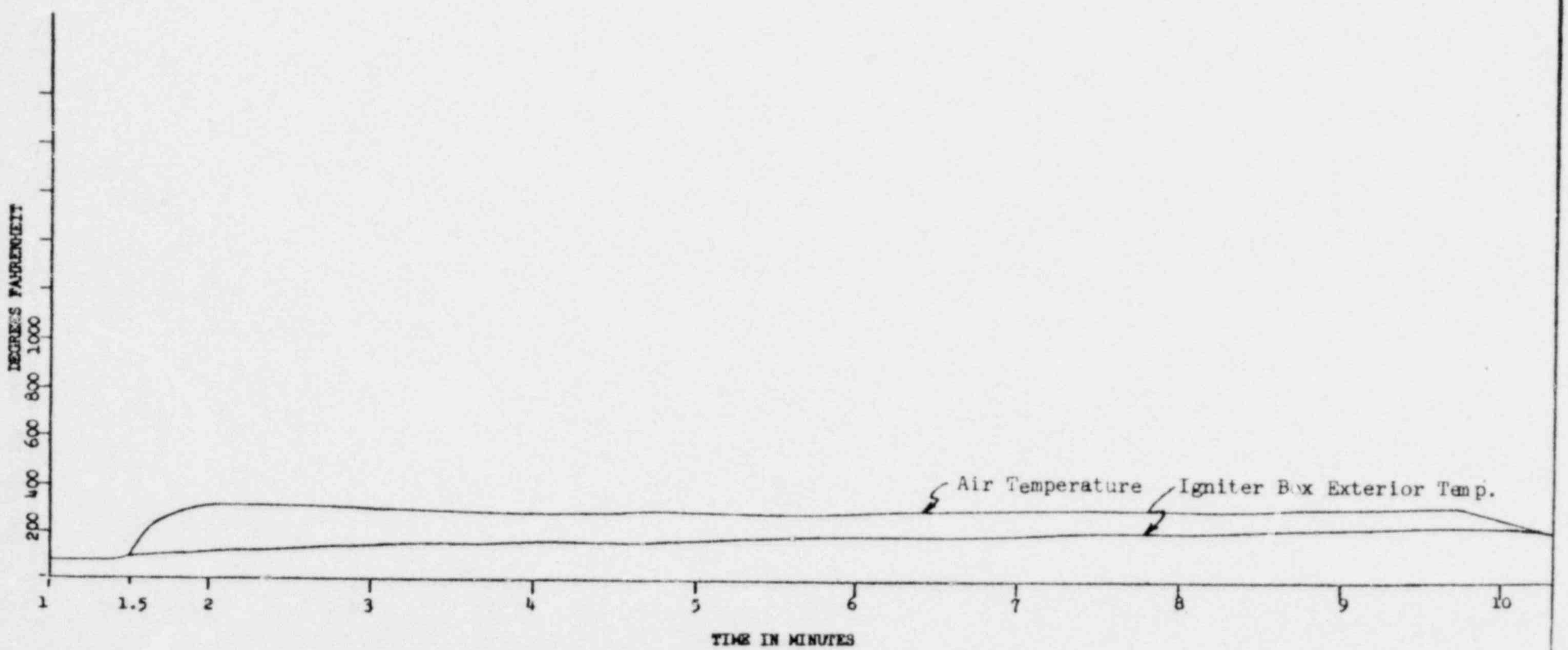


Figure No. 6
Phase No. 2
Part No. 2
Test No. 1
Initial Pressure - 14.67
Initial Temperature - 80° F
Volume % H_2 _____
H_2 Flow Rate - 4 scfm
Steam Flow Rate _____
Spray Flow Rate _____
Max. Burn Pressure - 7.8 lb/in^2g
Max. Air Temperature - 330° F

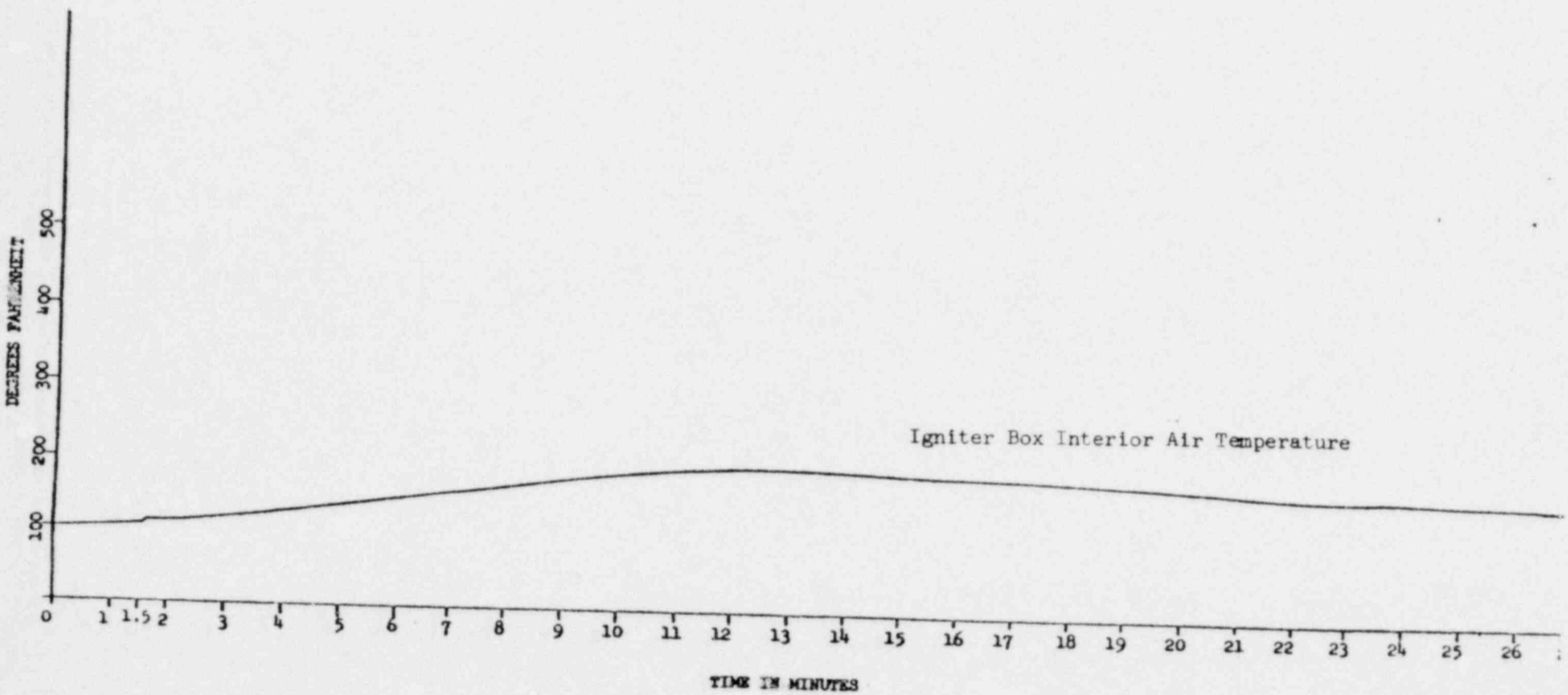
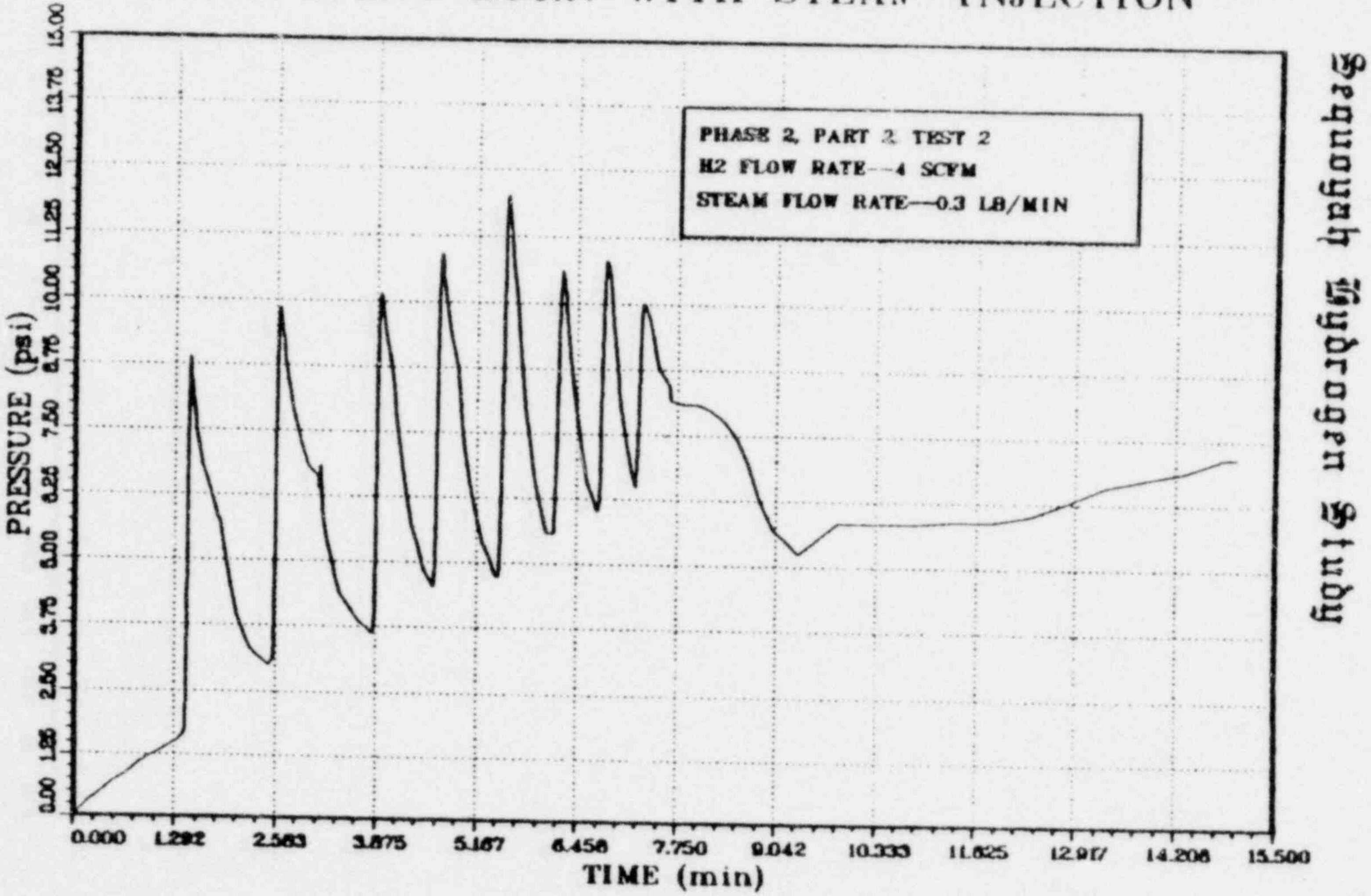


Figure No. 7
Phase No. 2
Part No. 2
Test No. 2
Initial Pressure - 14.85 psia
Initial Temperature - 160°F

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. Burn Temperature - 367°F

TRANSIENT BURN WITH STEAM INJECTION



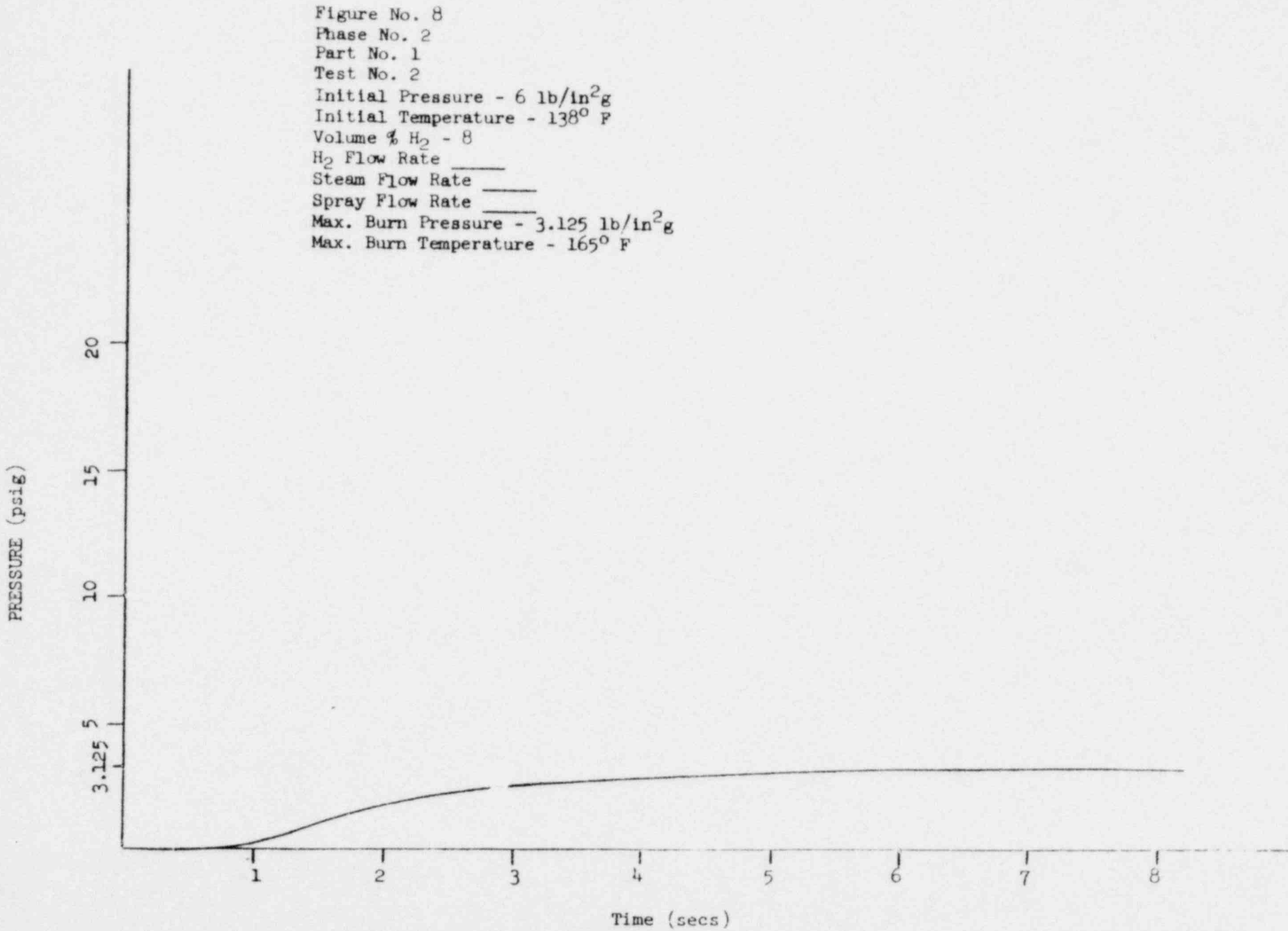


Figure No. 8
Phase No. 2
Part No. 1
Test No. 2
Initial Pressure - 6 lb/in^{2}g
Initial Temperature - 138° F
Volume % H_2 - 8
H_2 Flow Rate ____
Steam Flow Rate ____
Spray Flow Rate ____
Max. Burn Pressure - 3.125 lb/in^{2}g
Max. Burn Temperature - 165° F
PRESSURE (psig)
20
15
10
5
3.125
1
2
3
4
5
6
7
8
Time (secs)

Figure No. 9
Phase No. 2
Part No. 2
Test No. 2
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

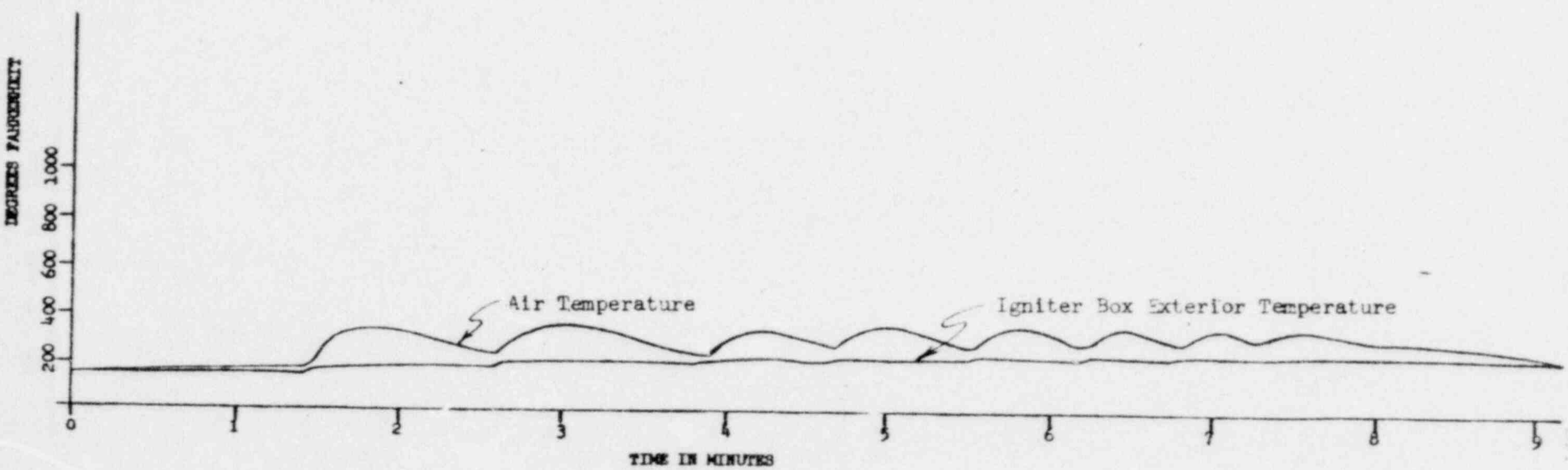


Figure No. 10
Phase No. 2
Part No. 2
Test No. 2
Initial Pressure - 14.85 psia
Initial Temperature - 160° F
Volume % H_2 ____
H_2 Flow Rate - 4 scfm
Steam Flow Rate - 0.3 lb/min
Spray Flow Rate ____
Max. Burn Pressure - 10.15 lb/in^2 g
Max. Air Temperature - 367° F

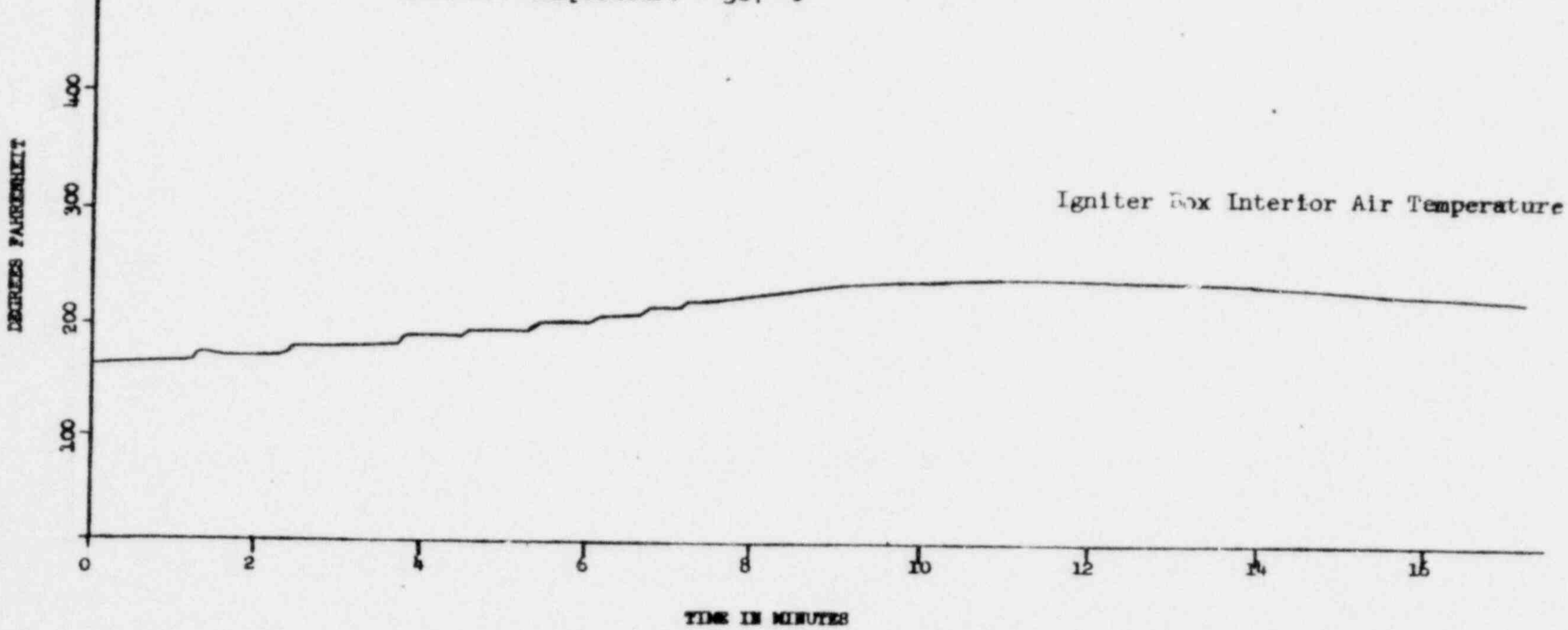


Figure No. 11
Phase No. 2
Part No. 3
Test No. 3
Initial Pressure - 14.60 psia
Initial Temperature - 80° F

Volume % H_2 ___
H_2 Flow Rate - 4 scfm
Steam Flow Rate ___
Spray Flow Rate - 1.9 gal/min
Max. Burn Pressure - 3.[illegible] psid
Max. Air Temperature - [illegible] F

TRANSIENT SPRAY TEST

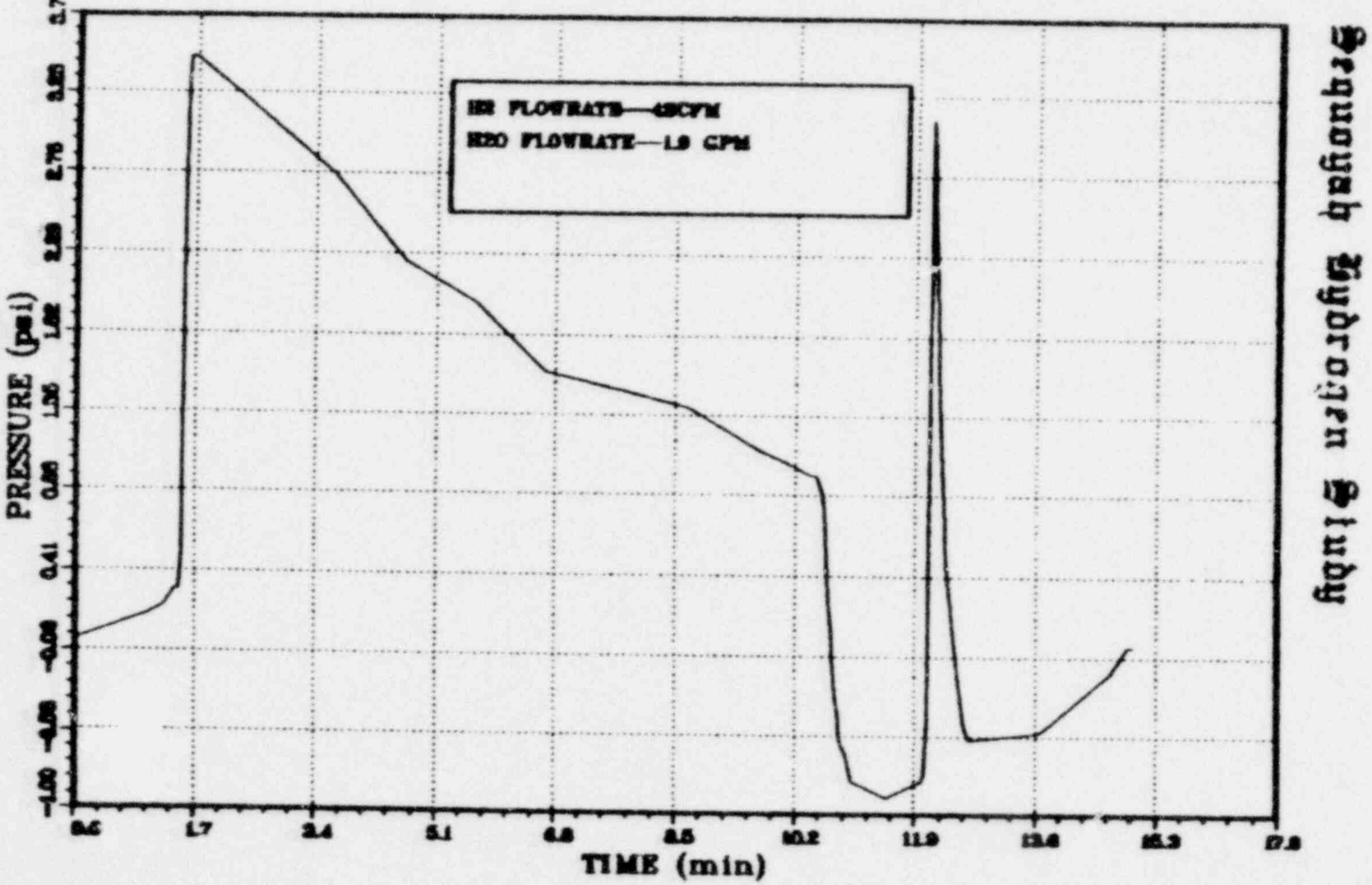


Figure 12
Temperature vs. Time to Ignition

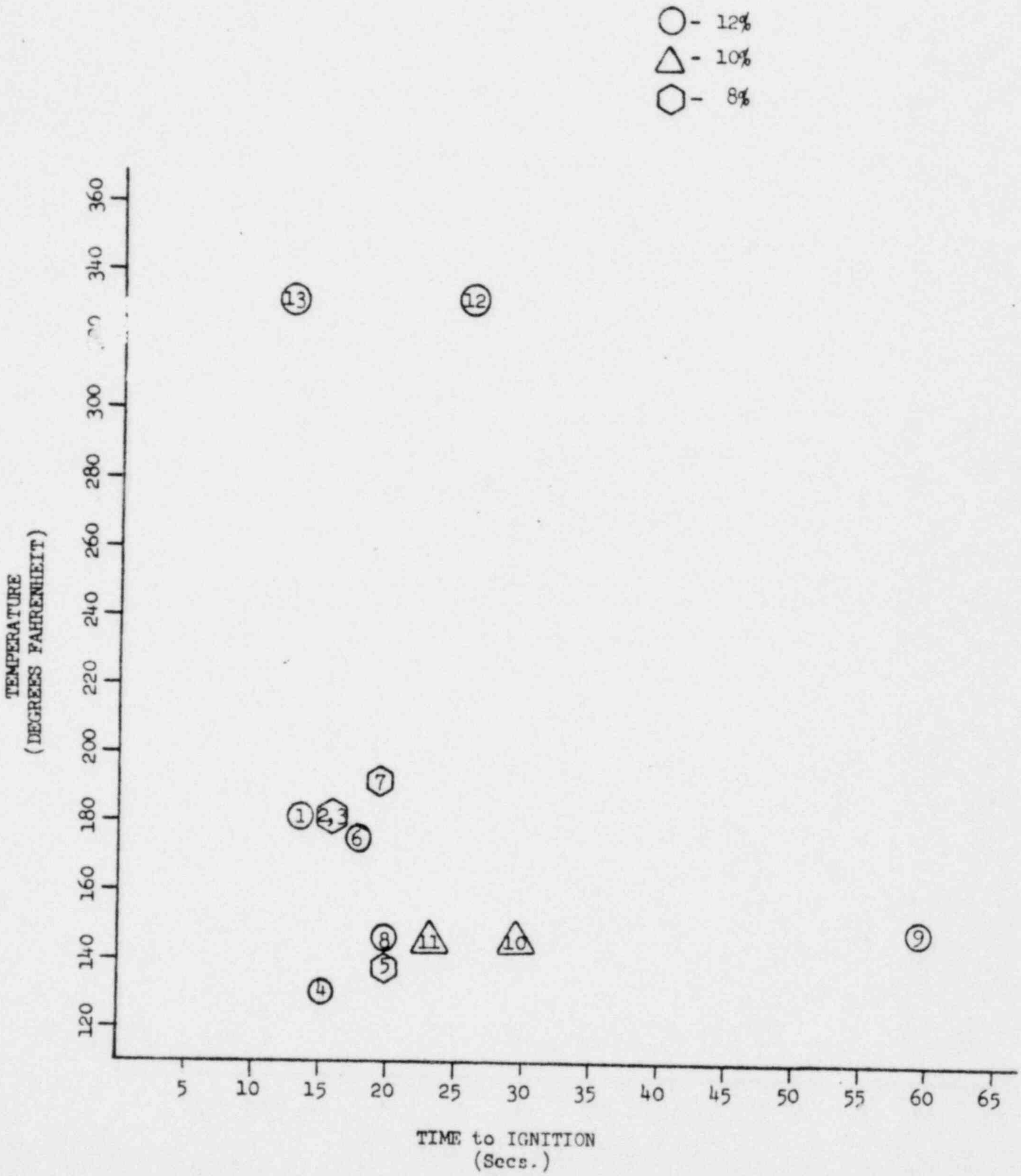
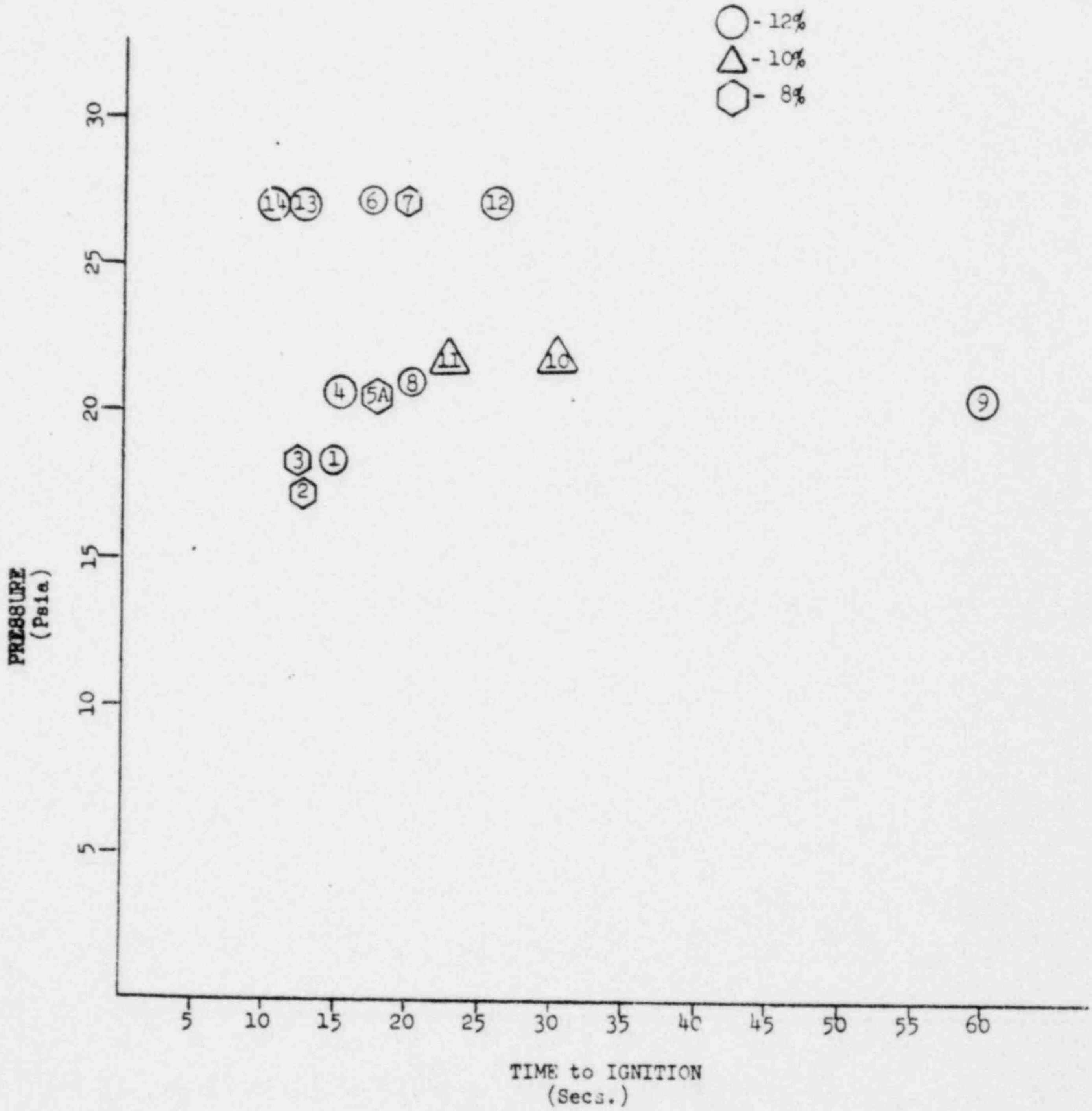


Figure 13
Pressure vs. Time to Ignition



FENWAL TEST DATA

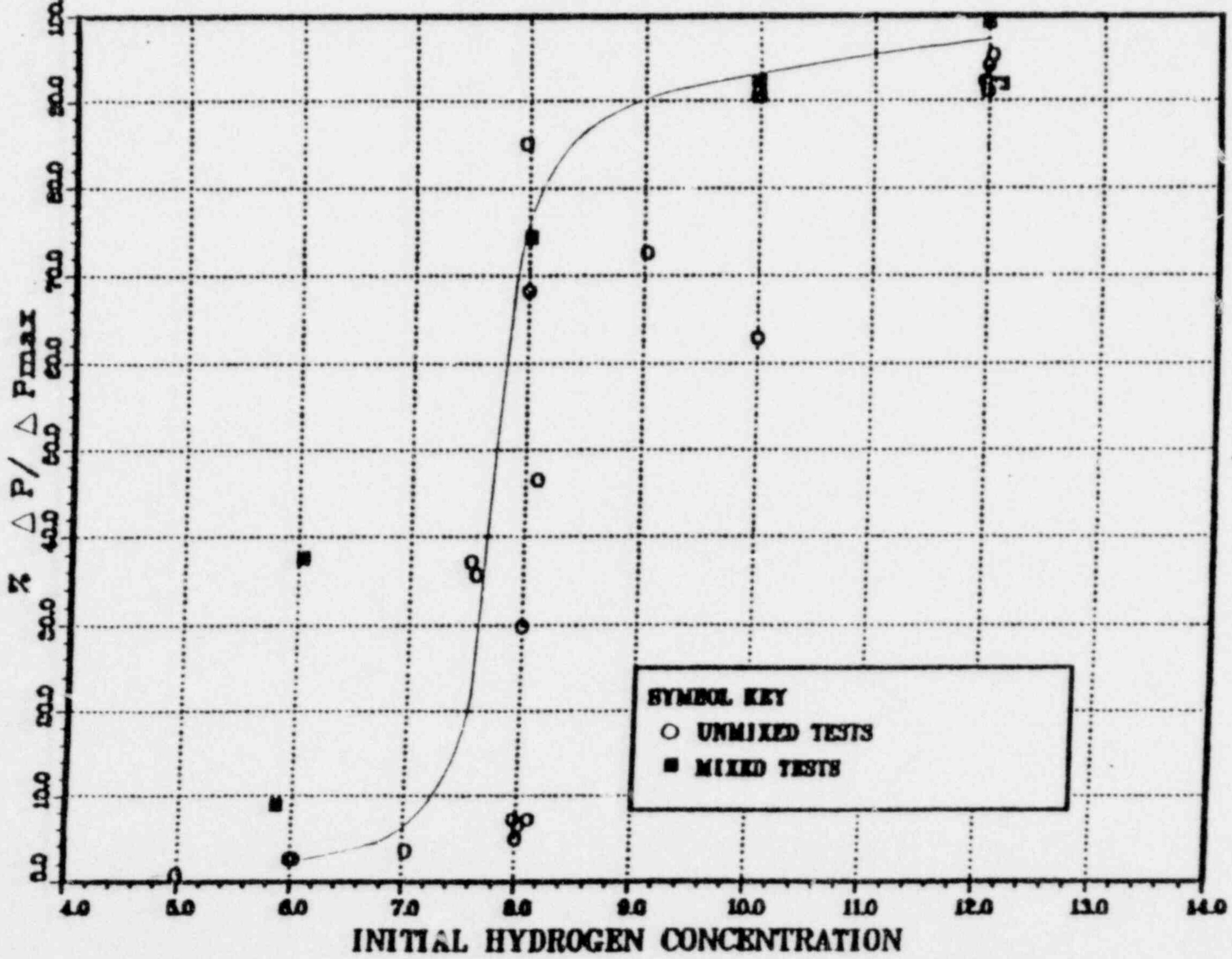


Figure 14 - (Includes all Fenwal tests except transient cases)