REACTOR SAFETY HYDROGEN RESEARCH IN CANADA – AN OVERVIEW

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1. Introduction

A scientific and engineering research program to investigate the impact of hydrogen in a post-accident nuclear containment has been under way at AECL since 1977 [1-3]. The objectives of the program are 1) to gain an understanding of combustion mechanisms and phenomena to enable prediction of combustion behavior in post-accident containment atmospheres, 2) to acquire a database to validate calculations, and 3) to develop and demonstrate mitigation measures. The program has contributed data on topics such as flammability limits [4], burning velocities [5,6], detonation cell widths [7], ignitor effectiveness [8-11], vented combustions [12], and Deflagration to Detonation Transition [13,14]. On-going topics of investigation include gas mixing, standing diffusion flames, combustion in inter-connected chambers, flame acceleration and flame jet ignition.

Gas mixing and hydrogen are combustion complex phenomena that involve many complex processes. Furthermore, these processes often interact with one another in a non-linear fashion. Presently, the understanding of these processes and phenomena is still qualitative in nature. Development of comprehensive models that can predict these complex phenomena is currently being carried out in many research establishments. AECL has several facilities designed for examining various gas mixing and combustion phenomena. These facilities are: the Large Scale Gas Mixing Facility, the Containment Test Facility, the Large Scale Vented Combustion Test Facility and the Diffusion Flame Facility. Over the past years, we have completed many research programs using these facilities. Data from our test programs have enabled us to understand many of these phenomena and to validate our computer codes.

This paper describes three of our facilities and recent results on three research programs. These programs are of common interest in reactor safety irrespective of reactor design. They also provide a highlight of our activities as well as a demonstration of the capability of these facilities. These programs are: buoyancy-induced convection in partitioned volumes, combustion in inter-connected chambers, and flame-jet ignition. The first program investigates the hydrogen distribution inside a containment that has partitioned chambers. The second and third programs investigate the pressure development inside containment in the event the hydrogen is ignited.

2. Large Scale Gas Mixing Facility

The Large Scale Gas Mixing Facility (LSGMF), located at the Whiteshell Laboratories of Atomic Energy of Canada Limited, is used for gas mixing experiments. The main facility for this program is a 10.33 m by 10.95 m by 8.20 m concrete enclosure with a small annex, giving an internal volume of 1000 m^3. Helium and steam can be injected through 0.051-m diameter nozzles at various locations in the facility. The injection simulates a break in the primary heat transport system inside a reactor containment building or sub-compartment. The LSGMF is suitable for examining different parameters that can affect the distribution of the injected gas: e.g., obstructions, jet diameter and velocity, temperatures, forced flow, pre-stratified steam, and the elevation and orientation of the injection point. The experimental results provide anunderstanding of gas mixing mechanisms and data for validating computer models and codes.

2.1 Buoyancy Induced Convection in Partitioned Volumes

A central issue in post-accident hydrogen-management in current CANDU containments is the predictability of the hydrogen-steam distribution. The expelled hydrogen inside the reactor vault migrates upward because of buoyancy effects. This buoyancy-induced flow not only assists the migration of the hydrogen and steam, it also entrains air from nearby inter-connected chambers. Data from these tests are also used to validate predictions by computer codes. Results also help safety analysts to determine the optimum placement of igniters or recombiners for hydrogen management [15].

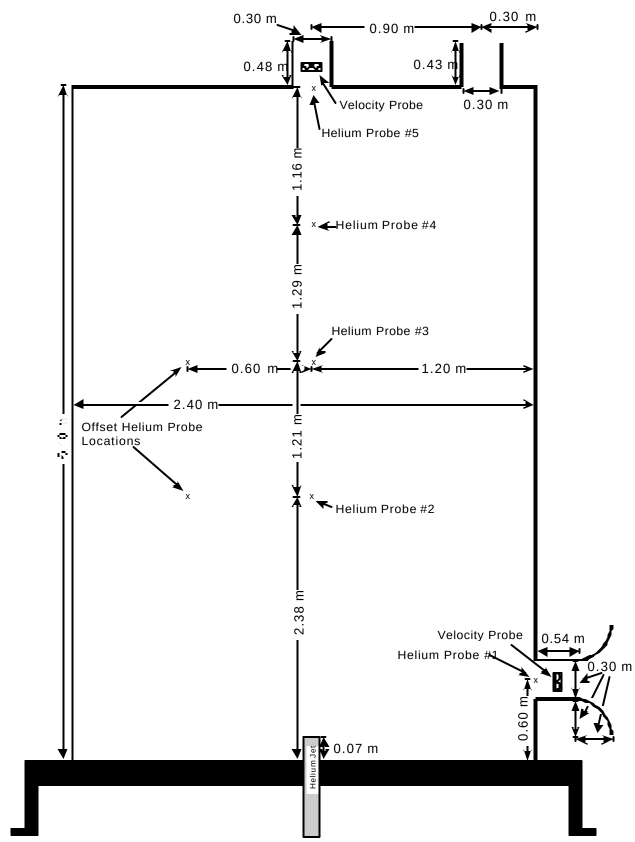

Figure 1. A Schematic of the Gas Mixing Apparatus for Buoyancy Induced Convection Tests

2.1.1 Experimental facility

A series of tests was performed in the Large-Scale Gas-Mixing Facility. To create a partitioned volume, a 2.44 m x 2.44 m x 6.10 m enclosure (Fig. 1) was added to the LSGMF. This enclosure has openings at various locations to allow inflow of air and outflow of helium-air mixture. Helium was used in these tests to simulate hydrogen for safety reasons. This enclosure, formed by a metal frame sitting on a raised steel floor, is covered

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on three sides with polyethylene wrap while the front wall is constructed of Plexiglas sheets to provide flow visualization. There are three 30-cm-diameter openings (0.071m^3) in this enclosure, two are at the ceiling and one is on the sidewall near the bottom. By covering portions of the outlets, the outlet area ranged from 0.018 m^2 to 0.142 m^2 can be achieved. With a flexible piping attached to the helium jet, the elevation of the helium jet could be varied by re-positioning the helium nozzle. The helium flow rate was controlled by a set of calibrated rotameters.

Gas concentrations at various locations inside the enclosure are measured using Nova Instruments gas analysers. The Nova analyser gives direct readings of gas concentration (percent helium). The probe positions (P1 - P5) are shown in Figure 1. An OMEGA Hygro-Thermo Anemometer was used for monitoring the gas velocity at the inlet and outlet. This meter uses a 2.75 in. vane-type probe and measures velocity in metres per second with a resolution of 0.01 m/s. To reduce any boundary layer effects, a converging cone is attached to the bottom opening so that velocity measurement at the inlet opening can be used to calculate the airflow rate.

Three sets of tests were conducted. The main experimental parameters for these tests were:

1 changing the injection rate while keeping the outlet area constant
2 changing the outlet area while keeping the injection rate constant
3 changing the helium injection elevation while keeping the injection rate constant.

Only the first series of tests is discussed in this paper.

2.1.2 Results and Discussion

In general, the magnitude of the buoyancy-induced flow (or the chimney effect) is controlled by the height of the enclosure, the helium injection rate, and the opening areas of the inlet and outlet. In this series of tests, the height of the enclosure and the areas of the inlet and outlet were not changed. Both the inlet and outlet opening areas were 0.071 m^2. Only the helium injection rates were varied. A converging nozzle was also added to the upstream side of the inlet to minimize the boundary effects. It was observed that, with this converging nozzle added, a uniform velocity across the inlet opening could be achieved. The inlet air volume flow rate can be calculated based on the velocity measurement. Figure 2 shows the inlet velocity for various helium injection rates. The duration of helium injection for this series of test was 800s. This duration was limited by the helium inventory in the facility. It was observed the inlet velocities increased as more and more helium was injected into the enclosure. At 800s the inlet velocity seems to be approaching a steady state value indicating that the velocity would not further increase. Results show that for a 4 times increase in the injection rate (g/s), the peak velocity increased from about 1.1 m/s to 1.45 m/s (about a 30% increase). This result suggests that the

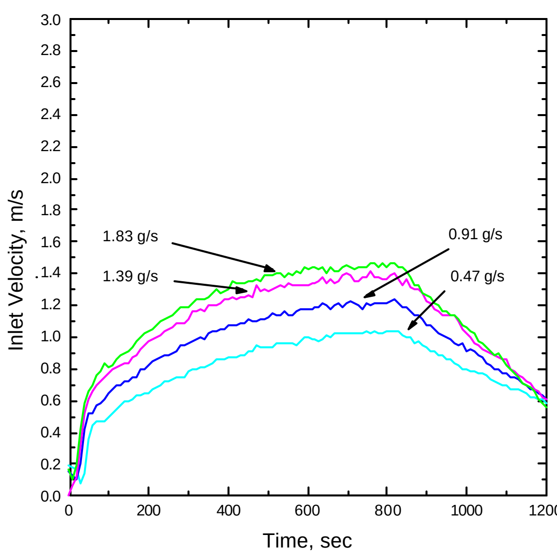

Figure 2. Inlet Velocities for Various Helium Mass Flow Rates

geometry of the enclosure (height of the enclosure, area and location of the openings) may play a role in controlling the magnitude of the buoyancy-induced flow.

The Volume Flow rate Magnification Factor (VFMF) is the ratio of the amount of air entrained (or sucked into the enclosure) to the amount of helium injected. This parameter indicates, the effectiveness of the buoyancy-induced flow (the chimney effect) in sucking in air and eventually diluting the injected helium. Figure 7 shows that the VFMF for various opening areas at the top of the enclosure. Results show that the factor decreases as the helium injection rate increases. For an injected helium flow rate of 0.46 g/s, the VFMF has a value of about 27. This value is expected to depend on the geometry of the enclosure such as height of the enclosure and area and location of the openings. The significance of this value is in its magnitude. In our facility, every cubic meter of helium injected into the enclosure is capable of sucking 27 cube meters of air from the inlet. This implies that the average helium concentration inside the enclosure is about 3.7%. This value quantifies the effectiveness of using the buoyancy-induced flow concept as a mitigation scheme for hydrogen management in an event of an accident.

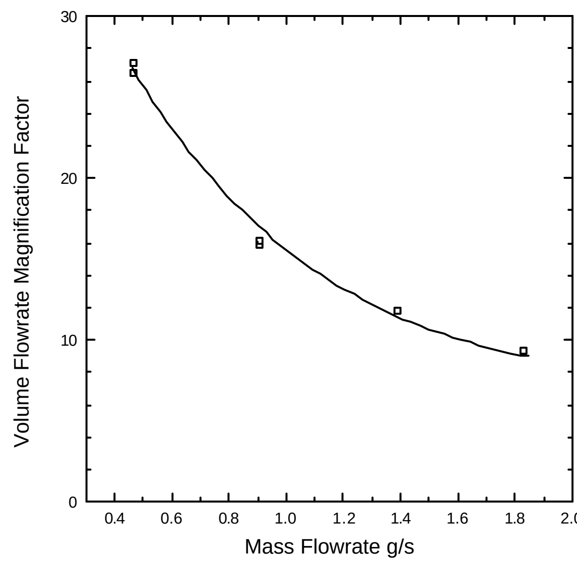

Figure 3. Volume Flow Rate Magnification Factor for Various Helium Mass Flow Rates

2.1.3 Summary

The experiments described in this section are the first phase of a study on the effect of internal partition on gas distribution. In the present series of experiments, helium was injected at a constant rate into the facility at the bottom of an enclosure. The experiments examined the buoyancy-induced convection loop by measuring the velocities at the inlet of the enclosure. Results show that because of the chimney effect created by the buoyancy-induced flow, air was sucked into the enclosure while the helium-air mixture was forced out through the top opening. It was observed that entrained air volume flow rates as high as 27 times the helium injection flow rate can be achieved. The air mixes with the injected helium fairly quickly, preventing the helium from accumulating to high concentrations within the enclosure.

3. Large Scale Vented Combustion Test Facility

The Large Scale Vented Combustion Test Facility (LSVCTF) is a 10-m-long, 4-m-wide, and 3-m-high rectangular enclosure with an internal volume of 120 m^3. It is constructed of 1.25-cm-thick steel plates welded to a rigid framework of steel I-beams. The entire structure is anchored to a 1-m-thick concrete pad. Two roller-mounted movable end walls are provided to open the vessel for internal modifications or to move in bulky experimental equipment, when needed. The combustion chamber, including the end walls, is electrically trace-heated and heavily insulated to maintain temperatures in excess of 100°C for extended periods of time. The entire combustion chamber is enclosed in an insulated metal Quonset, which houses the gas analysis and hydraulic fan systems on one side and all the process piping on the other side. A schematic of the facility configured with 3 internal chambers is shown in Fig. 4.

The LSVC TF was designed and built to systematically quantify effects of key parameters affecting pressure development of vented combustion under conditions relevant to deliberate ignition. Some of the key features considered in the design of the facility were (a) accurate control of initial thermodynamic conditions, (b) instrumentation capability for validation of three-dimensional combustion codes, (c) variable geometric configuration, (d) geometric similarity to actual rooms, (e) short duty cycle, (f) easy access to the interior of the combustion chamber, and (g) increase in scale to our existing test facilities. The facility is sufficiently large to capture effects of scale and has geometric similarity to actual rooms (i.e., flat walls and square corners). The facility provides quality data over a wide range of the key paramenters affecting combustion pressure development, for validation of containment codes (such as GOTHIC) for hydrogen combustion behaviour. In this project, engineered combustion tests are carried out for a matrix of initial conditions relevant to deliberate ignition in CANDU containments.

The LSVCTF has been used to perform a wide variety of experiments. Some of these are (a) unobstructed vented combustion experiments in 30, 60, or 120 m^3 volumes to evaluate the effects of scale, (b) turbulent vented combustion experiments to study the effects of initial turbulence, (c) flame propagation studies between interconnected compartments, (d) catalytic recombiner testing for hydrogen mitigation applications in large enclosures, and (e) critical safety equipment qualification tests.

Figure 4. A Schematic of the Large-Scale Vented Combustion Test Facility

Previous test campaigns have resolved the effects of key parameters affecting pressure development - hydrogen concentration, initial temperature, initial turbulence, vent area, vent location, ignitor location, ignitor number and volume of enclosure. The current and proposed test campaigns are examining effects of key geometric features affecting combustion pressure development (two and three room chains) and behaviour under dynamic conditions simulating realistic sequences (continuous hydrogen injection). Results of combustion tests in the two-chamber configuration are presented in this paper.

3.1 Combustion in Inter-connected Chambers

Hydrogen combustion in containment presents a challenge to containment integrity that could alter the fission product release source from containment. As well, hydrogen combustion poses a threat to critical equipment needed to manage the accident. Demonstration of the effectiveness of hydrogen mitigation features (ignitors or recombiners) is required to provide assurance that accident consequences are bounded and that progression to a more severe event does not occur due to consequential failure of containment or essential equipment. This project supports the assessments of consequences of deliberate ignition.

The facility was divided into two chambers of equal volume. A 0.5-m-thick internal wall of structural steel divides the test chamber into two rooms. The internal wall has openings covered with rectangular steel plates that can be removed to allow venting from one chamber (inner chamber) to the next (outer chamber). The gas in the outer chamber can also be vented out through a vent opening at the end wall. The vent area at the end wall can be changed by removing the appropriate number of panels and covering the openings with aluminium foil and/or Styrofoam panels. Three specific test programs are described in this section to illustrate the capability of this facility.

3.1.1 Variation in H_2 Concentration Between Chambers

Test Conditions

The hydrogen concentrations in the rear chamber and the front chamber were varied in two ways: (1) by keeping the concentration in the rear chamber constant (10%) and increasing the concentration in the front chamber from 0 to 10%, and (2) by adding the same amount of hydrogen to each chamber and varying the concentration from 8% to 10%. These tests were performed at ~25°C, with a 0.38 m^2 inner vent and a 1.1 m^2 outer vent. The igniter was located in the centre of the rear chamber. The gas mixture was quiescent at the time of ignition. Styrofoam panels were used in the vent openings.

Test Results

Figure 5 summarizes results for those tests that have 10% hydrogen in the rear chamber and various hydrogen concentrations in the front chamber. Results show increasing pressure peaks as the hydrogen concentration increases. With 10% H_2 in the rear chamber and 0% H_2 in the front chamber, the peak pressure in the rear chamber varied between 11 kPa and 27 kPa. As the concentration in the front chamber increased, so did the peak pressure in the rear chamber, up to 39 kPa with 10% H_2 in both the rear and front chambers. Figure 6 shows that with the same concentration of hydrogen in both chambers, the peak pressures in the rear chamber varied from 1 kPa at 8% H_2 to 39 kPa at 10% H_2. The peak pressures for 9% H_2 were not reproducible; they varied between 5 kPa and 15 kPa in the rear chamber. Large variations in combustion behaviour at 9% H_2 are also observed in previous tests in the single chamber geometry.

Given the same total mass of hydrogen, an uneven distribution of hydrogen between chambers can produce a higher overpressure than an even distribution. This occurs when a faster burning, richer mixture produces a higher pressure rise in the rear chamber and a faster, more turbulent jet

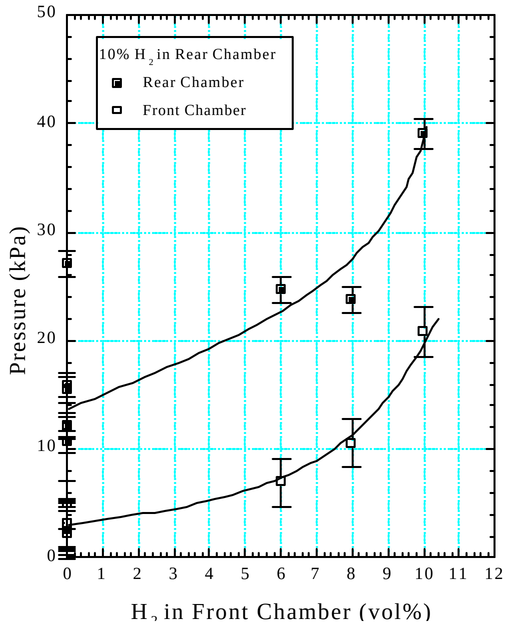

Figure 5. Pressure Peaks for Variation of Hydrogen Concentration Between Chambers. (Inner vent area = 0.38 m^2, outer vent area = 1.1 m^2. Ignition in centre of rear chamber.)

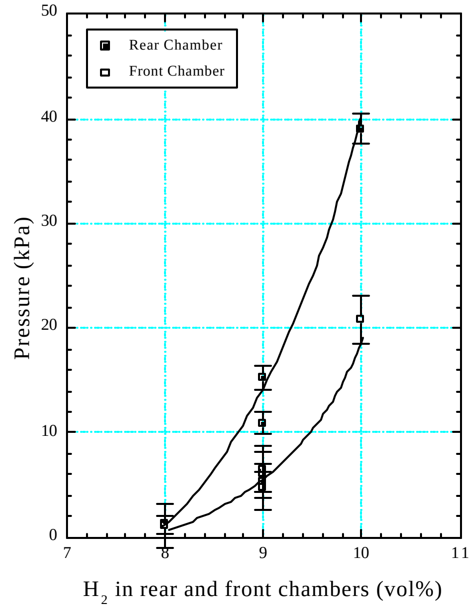

Figure 6. Pressure Peaks for Variation of Hydrogen Concentration. (Inner vent area = 0.38 m^2, outer vent area = 1.1 m^2. Ignition in centre of rear chamber. T = 25°C.)

into the front chamber, enhancing the burning rate in the front chamber and reducing the vent effectiveness for the rear chamber. For example, higher overpressures were seen with 10% H_2 in the rear chamber and 6% or 8% in the front chamber (~24 kPa) than those seen with 9% H_2 in both chambers (~10 kPa).

3.1.2 Variation of Vent Area

Test Conditions

The vent area for the outer chamber was varied from 0.55 m^2 to 2.2 m^2, while the inner vent was kept constant at 0.38 m^2. These tests were performed at ~25°C, with 10% H_2 in both test chambers. The igniter was located in the centre of the rear

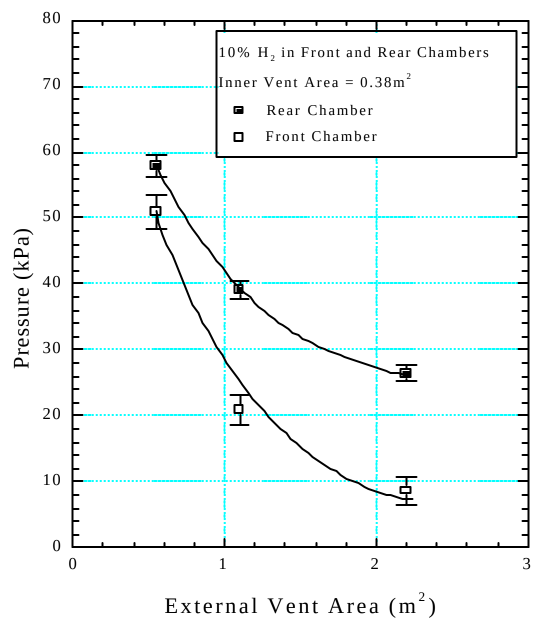

Figure 7. Pressure Peaks for Variation in External Vent Area.

chamber. The gas mixture was quiescent at the time of ignition.

Test Results

Figure 7 shows increasing pressure peaks as the external vent area decreases. At an external vent area of 0.55 m^2, the peak pressure in the rear chamber is 58 kPa, while a vent area of 2.2 m^2 produces a peak of 26 kPa. Increasing the external vent area also increases the effectiveness of the internal vent; the pressures of the rear and front chambers are 58 kPa and 51 kPa, respectively, for the 0.55 m^2 vent while they are 26 kPa and 9 kPa, respectively, for the 2.2 m^2 vent. It is expected that the peak overpressure in the rear chamber would reach a minimum value as the vent area in the front chamber increases and the overpressure in the front chamber approaches zero.

3.1.3 Variation of Vent Location

Test Conditions

In the vent location test, a pipe was attached to the centre vent at an angle, so that the vent between the 2 chambers could be varied from very low to very high. Figure 8 shows the four vent configurations used in these tests. These tests were performed at ~25°C, with either 8% or 9% H_2 in both test chambers. The gas mixture was quiescent at the time of ignition. The igniter was located in the centre of the rear chamber. Styrofoam panels were used in the vent openings.

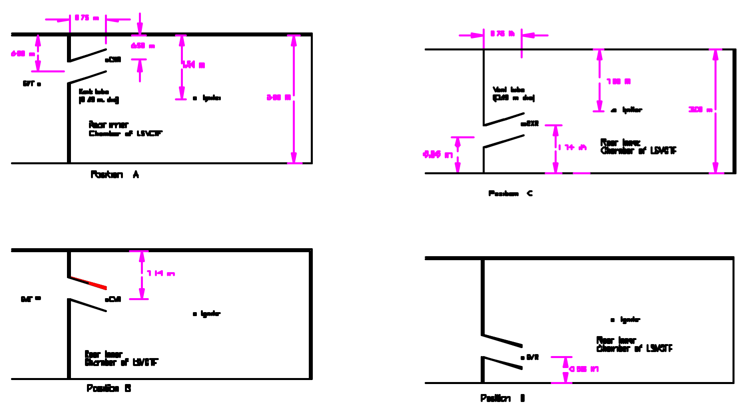

Figure 8. Vent Configuration for Vent Elevation Tests

Test Results

The results for this series of tests are summarized in Fig 9. The pressure peaks were less than 10 kPa for most test conditions except three. In the one test at 9% H_2 with the pipe in position D (lowest position, pointed down into the rear chamber), the peak pressure in the rear chamber was 18 kPa. In the two tests at 9% H_2 with the pipe in position A (highest position, pointed up into the rear chamber), the peak pressures in the rear chamber were 40 kPa and 45 kPa. In these three tests, acoustic oscillations were observed on the pressure trace. These oscillations interacted with the combustion and enhanced the burning rate, creating the higher pressure-peaks (compared to tests where no oscillations were observed). It is not obvious what caused the oscillations to occur in these particular tests and not the others. These tests demonstrate that vent location, and not just vent area, can also be an important factor affecting combustion behaviour, specifically, the peak pressure.

3.2 Summary

Combustion tests were performed in the double chamber geometry of the Large Scale Vented Combustion Test Facility varying the following parameters: hydrogen concentration, vent area, and vent location. In the mixtures tested, 6%-12% H_2, and 0-30% steam, the overpressures for quiescent tests were very low, less than 45 kPa for mixtures with 9% H_2 or less, and less than 80 kPa for mixtures with up to 12% H_2. The combustion phenomenon at near-lean-limit H_2-air mixtures showed wide variations in combustion pressure history and peak pressure with the same initial conditions, due to inherent combustion instabilities and low burn completeness in this range of compositions. The details of the effects of flame instabilities on the burning process are not yet clearly understood. More tests are underway to examine these effects.

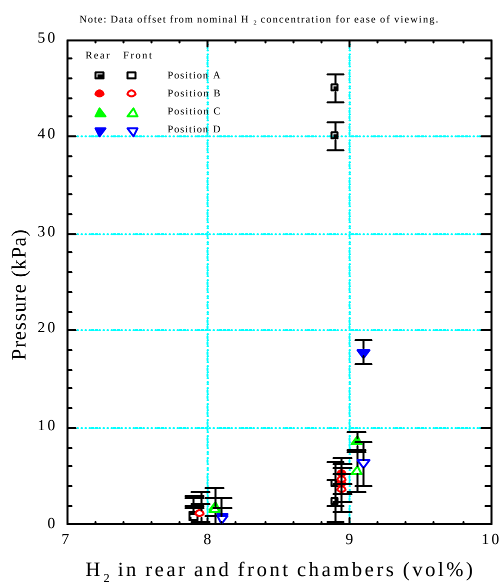

Figure 9. Pressure Peaks for Variation of Internal Vent Location, Pipe Vent 0.19m^2. Inner vent area = 0.19 m^2, outer vent area = 1.1 m^2. Ignition in centre of rear chamber. T = 25°C.

4. Containment Test Facility

The Containment Test Facility (CTF) at AECL Whiteshell Laboratories consists of a 6-m-high and 1.5-m-diameter cylindrical vessel (volume = 10.7 m^3) and a 2.3-m-diameter sphere (volume

= 6.3 m^3). The two vessels can be joined together by a 2.7-m-long pipe with an inside diameter of 0.45 m. The entire system is rated for a pressure of 10 MPa. These vessels are equipped with access ports allowing large pieces of equipment to be installed inside. They are also equipped with a gas sampling and analysis system allowing gases to be monitored from various locations. A 45-cm-diameter vent-tube can be attached to the sphere to allow vented combustion tests to be performed. A large number of test program have been completed using these vessels in the CTF. These programs include a) combustion in non-uniform mixtures, b) combustion in inter-connected vessels, c) combustion with initial turbulence, d) vented combustion, e) flame acceleration induced by obstacles and f) flame jet ignition. Results from flame-jet ignition tests are being outlined here to illustrate the capabilities of this facility.

4.1 Flame Jet Ignition Tests

In an adiabatic constant volume complete combustion, the peak pressure generated is primarily a function of the energy content in the fuel and does not depend on the burning rate. For burning in interconnected vessels, however, the pressure development in the second (downstream) vessel is primarily affected by two parameters. These parameters are pressure relief due to venting in the upstream vessel and the turbulence effects on combustion in the downstream vessel. These two parameters are influenced both by the geometry of the vessels and by the geometry of the opening between them. Since the flow velocity through the opening depends on the pressure differential between the two vessels, the amount of turbulence in the downstream vessel thus depends on the burning in the upstream vessel. When the flame kernel in the upstream vessel finally emerges from the opening, the jet velocity can be very high and can penetrate deep into the downstream chamber. As a result of the penetration of the flame jet, ignition of the gas mixture in the downstream chamber can occur at many locations almost simultaneously. Depending on the structure of the flame jet, the subsequent burning in the downstream vessel can be extremely rapid.

The purpose of this study is to determine the role of flame-jet ignition on the burning rates of near-flammability limits of hydrogen–air mixtures in interconnected vessels. In particular, the project examines combustion behaviour in the downstream vessel as a function of the hole-configuration of the opening between the two vessels. Three types of experiments were performed to determine the burning rates in the sphere caused by spark ignition in the sphere, single-flame-jet ignition and multiple-flame-jet ignition.

4.1.1 Experimental Apparatus

The experiments were performed in the 6.3 m^3 sphere in the Containment Test Facility (CTF). A schematic of the test vessel is shown in Figure 10. It consists of a 2.29-m-diameter sphere (volume = 6.29 m^3) attached to a 2.85-m-long pipe with an inside diameter of 0.45 m (volume = 0.45 m^3). A spark igniter was mounted in the plate at the end of the pipefor the flame-jet ignition tests. For the central ignition tests, a spark igniter was placed at the centre of the sphere. For flame-jet ignition tests, an orifice plate—having a single hole (15 cm in diameter), or a multi-hole (8 holes each 5.65 cm-diameter with an equivalent hydraulic diameter of 16 cm)—was placed between the pipe and the sphere. The gas mixture was ignited in the far end of the pipe.

4.1.2 Ignition at the Centre of Sphere

For comparison purposes the first set of tests was designed to determine the effective burning velocity in the sphere by igniting the mixtures with an electric spark at the center of the sphere. The effective burning velocity was calculated based on the pressure and the rate of pressure rise

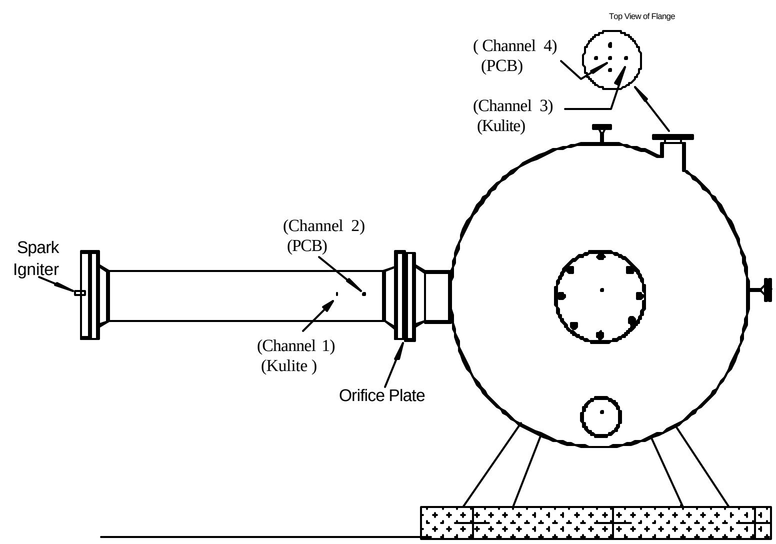

Figure 10. A Schematic of the Experimental Facility for Flame Jet Ignition Tests

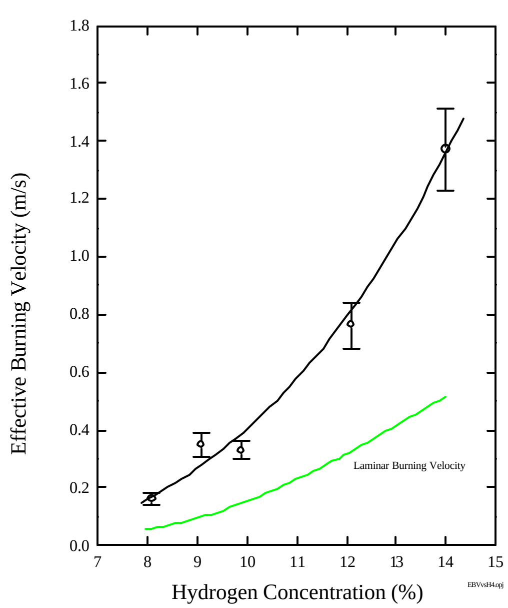

Figure 11. Effective Burning Velocity versus Hydrogen Concentration for Central Ignition.

in the vessel. By assuming that the expanding flame kernel is spherical in shape, an effective burning rate (expressed as the effective burning velocity) can be calculated as the flame kernel expands. The reported values are at the point when the flame radius reaches 0.5 m. These results (Figure 11) show that the value at 8% hydrogen was about 3 times the laminar burning velocity, and at 14% hydrogen about 2.7 times the laminar burning velocity. The effective burning velocity for the central ignition is about three times higher than for the laminar effective burning velocity. The higher values may be caused by flame instability and buoyancy effects. Lean hydrogen-air flames are known to be unstable. At a flame radius of 0.5 m, flame instability may have caused the flame surface to wrinkle, thus increasing its flame surface area and its effective burning rate. Buoyancy effects may also have altered its spherical flame shape. There was some unusual behavior where the 9% value is higher than the 10% value (0.348 versus 0.33 m/s). This discrepancy may be caused by flame instability or by a non-spherical flame shape. The flame kernel for the 9% H2 mixture is more affected by buoyancy and may have a larger surface area and hence a higher burning rate. A non-spherical flame can produce a higher effective burning velocity.

4.1.3 Single-Flame-Jet Ignition Tests

In the flame-jet ignition experiments, the gas mixture was ignited at the far end of the pipe by an electric spark, so it would burn through the pipe and jet into the sphere through the orifice at similar velocities. Two orifices, placed in between the two vessels, a single-hole and an 8-hole (with similar opening area) configuration, were used to create different flame-jet structures. The calculation of the effective burning velocity for these tests also assumes that the flame structure is spherically shaped although it is

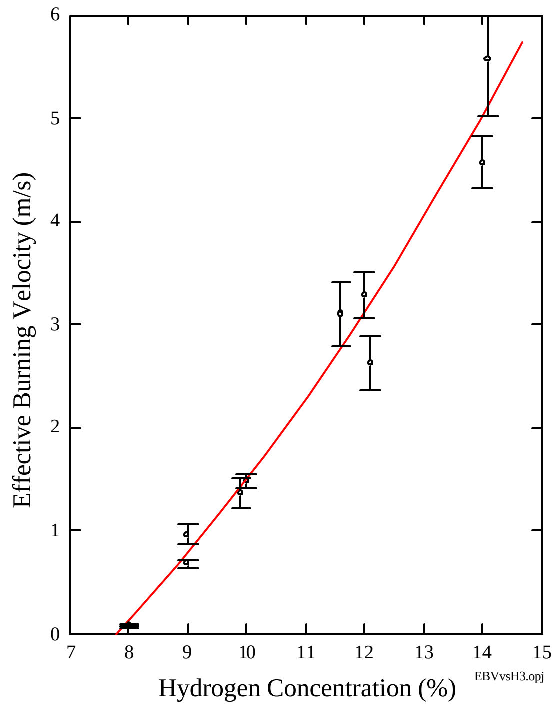

Figure 12. Effective Burning Velocity versus Hydrogen Concentration for Single-Flame-Jet Ignition

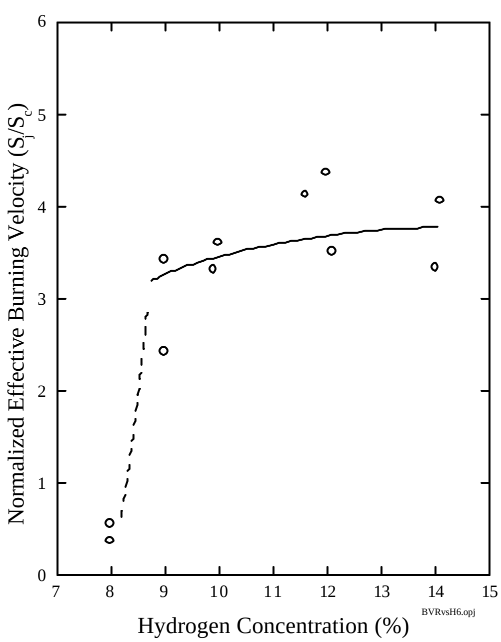

Figure 13. Effective Burning Velocity Ratios (S_j/S_c) versus Hydrogen Concentration for Single-Flame-Jet Ignition

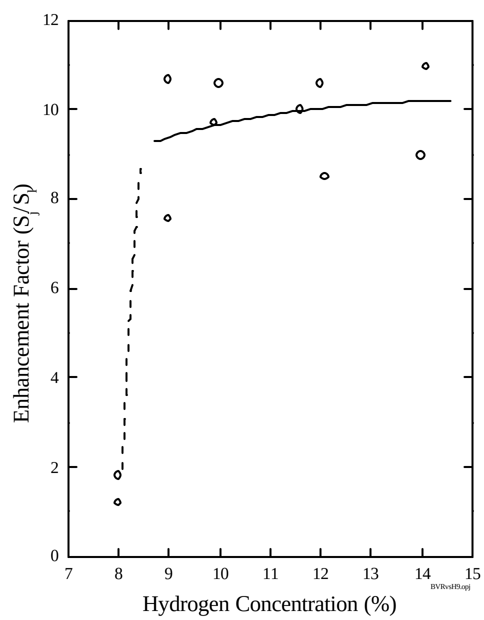

Figure 14. Enhancement Factor versus Hydrogen Concentration for Single-Flame-Jet Ignition

obviously wasn't the case for flame-jet ignition. To have a consistent comparison of the burning velocity for different cases, burning velocities for the flame jet ignition and central ignition would be compared at an equivalent flame radius of 0.5 m .

The effective burning velocities for the jet ignition with single-flame-jet, S_j, and the ratio of effective burning velocity with the flame-jet ignition to the effective burning velocities with central ignition, S_j/S_c are shown in Fig. 12 and Fig. 13. The values for S_c are the fitted values from the central ignition plot shown in Fig. 11. Figure 14 also shows an enhancement factor for flame-jet ignition derived from the ratio of maximum effective burning velocity from jet ignition to the laminar burning velocities of the mixture, S_j/S_l.

At 8% hydrogen, the effective burning velocity for the single-flame-jet ignition was a bit lower than that for the central ignition. From 9% to 14% hydrogen, the effective burning velocities were higher than those of the central ignition, ranging from 2.4 to 4.3 times higher (see Figure 13). The enhancement factor (S_j/S_l) for the single-flame-jet ignition ranged from about 7.6 times (for 9% hydrogen) to about 10.9 times (for 14% hydrogen), as shown in Figure 14. At 8% hydrogen, no enhancement was noticed.

4.1.4 Multiple-Flame-Jet Ignition Tests

The effective burning velocities for the multiple-flame-jet ignition, (S_m), and enhancement factor for flame-jet ignition with multiple jets derived from the ratio of maximum effective burning velocity from flame-jet ignition to the laminar effective burning velocities, S_m/S_l, are shown in Fig. 15 and Fig 16.

At 8% or 9% hydrogen, the effective burning velocities were less than 0.2 m/s. From 10% to

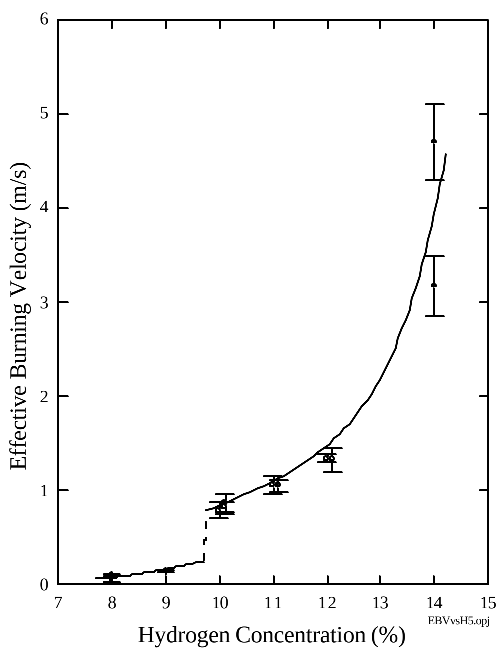

Figure 15. Effective Burning Velocity versus Hydrogen Concentration for Multiple-Flame-Jet Ignition

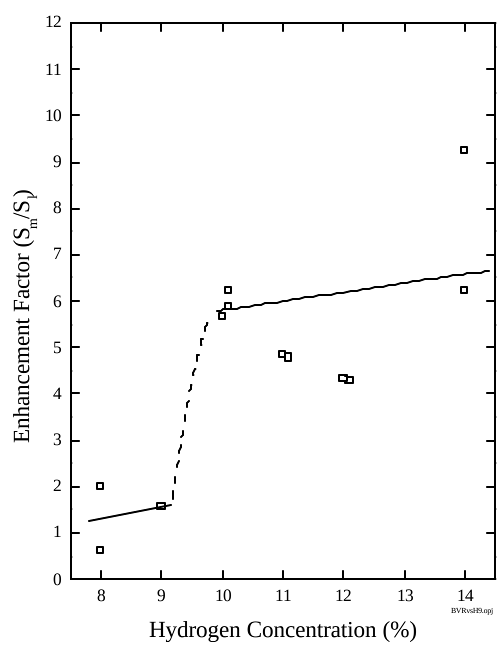

Figure 16 Enhancement Factor versus Hydrogen Concentration for Multiple-Flame-Jet Ignition

14% hydrogen, the effective burning velocities were ranged from 0.9 m/s to 4.0 m/s (see Figure 15). The enhancement factor (S_m/S_l) for the multiple-flame-jet ignition varied from 5.6 (for 10.0% hydrogen) to 9.2 (for 14% hydrogen), as shown in Figure 16. In general, the single-flame-jet ignition caused a larger increase in the effective burning velocity than the multiple-flame-jet ignition. This is probably because a single flame jet may have a large penetration distance and hence a wider ignition zone and higher burning rate.

4.2 Summary

Upon ignition of the gas mixture in the pipe, the flame propagated down the pipe and subsequently emerged into the sphere igniting the gas mixture. Results have shown that depending on the size and configuration of the orifice area and the mixture composition, the combustible mixture in the downstream vessel burned at higher rates. This higher rate is due to the velocity and the structure of the flame jet emerging from the upstream vessel. The single-flame-jet ignition created the highest enhancement factor with results increased by as much as 10.9 for concentrations of hydrogen above 9.0%. Below 9.0%, the hydrogen enhancement factor was found to be below two. This series of flame-jet ignition tests, in a closed vessel system, provides a benchmark. The next phase of the test program will examine the effects of flame-jet ignition in a vented vessel.

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