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INITIAL HYDROGEN DETONATION DATA FROM THE HIGH-TEMPERATURE COMBUSTION FACILITY*

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ABSTRACT

The Brookhaven National Laboratory High-Temperature Combustion Facility (HTCF) is described and data from initial hydrogen detonation experiments are presented. The HTCF was designed to provide a capability to investigate detonation phenomena characteristics of hydrogen-air-steam mixtures at initial temperature up to 700K and initial pressures up to 3 atmospheres. The Large Detonation Vessel used in the experiments is a 27-cm diameter, 21.3-m long, stainless steel detonation tube, constructed in modular 3.05-m long sections. The vessel can be heated to 700K in five hours to a uniformity of $\pm$14K.

The initial phase of the inherent detonability experimental program is described. Detonations are initiated in hydrogen-air test mixtures using an oxyacetylene gas driver system, together with a high-voltage capacitor discharge system. Test gases thus far tested are hydrogen-air mixtures at one atmosphere initial pressure and temperatures in the range 300K-650K. Measurements of detonation pressure, wave speed, and detonation cell size have been made.

The data from these experiments are consistent with the earlier SSDA test results. The HTCF results confirm the conclusion from the SSDA program that the effect of gas temperature is to decrease the cell size and, therefore, to increase the sensitivity of mixtures to undergo detonation. The data from the larger HTCF test vessel, however, also demonstrates that the effect of increased scale is to extend the range of detonable mixtures to lower concentration.

Additional data will be obtained at several temperatures for leaner mixtures of hydrogen and air, and the detonability limits will be obtained. Experiments with steam will be conducted at 400K-650K, with steam content up to about 50 percent steam. Cell size data will be obtained for high-temperature mixtures in order to provide an extensive database for assessment of the Zel'dovich-von Neumann-Doring (ZND) model for detonation cell size.

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1. INTRODUCTION

The Brookhaven National Laboratory (BNL) High-Temperature Combustion Facility (HTCF) has been constructed as an experimental research tool for the purpose of characterizing the influence of elevated gas mixture temperature on:

- the inherent sensitivity of hydrogen-air-steam mixtures to undergo detonation,
- the potential for deflagration-to-detonation transition (DDT),
- the phenomena of hot jet initiation of detonation, and
- detonation transmission.

Previously, high-temperature gaseous detonability data, and their interpretation, have been presented from experiments conducted in the BNL Small-Scale Development Apparatus (SSDA) [1]. The HTCF was designed to study a broader range of test conditions, which required a larger-scale test apparatus than the SSDA. Table 1 shows the range of conditions which are the focus of the experimental program in the HTCF.

This paper presents a description of the facility, describes the initial inherent detonability test program, and presents results of experiments performed as part of the initial phase of the planned testing program.

2. DESCRIPTION OF THE HTCF

The HTCF consists of the Large Detonation Vessel (LDV) and the support facilities which are required in order to perform high-temperature detonations within the test vessel. Figure 1 is a schematic of the HTCF site, and Figure 2 is a photographic view of the site. Table 2 summarizes the essential systems of the facility and the work that was performed in order to support the experimental effort. The schematic diagram shows the LDV located within a 10-ft diameter underground tunnel and shows the various support systems which are located at the site, including the gas storage pad, electrical distribution house, and vacuum house. Figure 2 shows these structures along with the ventilation and gas purging equipment located over the tunnel.

The central feature of the facility is the Large Detonation Vessel (LDV), a 27-cm diameter, 21.3-m long, stainless steel detonation tube, constructed in modular, flanged, 3.05-m long sections. Figure 3 is a photographic view of the vessel within the tunnel. The Maximum Allowable Working Pressure of the LDV, fabricated to ASME Boiler Code requirements, is 100 atm. The vessel is electrically heated using heating blankets which surround the tube and the flanges and was designed to operate at a maximum temperature of 700K and with a temperature uniformity of $\pm$14K. The HTCF is capable of serving as a test vehicle for detonation experiments using gaseous mixtures of hydrogen, air, and steam at initial pressures up to 3 atm and initial temperatures up to 700K. Additional gases, such as nitrogen, carbon monoxide, carbon dioxide, and oxygen, can also be introduced as components of the test mixtures.

Figure 4 is a schematic of the instrumentation configuration of the LDV. Instrumentation includes distributed thermocouples (TC), ion probes (IP) to measure flame front position vs. time, pressure transducers (PT) to measure detonation pressure, pressure transducers (PS) to measure initial vessel pressure, and sampling ports to permit measurement of initial composition. Detonation cell width is

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measured using smoked foils, which are carbon soot coated foils of aluminum inserted into the test vessel prior to an experiment. When a detonation wave passes over the foil, it leaves a pattern of cells imprinted on the foil, from which a measure of cell size can be obtained. The available instrumentation provides measurements of detonation wave speed, detonation pressure, and detonation cell width.

The inherent detonability test program requires initiation of a detonation in a gaseous test mixture of hydrogen, air, and steam. Measurement of the detonation characteristics as the detonation propagates along the test vessel is also required. In the BNL program, detonations are initiated using a "gaseous driver system," described below in more detail. Figure 4 shows a schematic representation of the driver gas system. Oxygen and acetylene are mixed, and the mixture is used as the driver gas. A pair of electrodes penetrate the vessel into the driver gas mixture. A high-voltage discharge circuit (not shown) is used to discharge a capacitor across the electrodes, thereby initiating a detonation in the oxyacetylene mixture.

Figure 5 is a schematic of the gas delivery system, which shows the method of introduction of combustible test mixture in the test vessel. Sources of hydrogen, air, steam (and nitrogen for purging purposes) are available. The gases are supplied, controlled, and metered using choked venturis and flow through the mixing chamber, where they form a homogenous mixture. The gases are preheated to the desired temperature prior to entering the test vessel through the end flange. The gas concentrations are determined by ratio of the volumetric flowrates and are checked by sampling and gas chromatography.

3. INHERENT DETONABILITY EXPERIMENT DESCRIPTION

The initial phase of the HTCF test program addresses the effect of temperature on the sensitivity of gaseous mixtures to undergo detonations and on the limits of detonability of the HTCF test vessel. An experimental run begins with drawing a vacuum on the test vessel and preheating the vessel to the desired temperature. Upon reaching the desired temperature, the gas delivery system, shown schematically in Figure 5, is activated remotely at a computer-control console. Gases are metered and heated and delivered at the desired temperature and composition into the test vessel, and the gases fill the vessel to the desired initial pressure. A small volume of driver gas is then delivered to the initiation end of the LDV, and the detonation firing circuit initiates a detonation in the oxyacetylene mixture. The detonation propagates in the driver gas which is about 2-3 meters long and transmits the detonation to the test mixture of hydrogen, air, and steam. The detonation in the test gas then propagates down the remaining 15 meters of the vessel.

Measurements are made of the detonation cell width and detonation wave speed, which provide the necessary data for assessment of mixture sensitivity and (lean) detonability limits. The cell size data are compared with predictions based upon the ZND detonation model [2], and the wave speed data are compared with Chapman-Jouget (C-J) [3] calculations.

4. INHERENT DETONABILITY EXPERIMENTAL RESULTS

As indicated in Table 1, experiments are conducted in the HTCF using hydrogen-air-steam mixtures with compositions up to 50 percent hydrogen (all compositions are by volume), steam fractions greater than 30 percent, initial pressure in the range 1 to 3 atm, and initial temperature between 300K-650K. (Temperatures greater than 650K could not be tested because of observed preignition chemical reactions.)

Initial Cold Detonation Experiments

The HTCF test program was initiated with experiments using mixtures of hydrogen and air at one atmosphere and at 300K. Hydrogen composition varied between 14 percent and 50 percent. The objective of these early "cold" experiments was to establish that the data are consistent with results obtained from experiments reported previously in the literature and to determine the limits of detonability of the HTCF vessel at 300K. The speed of the detonation wave was constant along the vessel and also was in agreement within 2 - 3 percent of the detonation speed predicted by the C-J theory, as shown in Figure 6. Figure 7 shows that the detonation cell width data are in good agreement with previous data, both from the BNL Small-Scale Development Apparatus experiments and from experiments performed at other laboratories. These results indicate that the detonations are stable and fully developed and, therefore, that the method of initiation of the detonation is successful at cold temperatures. Additional data demonstrates that the lean limit for detonation of hydrogen-air mixtures at 300K in the Large Detonation Vessel (270-mm diameter) is 14 percent hydrogen, compared with 16 percent hydrogen in the SSDA vessel (100-mm diameter).

Thermal Calibration Experiments

Thermal calibration experiments were performed to measure and document the temperature uniformity of the LDV. A total of 55 thermocouples were used to measure the temperature distribution along the entire length of the vessel. The thermocouples were placed on the inside and outside surfaces of the vessel, at locations representative of all major structural elements of the vessel. The vessel was heated to 500K and to 650K in approximately 5 hours, at which time the final temperatures were recorded. The experimental data demonstrates that the temperatures reached steady-state conditions and that the uniformity specification of $\pm$14K was satisfied.

Additional Operational Testing

Extensive testing was performed to measure and document the gaseous mixture composition along the axis of the LDV. These experiments have led to the conclusion that the uniformity of hydrogen concentration along the vessel axis is acceptable. Additionally, extensive gas driver detonation initiation system testing was performed to demonstrate that the minimum quantity of driver gas was being used.

Initial Heated Detonation Experiments

Initial heated detonation experiments were carried out with hydrogen-air mixtures at 500K and at 650K. The preliminary results for detonation velocity and cell size are shown in Figures 8 and 9. The results indicate that the detonation velocities agree with the C-J calculations and that the detonation wave speed agrees with data from the SSDA experiments.

5. SUMMARY AND FUTURE PLANS

The HTCF has been completed, operational testing has been completed, and the inherent detonability experimental program has been initiated.

Detonation experiments at 300K have been performed. Within the applicable range of hydrogen concentrations, detonation wave speed and detonation cell size data from the LDV are consistent with the SSDA test vessel. Preliminary high-temperature detonation experiments have been performed at 500K and at 650K, with mixtures of hydrogen and air. The data from these experiments are also consistent with the earlier SSDA test results. The HTCF results confirm the conclusion from the SSDA program that the effect of gas temperature is to decrease the cell size and, therefore, to increase the sensitivity of mixtures to undergo detonation. The data from the larger HTCF test vessel, however, also demonstrates that the effect of increased scale is to extend the range of detonable mixtures to lower concentration.

Much additional data will be obtained in the inherent detonability test program. Additional data will be obtained at all temperatures for leaner mixtures of hydrogen and air, and the detonability limits at all temperatures tested will be obtained. Experiments with steam will be conducted at 400K-650K, with steam content up to about 50 percent steam. For each hydrogen-air ratio tested, the steam detonability limit will be determined. Cell size data will be obtained over a broad range of conditions in order to provide an extensive database for assessment of the ZND model for detonation cell size.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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Table 1 - Experimental Conditions for HTCF Large Detonation Vessel

PARAMETER	RANGE
Temperature	300 K - 650 K
Scale	27-cm diameter (10 cm - SSDA)
Pressure	1 - 3 atm
Mixtures*	< 15% hydrogen at 300K < 11% hydrogen at 500K < 10% hydrogen at 650K
Steam Dilution	> 30% steam, off-stoichiometric mixtures

*Mixtures with greater hydrogen content were the focus of the SSDA experiments.

Table 2 - Major Systems of the High-Temperature Combustion Facility

FACILITY SYSTEM	WORK PERFORMED
Large Detonation Vessel	Vessel fabricated to BNL specs to satisfy research objectives; installed, integrated with other systems and tested
Electrical Power Supply System and Vessel Heating System	Connection to preexisting high-voltage power transformer; switchgear, distribution hardware and enclosure designed and built; vessel heating system designed, tested, installed with vessel
Gas Storage and Handling System	Gas storage pad, gas pipe distribution and gas handling and metering equipment designed, installed, tested
Vacuum System	Existed previously; connections made to vessel
Ventilation and Purge System	Tunnel ventilation system, vessel purge, elevated release, and cooling air system installed; connect to interlock system
Safety and Interlock Systems	Design and reviewed for safety. Preexisting interlock system interfaced with present apparatus; gas detection and alarms system added
Control and Data Acquisition System	Adapted and expanded system used for SSDA
Detonation Instrumentation	Adapted from techniques used in SSDA

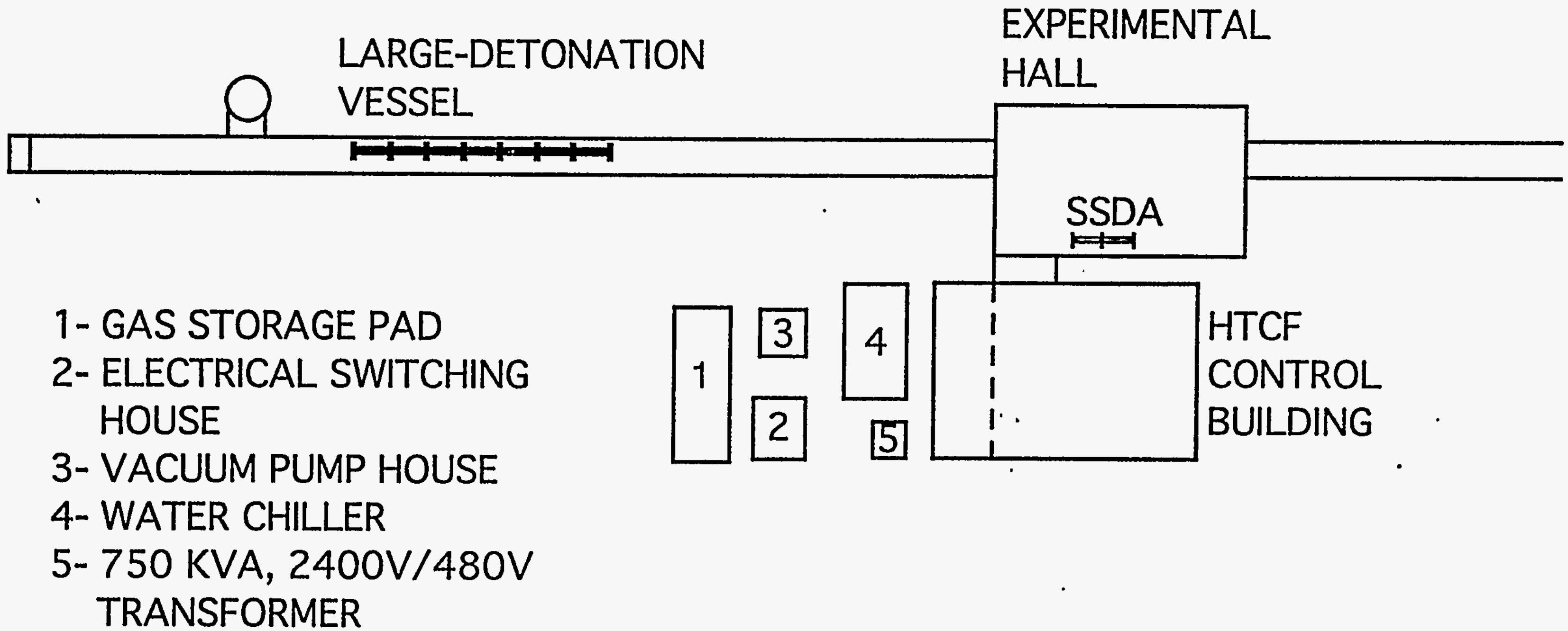

Figure 1: High-temperature combustion facility site layout

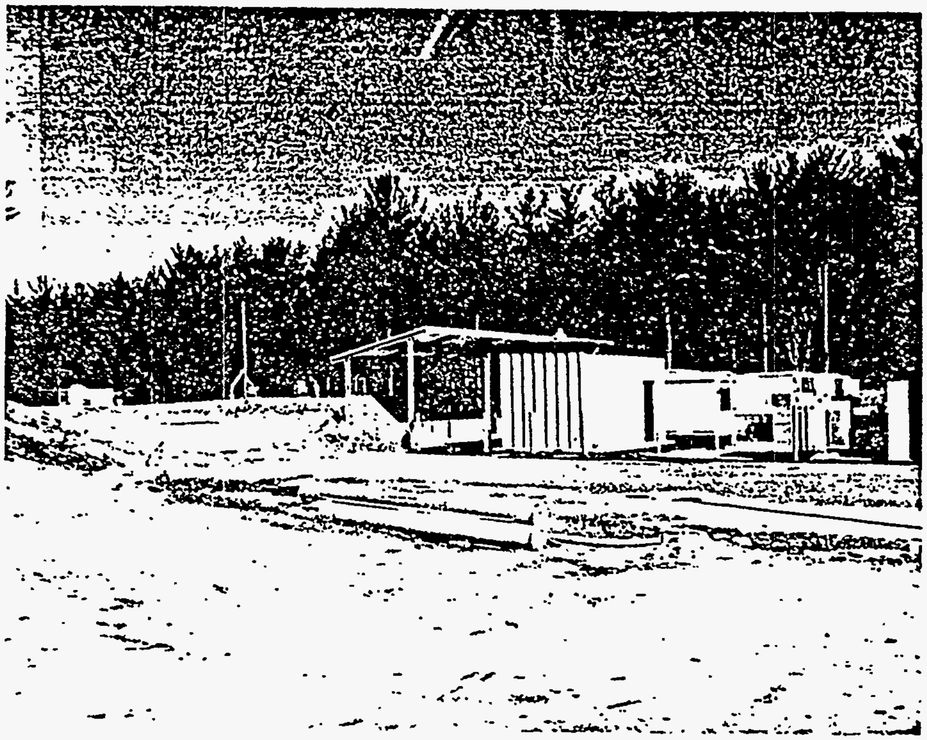

Figure 2 - Major Features of High-Temperature Combustion Facility Site

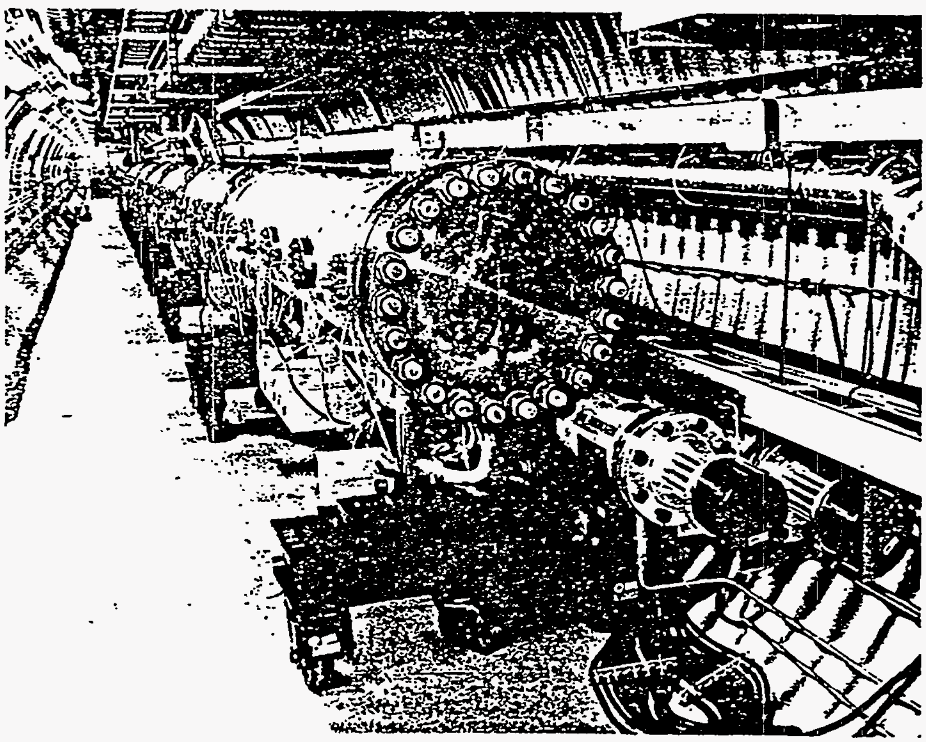

Figure 3 - High-Temperature Combustion Facility Large Detonation Vessel

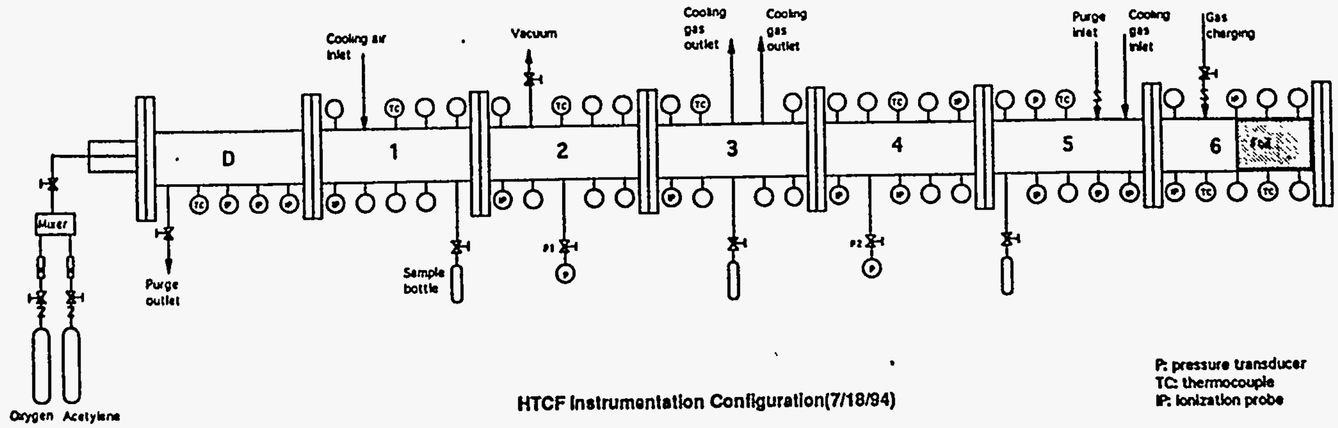

Figure 4 - Schematic of Instrumentation Configuration on the Large Detonation Vessel

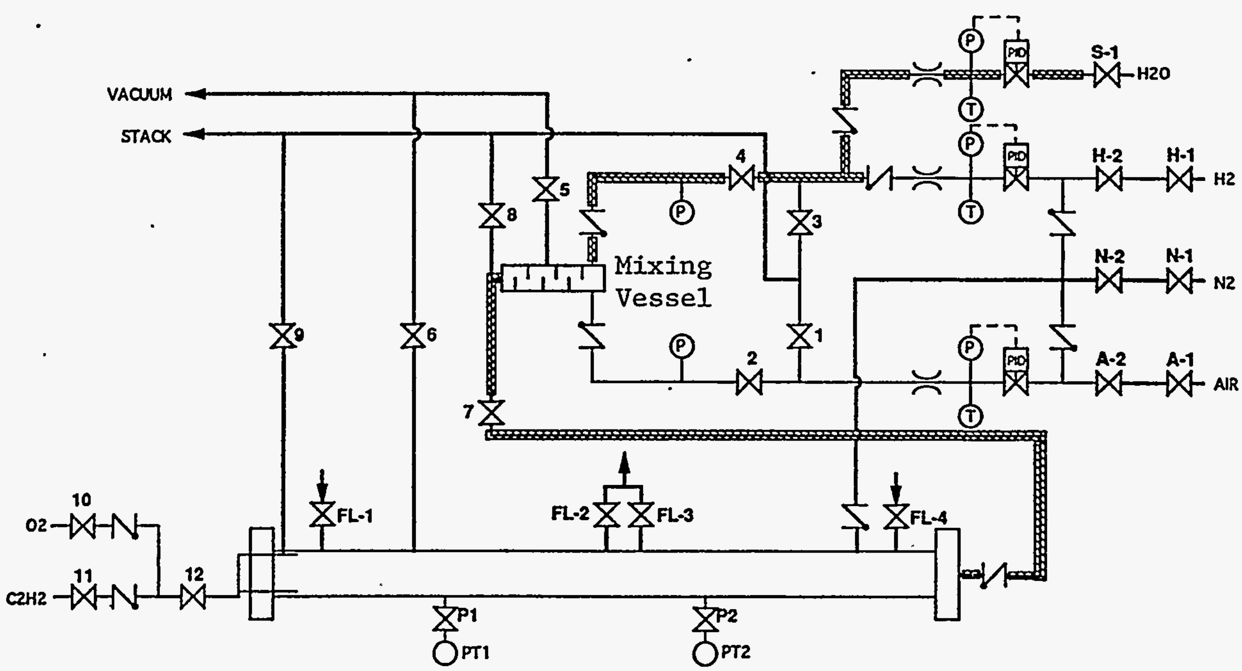

Figure 5 - HTCF Gas Delivery System With Axial Mixture Injection

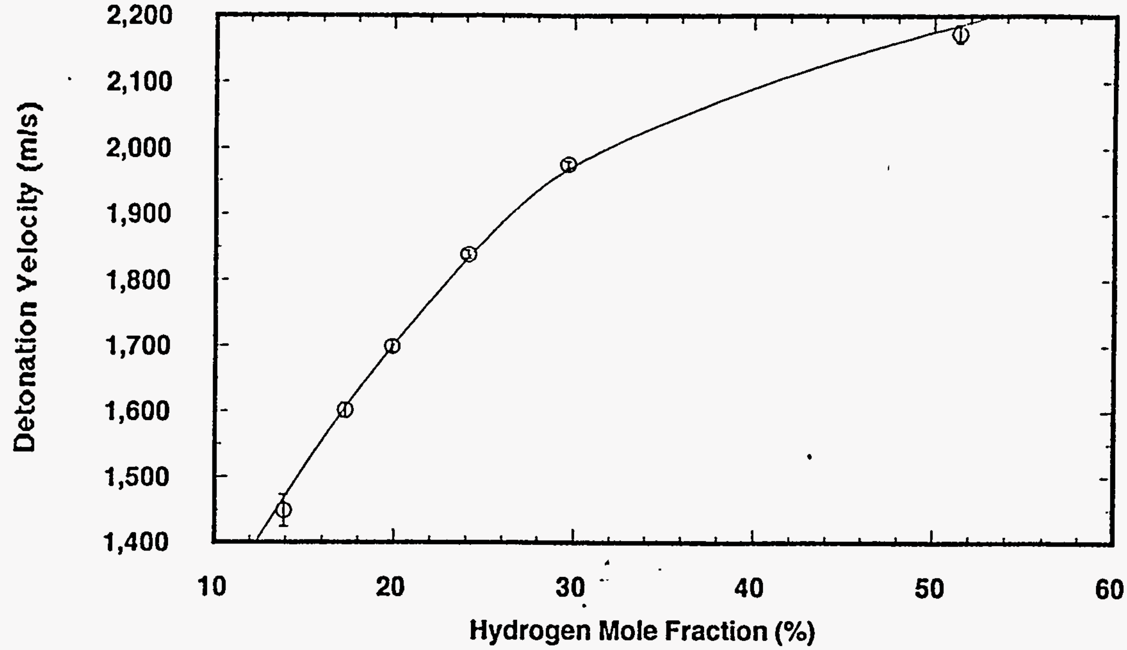

Figure 6 - Detonation Velocity for Hydrogen-Air Mixtures at 300K and 1 atm

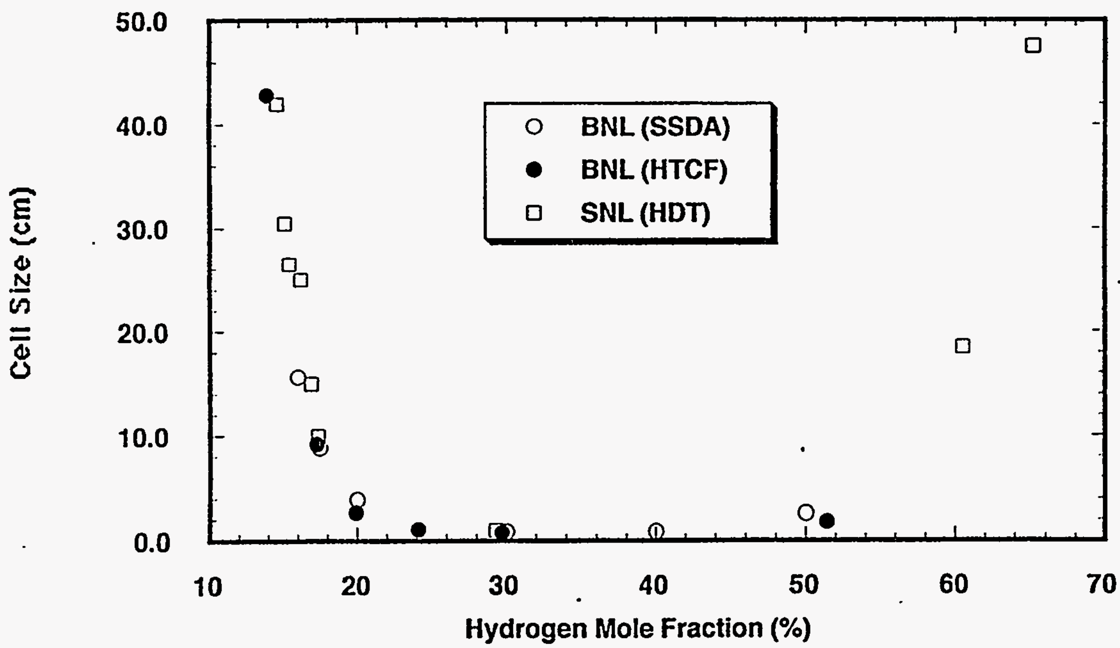

Figure 7 - Cell Size for Hydrogen-Air Mixtures at 300K and 1 atm

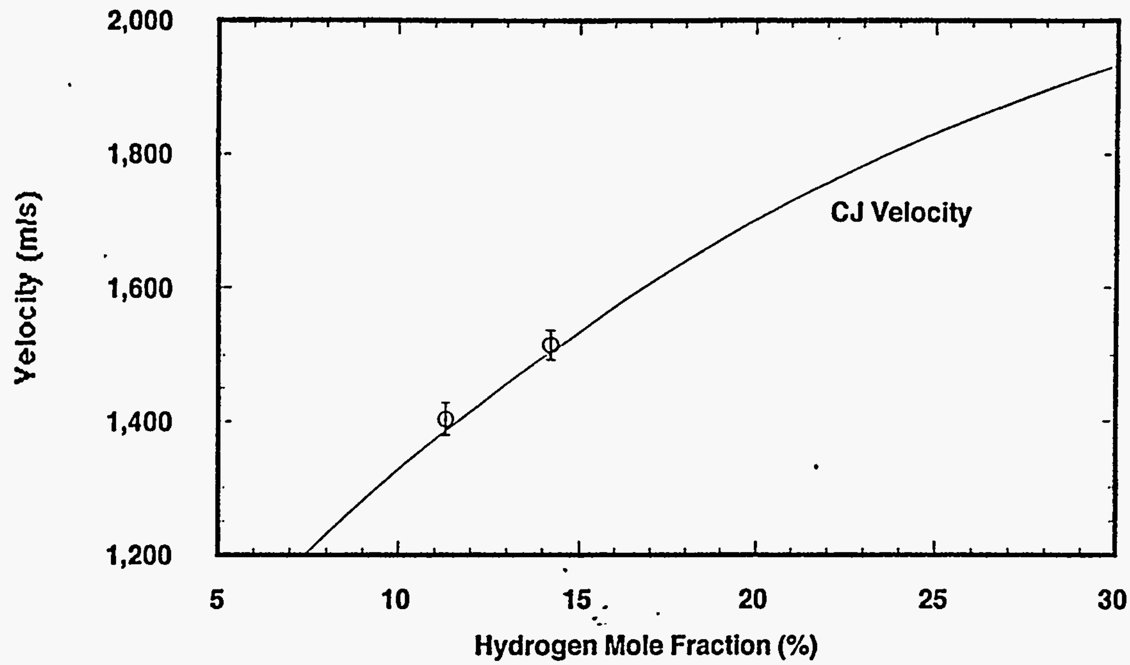

Figure 8 - Detonation Velocity for Hydrogen-Air Mixtures at 650K and 1 atm

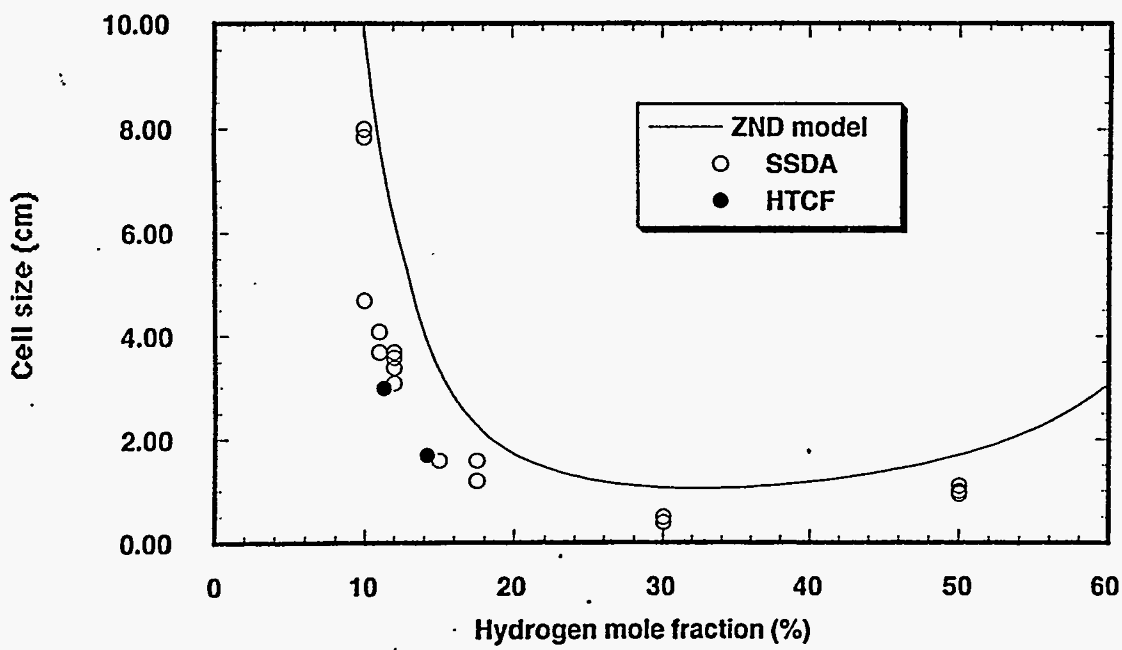

Figure 9 - Detonation Cell Size for Hydrogen-Air Mixtures at 650K