3.4 THE LARGE-SCALE VENTED COMBUSTION TEST FACILITY AT AECL-WL: DESCRIPTION AND PRELIMINARY TEST RESULTS

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Abstract

Implementation of hydrogen mitigation systems in nuclear reactor containments requires testing the effectiveness of the mitigation system, reliability and availability of the hardware, potential consequences of its use and the technical basis for hardware placement, on a meaningful scale. Similarly, the development and validation of containment codes used in nuclear reactor safety analysis require detailed combustion data from medium- and large-scale facilities. A Large-Scale Combustion Test Facility measuring 10 m x 4 m x 3 m (volume, 120 m^3) has been constructed and commissioned at Whiteshell Laboratories to perform a wide variety of combustion experiments. The facility is designed to be versatile so that many geometrical configurations can be achieved. The facility incorporates extensive capabilities for instrumentation and high speed data acquisition, on-line gas sampling and analysis. Other features of the facility include operation at elevated temperatures up to 150°C, easy access to the interior, and remote operation. Initial thermodynamic conditions in the facility can be controlled to within 0.1 vol% of constituent gases. The first series of experiments examined vented combustion in the full 120 m^3-volume configuration with vent areas in the range of 0.56 to 2.24 m^2. The experiments were performed at ~27°C and near-atmospheric pressures, with hydrogen concentrations in the range of 8 to 12% by volume. This paper describes the Large-Scale Vented Combustion Test Facility and preliminary results from the first series of experiments.

Introduction

Implementation of hydrogen mitigation systems in nuclear reactor containments requires testing the effectiveness of the mitigation system, reliability and availability of the hardware, potential consequences of its use and the technical basis for hardware placement, on a meaningful scale. Similarly, development and validation of many existing containment codes used in nuclear reactor safety analysis require detailed combustion data from medium- and large-scale facilities. To address combustion issues rising from hydrogen production and release, experimental work in medium- and large-scale facilities have been in progress in many organizations. Examples of work done in the medium-scale facilities include combustion experiments in the 6.3-m^3 and 10.3-m^3 Containment Test Facility (CTF) vessels at Whiteshell Laboratories, and the 5-m^3 VGES and 5.6-m^3 FITS cylindrical vessels at Sandia Laboratories [1-4]. Examples of work done in large-scale facilities include combustion experiments in the Battelle Model Containment [5], the HDR facility [6], and the 15.85-m diameter spherical vessel located at the Nevada Test Site (NTS) [7]. Recently, NUPEC has performed hydrogen combustion experiments in their 1/6-scale containment vessel.

In nuclear reactors equipped with deliberate ignition systems, a global hydrogen burn is unlikely. It is more likely that combustion will be initiated in a particular subvolume in the vicinity of the release where flammable mixtures first arise. Overpressures generated by combustion would be relieved by venting to adjacent compartments that contain no combustible gases via existing openings. Credit for the pressure relief by venting is used in the analysis of the integrity of these compartments.

At AECL Whiteshell Laboratories, vented combustion experiments were previously performed in the intermediate-scale 2.3-m diameter CTF sphere. However, the full range of vent ratios (vent area/[vessel volume]$^{2/3}$) of interest (0.1 to 2) could not be achieved. Moreover, questions regarding the effects of size and geometry of the enclosure were not entirely resolved. Design of a new facility was therefore undertaken to address these issues. The requirements for the new Large-Scale Vented Combustion Test Facility (LSVCTF) were:

- accurate control of initial thermodynamic conditions,
- instrumentation capability for validation of 3-D codes,
- variable geometric configuration,
- geometric similarity to actual rooms,
- short duty cycle, and
- easy access to the combustion chamber interior.

This paper describes the LSVCTF at AECL Whiteshell Laboratories, its capabilities, and results of some recent combustion experiments performed in the facility.

Description of the Facility and Instrumentation

Facility Description

Figure 1 shows a schematic of the facility. The LSVCTF is a 10-m long, 4-m wide, 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 frame work 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 up the vessel for internal modifications or to move-in bulky experimental equipment when needed. The whole facility, 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 (see Fig. 2), which houses the gas analysis and hydraulic fan systems on one side and all the valves and piping on the other side.

The end walls are covered with rectangular steel plates measuring 0.37 m by 0.74 m bolted to the end wall structure. The vent area can be changed by removing or replacing the appropriate number of panels.

The combustion chamber can be subdivided into 2 or 3 compartments using structural steel partitions. These partitions also have openings to allow internal venting. The partitions can be installed or removed in about one day.

A large number of penetrations are provided for mounting the required instrumentation in the vessel. These provide a means of varying the transducer locations for optimum transducer response.

Eight hydraulic fans, four on each side wall, are installed in the combustion chamber to mix the gases uniformly.

The facility is located in a fenced area and is remotely operated to ensure operator safety.

Instrumentation

Pressure and Temperature Measurement

The facility is designed to accommodate extensive instrumentation. Up to 144 channels of transient temperature and pressure data can be obtained at sampling rates ranging from 10 to 100 kHz, making it possible to acquire data from a variety of combustion experiments; from slow recombiner tests that last over several hours to fast turbulent vented deflagration tests that only last for several hundred milliseconds.

A schematic of the instrumentation employed in the present series of experiments is shown in Fig. 3. Transient pressures in the vessel were measured by six Kulite HEM-375 and XTME-190-high temperature pressure transducers. Because of the long combustion times, the transducers had to be protected from thermal loading. This was done by recess-mounting the transducers. Additional thermal protection of XTME-190 type of transducers was achieved by coating the transducer diaphragm with a thin layer of RTV.

Because of the very low pressures attained in this series of experiments, the pressure signals had a high degree of instrument and transducer noise. These were filtered out using a Fast Fourier Transform (FFT) filter. In all experiments, the outputs from HEM-375 and XTME-190 transducers were in good agreement.

Thirty fine-wire, type-S, thermocouples were installed along three principle axes to track the progression of the flame. Approximate flame shapes and flame speeds could be deduced from the flame arrival time versus thermocouple distance data. Signals from the thermocouples and pressure transducers were amplified, digitized, and stored on a hard drive for analysis and archiving. The amplifiers used for amplifying the signals were located in an adjacent building located ~30 m away from the combustion chamber.

Gas Analysis System

Accurate measurement of hydrogen concentrations in the combustion chamber is important in obtaining reproducible combustion behaviour, which is essential in interpreting the experimental data and in validating codes.

A mass-spectrometer with a 32-channel sampling capability is used to measure the hydrogen, air, and steam concentrations. Using this mass spectrometer the gases in the vessel, including steam, can be analysed to a precision of 0.1% or better. The mass spectrometer requires between 5 and 30 s for the analysis of each sample, depending on the number of gases and the required accuracy. The gas sampling lines are commercially available, electrically trace-heated and insulated, and enable steam concentrations in the combustion chamber to be measured accurately. A steam calibration system has been developed to provide steam for calibrating the mass spectrometer. The mass-spectrometer can detect any gas, provided it is first calibrated with a representative gas mixture.

Experimental Procedure

Safety, Quality Assurance and Documentation

To ensure operator safety and integrity of the facility, a detailed safety analysis report and standard operating procedures were prepared; employing advice from explosives consultants and human factors experts. To guide production of consistent, verifiable output from the facility, a quality assurance manual conforming to ISO Guide-25 documents was also prepared.

Facility Preparation

For vented combustion tests, the required number of steel vent panels are removed and the openings are covered with a thin aluminum foil. To prevent heat losses, the openings are further covered with light insulating panels.

Gas addition to the combustion chamber is performed from the remote control building, following a rigorous procedure to clear the fenced test area. During hydrogen addition, the mixing fans are automatically turned on so that hydrogen released into the combustion chamber mixes uniformly with air. The gas concentrations in the combustion chamber are monitored continuously on the mass spectrometer output during the addition of gases. When the gas addition is complete and the desired gas concentrations are reached, the mixing fans are operated for a further period of 2 min. The fans are then turned off and the power to the igniter turned on.

Figure 4 shows a typical plot of hydrogen concentration at three different locations. This figure shows that hydrogen concentration in the vessel is uniform during the addition.

In the tests reported here, a TAYCO glow-plug igniter located at the centre of the combustion chamber, operated by a 120-V supply line, was used. The data acquisition system was triggered by a fine-wire thermocouple located in the vicinity of the igniter. For most of the experiments, a sampling frequency of 1 kHz was used.

Results and Discussion

Scope of Investigation

All the tests reported here were performed at an initial temperature of ~27°C and at near-atmospheric pressures. Hydrogen concentrations in the range of 8 to 12% were studied. Central ignition was chosen for the initial tests. Three vent areas – 0.56, 1.12 and 2.24 m^2 – were investigated.

Pressure Transients and Peak Pressures

The following section describes results from selected tests illustrating the essential capabilities of the facility, accuracy of measurements and typical test outcomes.

For mixtures containing less than 8.5% hydrogen, the pressure rise due to combustion was small. The flame propagation below 10% hydrogen concentration is non-isotropic and is significantly influenced by buoyancy. Between 8.5 and 9% hydrogen, the flame propagation is first upwards and then downwards [8]. Fig. 5 shows the pressure transient at 8.5% hydrogen concentration. Three pressure peaks can be observed. The first two peaks correspond to the instant of rupture of the foil covering the vents and the instant of burnt gas venting respectively. The third peak corresponds to the final pressure realized by combustion. The peak pressure observed at 8.5% hydrogen is only about 1.5 kPa. This low pressure is expected because, for hydrogen concentrations below 9%, the burn fraction has been shown to be low [8] and the duration of combustion on the order of several seconds, allowing large pressure relief by venting.

Figure 6 shows the pressure transient for a 9% hydrogen mixture and a vent area of 0.56 m^2. In this case, there are three small peaks and a much larger fourth peak. The small peaks correspond to the vent panel rupture and the burnt gas venting, whereas the large peak corresponds to the final pressure realized by the hydrodynamic instabilities developing in the flame. Similar behaviour was observed for a 10% hydrogen mixture.

For vent areas of 1.12 and 2.24 m^2 and hydrogen concentrations of 11 and 12%, the pressure transients in the vessel exhibited pressure oscillations. Figure 7 shows the pressure transient registered by one of the transducers for a hydrogen concentration of 11% and a vent area of 1.12 m^2. The maximum pressure recorded in this series, about 35 kPa, occurred for a hydrogen concentration of 12% and a vent area of 0.56 m^2.

Effect of Scale and Geometry

It has been pointed out by Solberg et al. [9] that the overpressure in a vented deflagration depends on the scale of the confining vessel. From this point of view, it is interesting to compare the present results with the peak pressures measured in the 2.23-m diameter spherical vessel [10]. Figure 8 shows the peak pressures plotted as a function of the vent parameter, $A_v / V^{2/3}$ (where A_v = vent area, V = vessel volume), for both cases. The peak pressures measured in the 2.23-m diameter vessel (CTF) are higher than those measured in the LSVCTF. Though at first sight this behaviour may appear to be unexpected, it can be explained. It should be noted that the rate of pressure rise and thus the peak pressure in a vessel depends on the rate at which the flame surface area increases with time. Whereas in a spherical vessel, the flame surface area steadily increases with time (for a central ignition), in a vessel of rectangular geometry the flame surface area increases only until the flame touches the side walls. The flame surface area either decreases or remains constant after this. Calculations using VENT [11] show that, other factors being the same, this is indeed what happens.

Flame Speed Calculations

As mentioned previously, fine-wire thermocouples were installed along the three principal axes to track the flame movement. Tracking of the flame front provides a means of arriving at the flame shape as a function of time and of estimating the flame speeds. The instrumentation in this series of experiments provides only approximate flame shapes. A more extensive thermocouple arrangement is intended for future tests.

Figure 9 shows the typical thermocouple traces of two thermocouples installed along the axis, for an 11% hydrogen/air mixture. The flame arrival times can be determined from these traces fairly accurately. There is an abrupt increase in the temperature registered by the thermocouple when a flame contacts it.

Figures 10 and 11 show the flame arrival time plotted as a function of distance for flame fronts propagating in the direction of the vent and in the direction opposite to the vent. A third degree polynomial was fitted through the data points which was then differentiated to yield the flame speeds. The flame speed in the direction of the vent is much higher than that in the opposite direction by about a factor of five. The results are similar for other concentrations and vent areas.

Since the laminar burning velocity of a 11% hydrogen/air mixture is only about 0.3 m/s, the maximum expected flame speed in the direction away from the vent, based on expansion ratio of 4, is about 1.2 m/s. From Fig. 11, this is the initial flame speed calculated from the flame arrival time data. However, beyond 7 s, a short time after the burnt gas venting starts, the flame speed increases fairly rapidly, reaching about 4.5 m/s towards the end of combustion duration. This flame speed corresponds to a burning velocity of about 1.2 m/s, which is 4 times the laminar value. Such an increase in the burning velocity is possible only through flame front instabilities and wrinkling of the flame.

While the flame propagation can be highly turbulent in one direction, it could still be laminar in other directions. For example, Fig. 12 shows the flame speeds in the upward and sideways directions. In these directions, the flame speeds decrease with time indicating that burning velocities are decreasing. This is plausible because the flame propagates in an adverse velocity gradient. As well, the flame stretching causes burning velocity to decrease.

In the discussions presented above, only a selected few experiments were chosen to demonstrate some of the combustion behaviour. At the time of writing, the facility has been operating for only two months. Further work is required to come to definitive conclusions.

Future Work

The experimental work performed to date has provided knowledge of the duty cycle for operation of the facility and fine-tuning of the instrumentation and measurements. An ambitious experimental program is in place for the coming months. This program will study the effects of elevated initial temperatures, steam dilution, igniter location, initial turbulence, scaling, and flame propagation from one compartment to another. These experiments will provide an understanding of the combustion behaviour in large volumes and a database for validating the combustion models in our containment codes.

Conclusions

A large-scale vented combustion test facility has been constructed, instrumented, and commissioned to perform a variety of combustion experiments relevant to hydrogen behaviour in nuclear containments and meet the needs for codes predicting hydrogen combustion behaviour. Experience in operating the facility indicates that the facility is versatile, easy to operate, and that the gas concentrations in the combustion chamber can be maintained and measured very accurately. Instrumentation and facility modifications can be performed quickly due to easy access to the interior of the combustion chamber.

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References

1. Kumar, R.K., Tamm. H., and Harrison, W.C., "Studies in Hydrogen Combustion in an Intermediate-Scale Test Facility," Atomic Energy of Canada Limited Report, AECL-7814, January (1984).

2. Marshall, W., Jr., "Hydrogen:Air: Steam Flammability Limits and Combustion Characteristics in the FITS Vessel," Sandia National Laboratories Report SAND84-0383, December (1986).

3. Benedick, W.B., and Cummings, J.C., "Combustion of Hydrogen: Air Mixtures in the VGES Cylindrical Tank," Sandia National Laboratories Report SAND83-1022, May (1984).

4. Takumi, K., Nonaka, A., Moria, K., and Ogata, J., "Proving Test on the Reliability for Reactor Containment Vessel (2) Hydrogen Burning Test," proceedings of the workshop on *Hydrogen Behaviour and Mitigation in Water-cooled Nuclear Power Reactors*, Brussels (Belgium), March 4-8 (1991).

5. Kanzleiter, T.F., "Multi-Compartment Hydrogen Deflagration Experiments in the Battelle-Model Containment," proceedings of the 17th Water Reactor Safety Information Meeting, Rockville, MD, October (1989).

6. Wolf, L., Rastogi, A., Wennaberg, D. and Fogt, H., "Hydrogen Deflagration Experiments in the HDR-Three Subcompartment Geometry and Comparison with Computational Results," The Third International Conference on Containment Design and Operation, Toronto, ON, October 19-21 (1994).

7. Ratzel, A.C., "Data Analyses for Nevada Test Site (NTS) Premixed Combustion Tests," Sandia National Laboratories Report, SAND85-0135, May (1985).

8. Kumar, R.K., Tamm, H., and Harrison, W.C., "Combustion of Hydrogen-Steam-Air Mixtures Near Lower Flammability Limits," *Combust. Sci. and Tech.* 33, pp. 167-178 (1983).

9. Solberg, D.M., Pappas, J.A., and Skramstad, E., "Observations of Flame Instabilities in Large Scale Vented Gas Explosions," presented at the *Eighteenth (International) Symposium on Combustion,* August 17-22 (1980).

10. Kumar, R.K., Dewit, W.A., Greig, D.R., "Vented Explosion of Hydrogen-Air Mixtures in a Large Volume," *Combust. Sci. and Tech.* 66, pp. 251-266 (1989).

11. Mulpuru, S.R., and Wilkin, G.B., "A Model for Vented Deflagration of Hydrogen in a Volume," Atomic Energy of Canada Limited Report, AECL-6826, (1981).

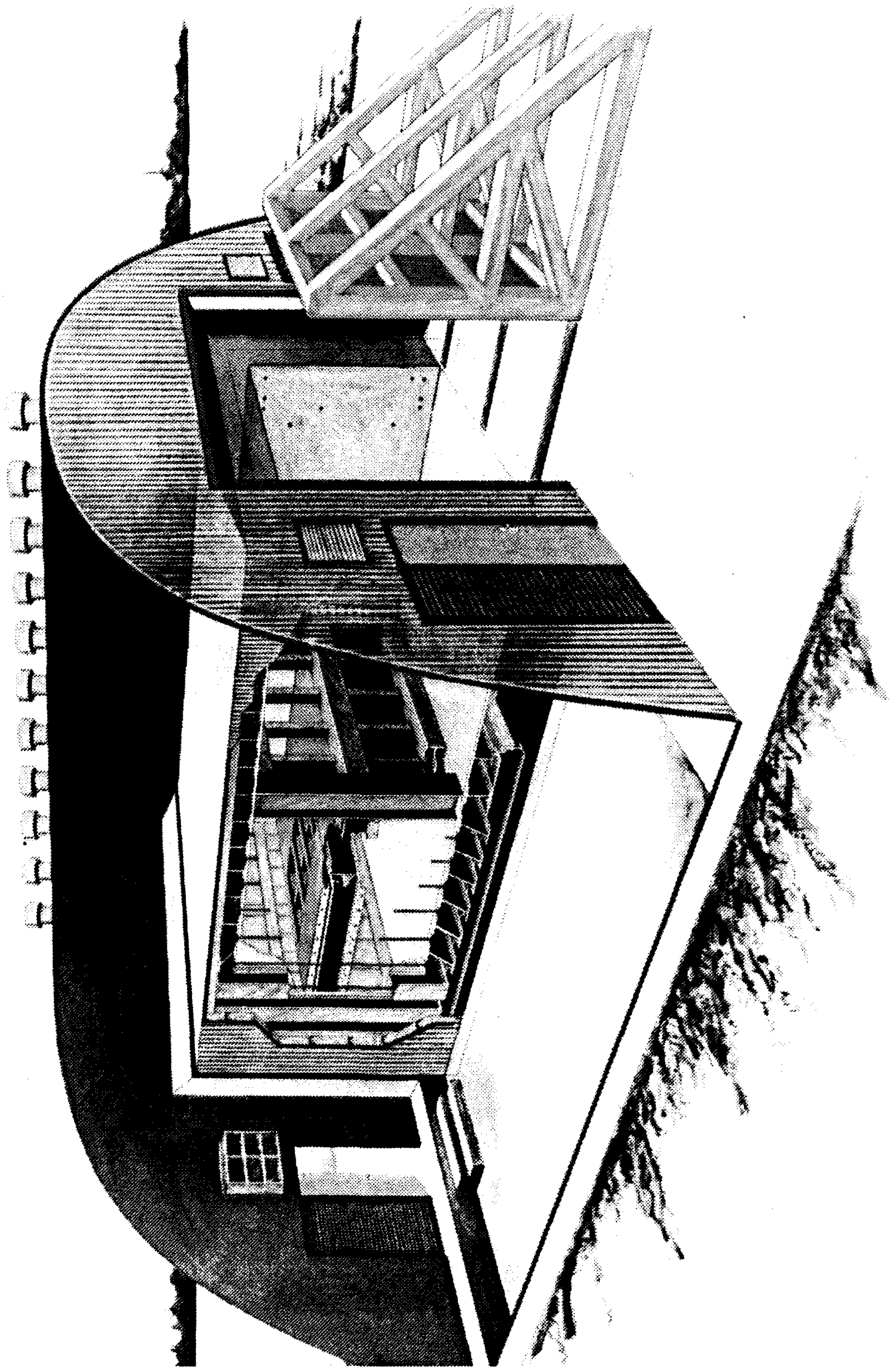

Figure 1: Schematic of the Large-Scale Vented Combustion Test Facility (LSVCTF)

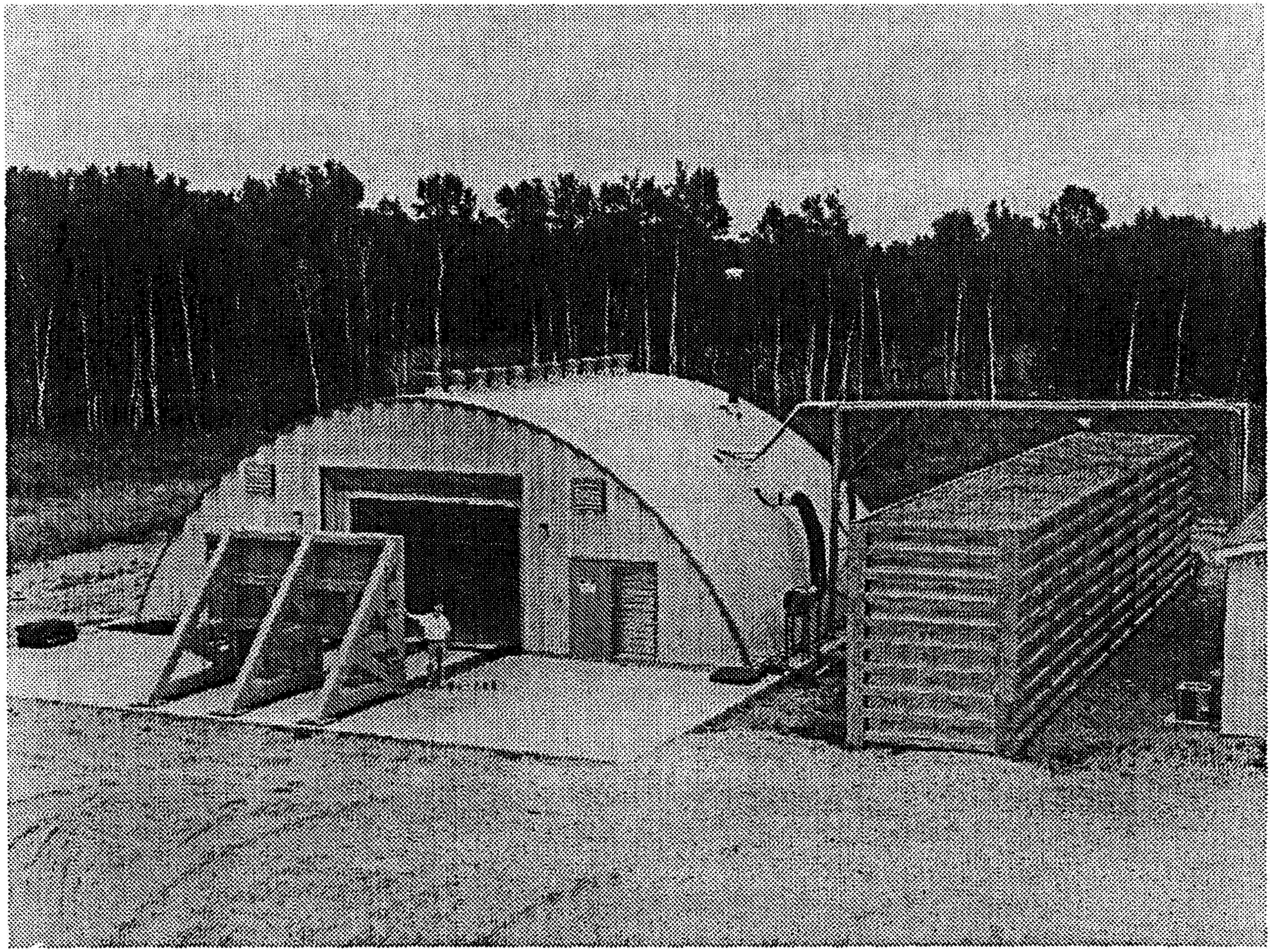

Figure 2. A View of the Large-Scale Vented Combustion Test Facility

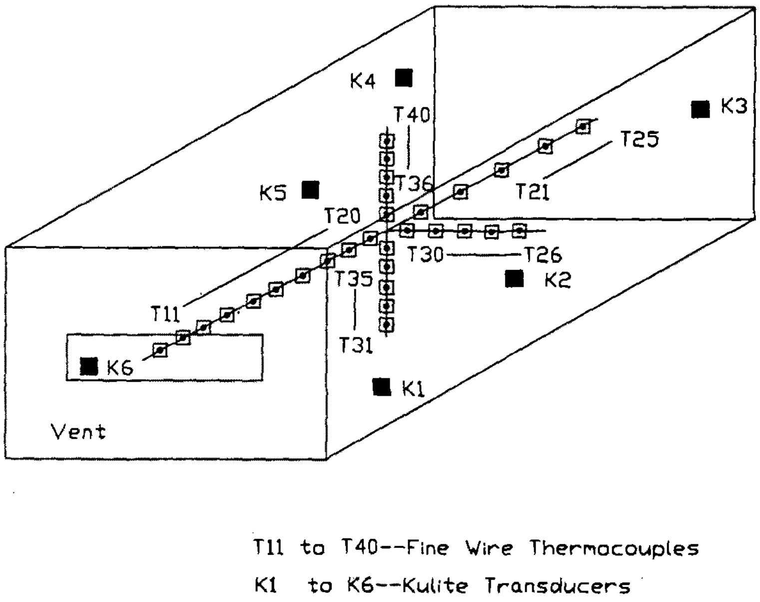

Figure 3. Schematic of the LSVCTF Instrumentation

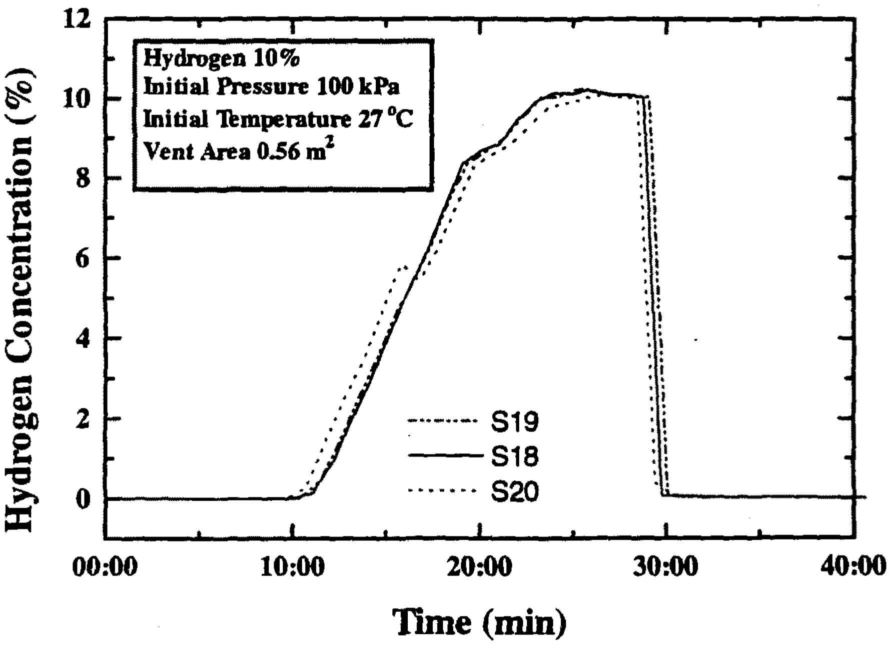

Figure 4. Hydrogen Concentrations at Various Sampling Ports in a Typical Test

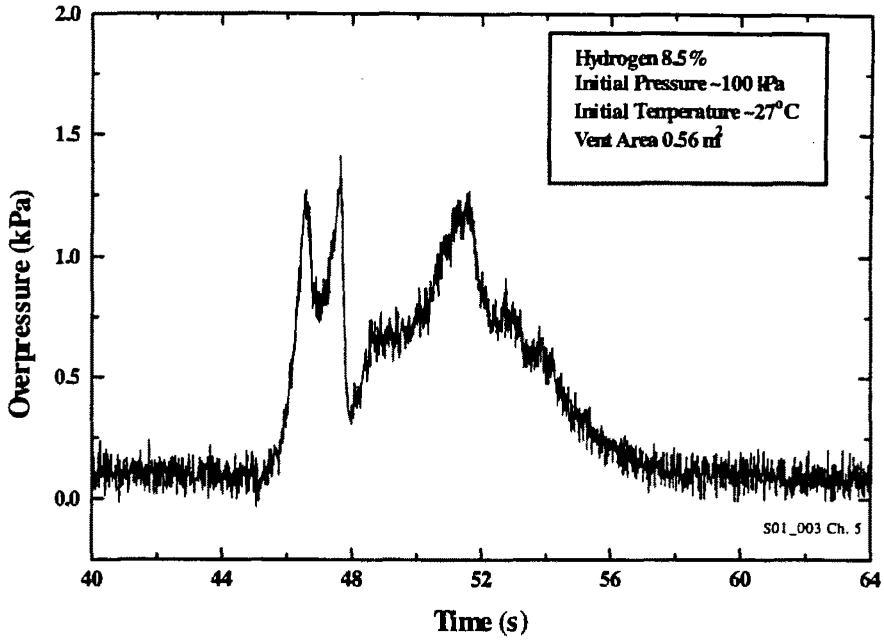

Figure 5. Pressure Transient in an 8.5% Hydrogen/Air Mixture

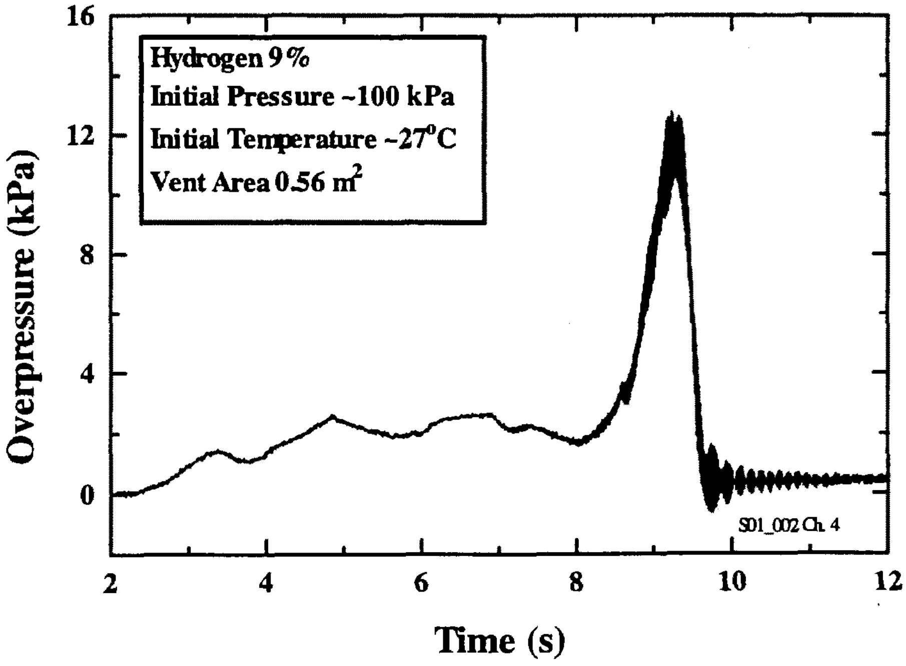

Figure 6. Pressure Transient in a 9% Hydrogen/Air Mixture

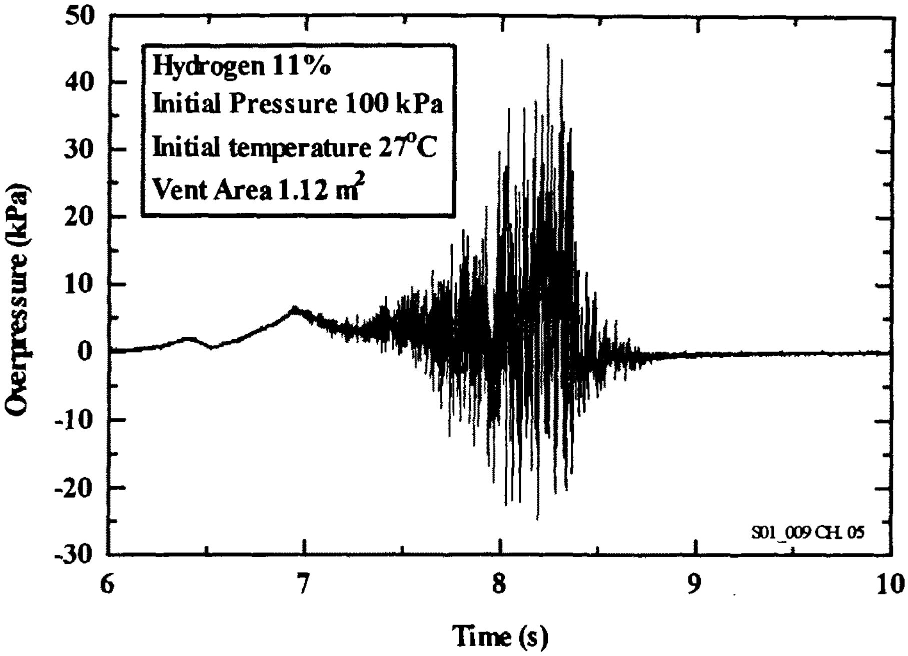

Figure 7. Pressure Transient in an 11% Hydrogen/Air Mixture. Large oscillations occur after the burnt gas venting begins

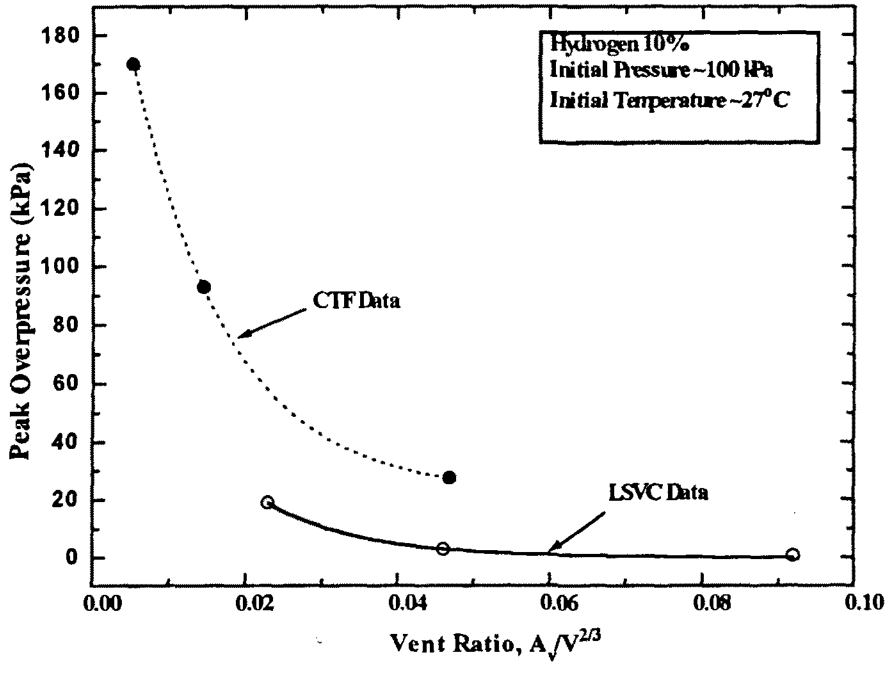

Figure 8. Comparison of CTF and LSVC Peak Overpressures

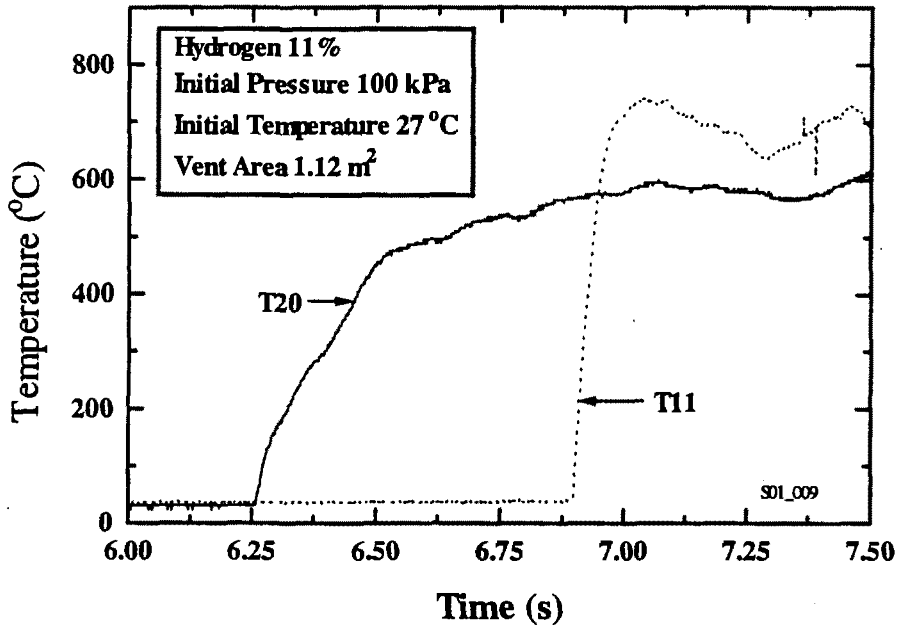

Figure 9. Typical Temperature Traces Recorded by Fine-Wire Thermocouples

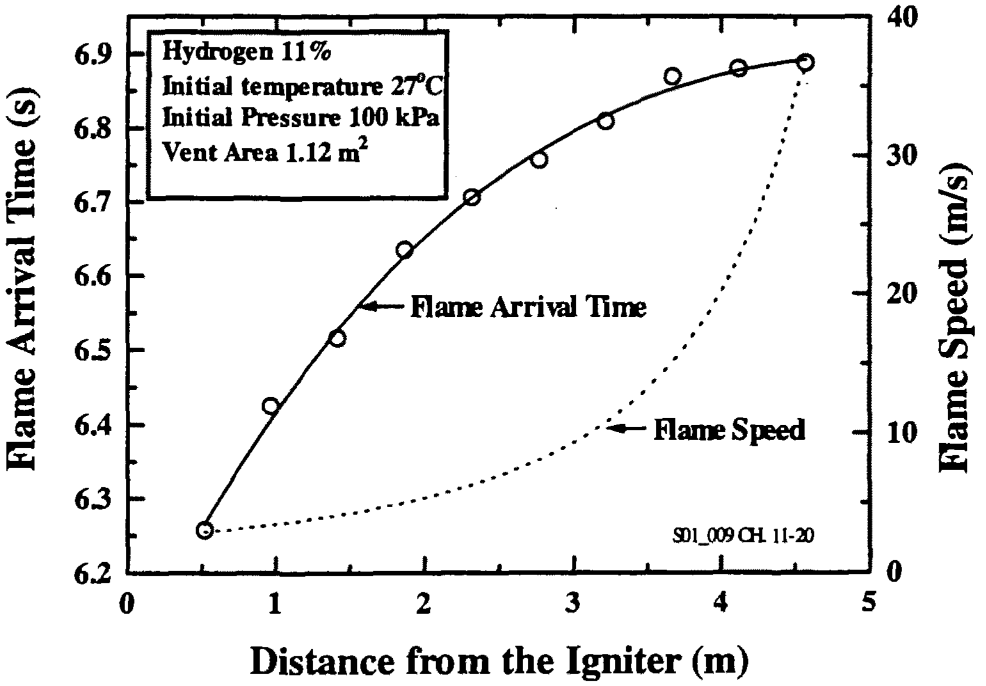

Figure 10. Flame Arrival Time and Flame Speed in the Direction of the Vent

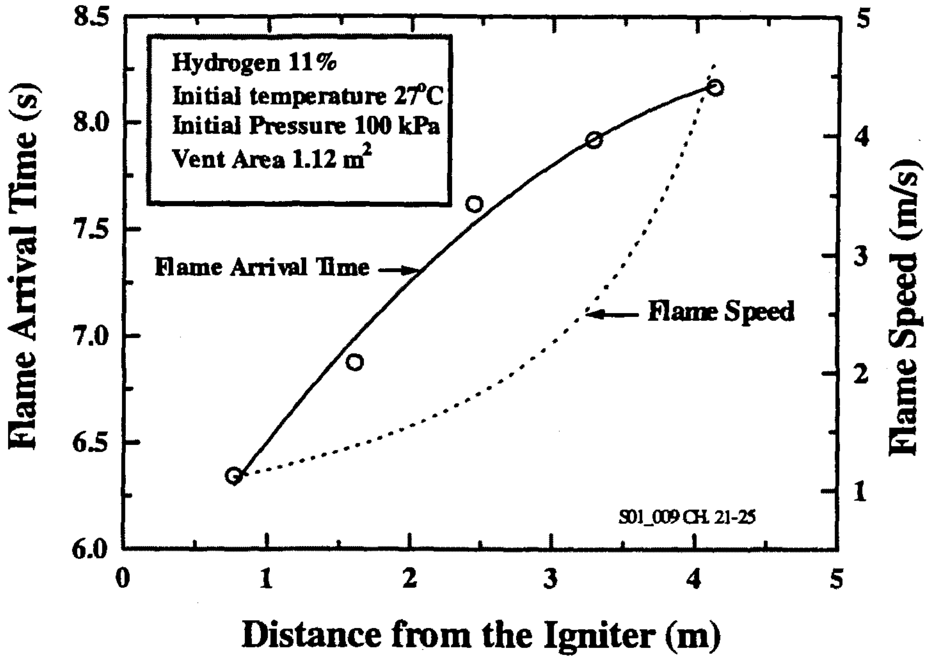

Figure 11. Flame Speeds in the Direction Away from the Vent

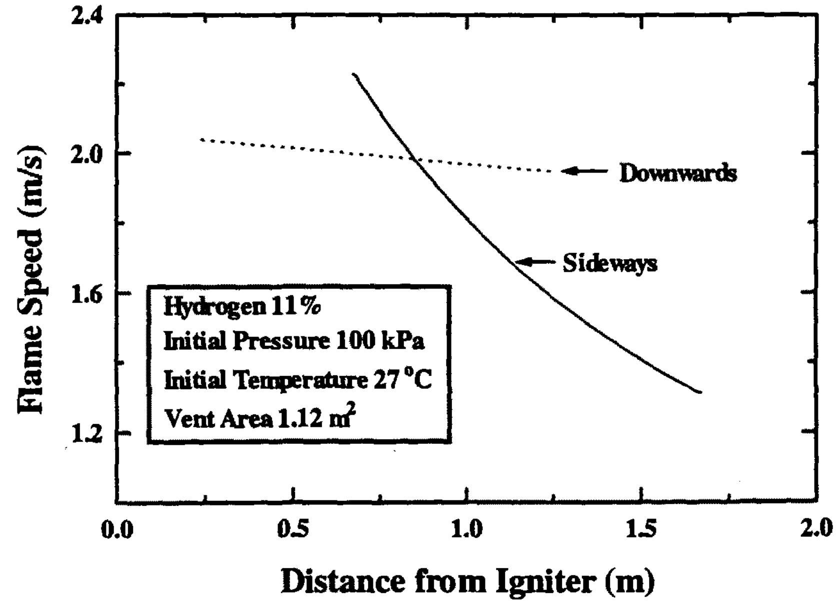

Figure 12. Flame Speeds in the Downward and Sideways Directions