

#### 4.1 HYDROGEN RECOMBINER DEVELOPMENT AT AECL

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#### Abstract

Catalytic recombiners have been developed at AECL for the purpose of hydrogen removal in post-accident nuclear containment buildings. The recombiners are based on a particular catalyst designed by AECL which has extraordinary resistance to fouling from water and water vapour and a large thermodynamic range of operation. The catalysts were developed, originally, for the purpose of heavy water manufacturing by way of a catalytic exchange process. Application of these catalyst materials in recombiners for containment applications began in the late 1980's. The first application was a passive recombiner, qualified for use in control of radiolytic hydrogen in the headspace of a pool-type experimental reactor of AECL design in 1988. The passive, or natural convection recombiner concept has continued development to commercial stage for application in power reactor containments. This paper reviews the AECL recombiner development, describes the current model and shows results from tests of full-scale recombiners in the Large Scale Vented Combustion Test Facility at AECL-WL.

The AECL recombiner is designed for compactness and ease of engineering into containment. The design is a simple, open-ended rectangular enclosure with catalyst elements arranged inside to promote optimum convective flow driven by heat of recombination at the catalyst surface. Self start, as evidenced by catalyst heating and initiation of flow, is achieved in less than 1% hydrogen, with available oxygen, at room temperature and 100% relative humidity. This low temperature start-up in condensing atmospheres is viewed as the most challenging condition for wet-proofing effectiveness. Cold start-up is a vital performance requirement in containments, such as CANDU<sup>®</sup>, where engineered air-cooling systems are operating and where long-term hydrogen control is required, after containment atmospheres have cooled. Once started, the removal capacity scales linearly with the inlet cross-section area and the partial pressure of hydrogen. The recombiner also reacts carbon monoxide, in the presence of hydrogen, at approximately the same rate as the hydrogen. The catalyst materials and wet-proofing are unaffected by radiation or high temperatures. Large scale tests confirm self-start behavior and demonstrate strong mixing, irrespective of recombiner placement.

## **Introduction**

Hydrogen gas generated in a reactor accident poses a threat to structures and essential equipment if allowed to accumulate to flammable concentrations and ignite.

Catalytic oxidation is a way of removing hydrogen at concentrations below flammability limits and has been demonstrated to be effective for containment applications [1-7]. Devices for catalytic hydrogen removal in containment are at the stage of commercial availability and are being installed in existing stations and included in new designs to improve safety margins for hydrogen [8,9]. The principle of operation can be described, briefly, as follows. Hydrogen molecules coming into contact with catalyst surfaces are reacted with oxygen in the air. The heat of reaction at the catalyst surface provides a driving force for buoyancy-induced flow over the catalyst elements, without mechanical assistance or outside power. The action is thus self-starting in response to the presence of hydrogen (with available oxygen) and continues until the hydrogen (or oxygen) in the vicinity has been consumed. Although the capacity depends on several factors (hydrogen concentration, the catalyst activity and aerodynamics of the catalyst arrangement), it is considered feasible by this method to process the entire volume of containment air on the order of hours.

Historically, an obstacle to total passive operation was that catalyst materials most suited to hydrogen were prone to deactivation by ambient water vapour and required outside heat or high ambient temperatures in order to start. However, catalyst materials developed at Atomic Energy of Canada Limited (AECL) have high activity for hydrogen oxidation and are active at ambient temperatures, wet or dry [10,11].

This paper describes the development and testing of catalytic recombiners, based on the AECL catalyst, for hydrogen removal in containment.

### **AECL Wetproofed Catalysts**

Engineering of wetproofed catalysts for the hydrogen-oxygen reaction has been underway at AECL for over 20 years as part of a continuing program of research into methods of producing heavy water using catalytic isotope exchange processes. The program is motivated by the need for new methods of producing heavy water - a key element of CANDU technology. The liquid-phase catalytic exchange process (LPCE) is the most promising candidate for safe and low-cost heavy water production in the future. Engineering of advanced catalysts for the LPCE process is a continuing high-priority activity at AECL and is at the pilot plant phase of development.

In the LPCE process, the catalyst must be near the mass-transfer surface, so wetproofing is required to prevent contact between the liquid and the catalyst surface. Optimizing wet-proofing characteristics is thus a priority. Further, the transfer of deuterium from hydrogen gas to liquid water is thermodynamically favoured at low temperatures, so optimizing low-temperature performance has also been a priority. The catalyst materials developed in this program are unsurpassed in wet-proofing and low temperature performance.

In the 1980's, many applications were identified where catalyst resistance to water vapour was desirable (see Table 1). Wetproofed recombiners that operate in cool humid conditions have a

significant advantage over conventional recombiners, which must be heated to prevent catalyst deactivation. For example, trickle-bed recombiners, which use liquid water to remove the heat of recombination from the catalyst, were developed for recombining near-stoichiometric mixtures of hydrogen and oxygen [11]. Gas-phase wetproofed recombiners were also developed for many diverse applications, such as tritium sampling [12] and removal of radiolytic hydrogen in canisters of wet radioactive material [13].

The catalyst used in the recombiners described in this work is a proprietary AECL formulation developed specifically for application in nuclear containments [2,3]. The catalyst has a high catalytic activity for hydrogen oxidation, is not deactivated by water vapour or steam, and is specially formulated for operation over a very wide range of temperatures. It operates at temperatures up to 1000 K without loss of wet-proofing or catalytic activity and is unaffected by high radiation exposures. It has shown resistance to poisoning by anticipated containment gases.

**Table 1**

**History of AECL Wetproof Catalyst Engineering**

<b>1972</b>	First wetproofed catalyst designs using coated catalyst pellets.
<b>1983</b>	Radiation-resistant, wetproofed catalysts.
<b>1984</b>	High-temperature wetproofing formulas; bonding agents developed for carbon, stainless steel and ceramic support materials.
<b>1985</b>	Large-scale trickle bed recombiners.
<b>1986</b>	Hydrogen control in canisters of wet, radioactive materials.
<b>1987</b>	Catalysts for tritium sampling.
<b>1988</b>	Natural convection recombiner qualified for hydrogen control in head space of SES-10 an experimental reactor of AECL design.
<b>1989</b>	Demonstration testing of a model catalytic combustor (forced convection recombiner) for ventilation systems of power reactor containments.
<b>1990</b>	Demonstration testing of autocatalytic (natural convection) recombiners for power reactor containments.
<b>1991</b>	Pre-engineering test program for autocatalytic recombiner - sponsored by the CANDU Owners Group.
<b>1994</b>	Full-scale prototype demonstration and qualification testing.
<b>1996</b>	Qualification testing of commercial model recombiners in the Large-Scale Vented Combustion Test Facility at AECL-WL.

## **AECL Recombiner Description**

**Design Considerations.** Based on prototype tests, plant analysis and feedback from designers and station owners, the following considerations guided the commercial design.

- cost of manufacturing
- ease of scaling the required capacity to containment subvolumes
- ease and versatility of interfacing to containment structures
- ease of installation
- ease of access to catalyst elements for testing
- protection from environment (sprays, missiles, etc.).
- function and performance
- qualification for service in severe accident environments

**Design Description** The commercial model of the AECL recombimer consists of open-ended rectangular catalyst modules mounted in a rigid steel frame with an attached cover (see Fig. 1). Each module contains flat, rectangular, catalyst elements arranged to allow optimum flow through the enclosure. The frame is made from rectangular steel tubing which provides a secure location for the catalyst module and an interface to containment structures. The optional cover provides physical protection to the internal elements from sprays or missiles. To optimize space usage, the frames are custom-designed and prefabricated for the particular proposed locations.

Installation is envisioned to proceed in three steps: first, the frames are installed in the chosen locations; then, the catalyst modules are set into the frames (for ease of installation, the catalyst modules are all the same size, weigh less than 25 kg and have no directional requirements - no front or back). Finally, the covers are installed on the catalyst holders - either a hooded-cover or a simple grill-cover - to direct flow or shelter the modules in the desired way, depending on location.

Catalyst elements are extracted for routine testing by releasing the hinged cover and lifting individual catalyst elements from the holders. The catalyst elements will be tested in a simple device which produces a positive indication of the required catalyst activity.

## **Demonstration Tests 1993-1995**

Function and performance of the AECL recombimer were demonstrated in the 6.6 m<sup>3</sup> and 10.7 m<sup>3</sup> Containment Test Facility vessels at AECL Whiteshell Laboratories using a 1/10-scale test model and a full-scale prototype recombimer [14]. Self-starting limits, operating limits, removal capacity, scaling parameters and mixing behaviour in the vicinity of an operating recombimer were demonstrated along with resistance to poisoning, fouling and radiation. The essential results of this phase of testing are summarized in Tables 2 and 3.

## Full-Scale Tests in the Large Scale Vented Combustion Test Facility

The AECL recombiners currently being tested in the newly-commissioned, Large-Scale Vented Combustion Test Facility (LSVCTF) at AECL-WL. The LSVCTF offers a high degree of control and accurate measurement of gas compositions as well as a larger volume than previous tests in the CTF.

Preliminary results from the first test series are given here. The aims of the first test series were:

- 1) to confirm the previously demonstrated self-start limits in 1% H<sub>2</sub> at room temperature in condensing atmospheres,
- 2) to confirm the previously established hydrogen removal capacity and single pass efficiency as a function of hydrogen concentration,
- 3) to measure mixing produced by the recombiner and the sensitivity to placement of the recombiner within the enclosure,
- 4) to provide validation data for the recombiner model in GOTHIC, and
- 5) to study effects of gratings and flow directing devices on recombiner performance.

**Facility Description.** The LSVCTF is a 120 m<sup>3</sup> (10-m long, 4-m wide and 3-m high) structural-steel enclosure, instrumented, insulated and temperature-controlled for operation from ambient temperature up to 140°C (see Fig. 2). The design pressure is 300 kPa (g), with a dynamic load factor of 2. The facility has systems for controlled addition of hydrogen, steam and inert gases. All aspects of facility operation are carried out from a remote location 400 m from the test chamber. The composition of gases is measured at several (up to 24) different locations using an industrial process mass spectrometer with a high speed rotary sampling valve. Hydrogen, oxygen, steam and other light gases are measured simultaneously within about 4 s of real time, with an accuracy of 0.1 vol.%. The time required between sample locations is between 5 s and 30 s, depending on the number of gases analyzed and the accuracy required. Further details of the facility are provided in another paper at this workshop [15].

**Test Description.** For these tests the recombiner module was fitted with a pneumatically-operated damper to remotely open and close the inlet and outlet of the module. This was to enable the experimenter to isolate the functional parts (i.e., catalyst elements) inside the recombiner from the surroundings (i.e., turn it 'off') while the initial conditions were being established. Once the target conditions were created and verified by the gas analyser output, the recombiner was turned 'on' by opening the dampers - providing a definitive starting point for the test.

Two sizes of recombiner were tested, the test model from the previous CTF tests and the commercial model. The test model was 32 cm x 50 cm high with a flow area of 0.1 m<sup>2</sup>. This is one half the area of the commercial model but the heights, spacings and types of catalysts are identical to the commercial model. The recombiner module was placed at one of two locations; the geometric centre of the enclosure or at one end of the enclosure (1.5 m from one end wall and 8.5 m from the other end wall). Fig. 3 shows a sketch of the facility configured for recombiner tests. Gas compositions were measured at the inlet and outlet to the recombiner and in the bulk gas at a point 1 m from the far wall at mid-height of the enclosure.

During the addition of gases, the dampers on the recombiner were closed to allow the desired mixture to be achieved before recombination started. The gases were added with the mixing fans running to allow rapid mixing. Steam was added first, then hydrogen. The steam was added to above the saturation pressure, so that there was initially 100% humidity plus wet fog in the combustion chamber before the hydrogen was added. The mixing fans were turned off for 2 minutes to allow the gases to become quiescent, then the dampers were opened to start the test. Tests were done at  $\sim 25^{\circ}\text{C}$ , at ambient pressure.

### **Test Results - 0.1 m<sup>2</sup> Test Model**

The first test demonstrated the self-start of the recombiner at 1% hydrogen, with the recombiner in the central location. Further tests were done at 2%, 4%, and 6% hydrogen in both the central and far wall positions. One additional test was performed at 4% hydrogen, with the recombiner centrally located, and with a 45° exhaust duct at the outlet and gratings on both the inlet and outlet. These obstructions were intended to represent the same geometry as the commercial recombiner options.

**Self Start and Mixing.** The mass spectrometer output for the 1% H<sub>2</sub> test is shown in Fig. 4. At time = 00:00:00, the recombiner dampers were opened and the catalyst elements became exposed to the hydrogen-steam-air mixture. The record of addition of gases to the chamber is shown on the negative side of the time axis. Immediate startup of recombination is evident from the abrupt drop in hydrogen concentration at the outlet of the recombiner. The extent of mixing of gases in the enclosure was good, as indicated by the fidelity of bulk gas and inlet samples.

**Placement and Obstructions.** Figures 5 and 6 show the results in 4% H<sub>2</sub> from two different locations of recombiner (central and far wall). It can be seen that the location of the recombiner did not have a strong effect on the overall recombination rate or the mixing of gases in the enclosure except for small differences in time delay due to distance. The gas composition at the bulk-gas measuring point with the far-wall placement required approximately 5 minutes longer to reach 1% H<sub>2</sub> than with the central placement. Figure 7 shows the results, in 4% H<sub>2</sub> with obstructions installed at the inlet and outlet to the recombiner. The obstructions also did not have a strong effect on recombiner performance.

The recombiner efficiency is approximately 0.6, as determined from inlet and outlet hydrogen concentrations. This recombination efficiency seems to be independent of hydrogen concentration, but is usually higher at the very beginning of a test. There is a trade-off between the reaction rate and the residence time. Low hydrogen concentrations produce a lower operating temperature, lower buoyant driving force and thus longer residence times. At higher concentrations, the temperature is higher and the catalyst is more active but the residence time is shorter due to higher flow velocities. At a particular concentration, obstructions to the flow have an effect of increasing the efficiency, but the net capacity is not improved.

### **Test Results - Commercial Model (0.2 m<sup>2</sup>) Recombiner**

The commercial recombiner was tested in the LSVCTF under conditions self-consistent with tests on the test model. The commercial model has two times the inlet area (i.e., two times the capacity) of the test model, has a lighter weight housing, gratings to protect the inlet and a partial cover to protect from sprays. But the commercial unit lacks the dampers to isolate it from its surroundings for test purposes.

Selected results of large scale tests of the commercial model are shown in Figures 8, 9 and 10. The cold, wet self-start behaviour at 1% hydrogen concentration is consistent with all previous tests (Fig. 8). It is noted, of course, that initial conditions are not as precisely defined as when the dampers were used with the test model. The measured capacity of the commercial model is shown in Fig. 10 as a function of hydrogen concentration. A full qualification test program for the commercial unit in the LSVCTF is continuing.

### **Conclusions**

Catalytic recombiners have emerged as a credible option for hydrogen mitigation in nuclear containments. Wet-proofed catalysts, developed at AECL, show superior self-start properties under cold-wet conditions and good resistance to poisoning and fouling. Recombiners have been designed using these catalysts and demonstrated under conditions relevant to post-containment atmospheres. The commercial recombiner design features a light-weight catalyst module in rigid frame, custom-designed for ease of sizing and installation. Large-scale tests in the LSVCTF confirm self-start capability and demonstrate strong mixing irrespective of recombiner placement in the enclosure.

### **References**

1. A.K. Chakraborty, "Catalytic Removal of Hydrogen," *Kerntechnik* **53**, 1 (1988).
2. G.W. Koroll, W.A. Dewit and W.R.C. Graham, "Passive Catalytic Hydrogen Mitigation," 2nd International Conference on Containment Design and Operation, Toronto, Canada, October 11-14 (1990).
3. G.W. Koroll, D.W.P. Lau, W.A. Dewit and W.R.C. Graham, "Catalytic Hydrogen Removal in Humid Hydrogen-Air Gas Streams," IAEA/CEC Workshop on Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Plants, 1991 March 04-08. Ed. E. Della Loggia, EUR 14039 (1992).
4. V. Behrens, M. Seidler and U. Wolff, "Hydrogen Mitigation Using Catalyst Modules," IAEA/CEC Workshop on Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Plants, 1992 March 04-08. Ed. E. Della Loggia, EUR 14039 (1992).

5. R. Heck, "Concept and Qualification of a Combined System for Hydrogen Mitigation after Severe Accidents," IAEA/CEC Workshop on Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Plants, 1991 March 04-08. Ed. E. Della Loggia, EUR 14039 (1992).
6. J. Rohde and A.K. Chakraborty, "Use of Catalytic Recombiners as a Hydrogen Mitigation Technique," OECD/CSNI Specialist Meeting, June 13-15, Stockholm (1994).
7. G.W. Koroll, W.A. Dewit, D.W.P. Lau and W.R.C. Graham, "Catalytic Recombiners for Severe Accident Hydrogen," ANS-ENS-EURATOM European Nuclear Congress (ENC '94) Lyon, France, 1994 October 2-6.
8. B. Centner. "The Architect Engineer Concerns about Hydrogen Releases and Behaviour Inside the Containment. The Belgian Approach." 4<sup>th</sup> International Topical Meeting on Nuclear Thermalhydraulics, Operation and Safety, Taipei, 1994 April 5-9.
9. G. Sliter, U. Wolf, H. Zimmer (EPRI), D. Gluntz and J. Thompson (GE), "Passive Autocatalytic Recombiners for Combustible Gas Control in SBWR Advanced Light Water Reactors." ANS/ARS '94 International Topical Meeting on Advanced Reactor Safety. Pittsburgh, 1994 April.
10. W.A. Seddon, K.T. Chuang, W.J. Holtslander and J.P. Butler, "Wetproofed Catalysts: A New and Effective Solution for Hydrogen Isotope Separation and Hydrogen/Oxygen Recombination," Proc. ASME Energy Sources Technology Conf. Paper 84-PET-11, New Orleans (1984 February).
11. R.J. Quaiattini, K.T. Chuang and L.J. Puissant, "Hydrogen Removal from Dissolver Off-Gas Streams," ANS International Meeting on Fuel Reprocessing and Waste Management, Jackson, WY (1984 August).
12. R.J. Quaiattini, W.R.C. Graham, M.J. Woods, R.G.C. McElroy, G.L. Ogram and K.E. Curtis, "Performance of a Wetproofed Catalyst in an Ambient Temperature Discriminating Tritium Samples," Fusion Tech. 14, 1085-1089 (1988).
13. J.O. Henri, B.D. Bullough and D.J. Flesher, "Catalyst Tests for Hydrogen Control in Canisters of Wet Radioactive Wastes," Rockwell Hanford Operations Report GEND-062 (1987).
14. G.W. Koroll, D.W.P. Lau, W.A. Dewit and W.R.C. Graham, "Catalytic Hydrogen Recombination for Nuclear Containments," ICHMT Seminar on Heat and Mass Transfer in Severe Reactor Accidents, Cesme, Turkey, May 21-26 (1995).
15. J. Loesel Sitar, G.W. Koroll, C. Sabanski, J. Harding, E.M. Bowles, W.A. Dewit and R.K. Kumar, "Large Scale Vented Combustion Test Facility at AECL-WL: Description and Preliminary Test Results," OECD/NEA/CSNI Workshop on Implementation of Hydrogen Mitigation Techniques, Winnipeg, Canada, 1996 May 13-15.

**TABLE 2**

**Summary of Experiments with Test Model AECL Passive Recombiner  
in the 6.6 m<sup>3</sup> and 10.7 m<sup>3</sup> Containment Test Facility Vessels**

Type of Test	# of Tests	Result
configuration and geometry of internals - axial channels - corrugated plates - flat plates - spacing/height ratio - effect of chimney	33	<ul style="list-style-type: none"> <li>•parallel flat plates with height to spacing ratio of 10 is the simplest configuration for optimum performance (capacity)</li> <li>•straight chimney increases capacity by 30% - 50% per metre of height</li> </ul>
capacity and the effect of initial thermodynamic conditions (pressure, temperature, humidity and concentration of reactants)	11	<ul style="list-style-type: none"> <li>•capacity is unaffected by humidity</li> <li>•capacity increases in proportion to initial pressure in the range of 1-2 bar</li> <li>•capacity is insensitive to initial temperature between 20 and 120°C</li> <li>•capacity increases with increasing concentration of the limiting reactive constituent (H<sub>2</sub> or O<sub>2</sub>)</li> </ul>
self-start limits	25	<ul style="list-style-type: none"> <li>•self-start is spontaneous at &lt;1% H<sub>2</sub> (with available O<sub>2</sub>) and &lt;1% O<sub>2</sub> (with available H<sub>2</sub>) at 25°C, 100% R.H.</li> <li>•self-start limits are unaffected by 90% H<sub>2</sub>O, CO<sub>2</sub> or N<sub>2</sub> diluents</li> </ul>
scaling 1/10-scale and full-scale tests	4	<ul style="list-style-type: none"> <li>•capacity increases in proportion to the inlet cross-section area</li> </ul>
mixing behaviour (10.7 m <sup>3</sup> cylinder)	6	<ul style="list-style-type: none"> <li>•stratified atmospheres over a 5 metre height are homogenized within 3 minutes by natural convection from an operating recombiner</li> </ul>
effect of water spray	4	<ul style="list-style-type: none"> <li>•direct spray into an uncovered recombiner cools the catalyst plates and reduces performance. When spray stops, the catalyst reheats and resumes normal performance</li> </ul>
effect of steam spray	4	<ul style="list-style-type: none"> <li>•direct steam spray increases hydrogen removal rate due to forced convection</li> </ul>
effect of radiation	2	<ul style="list-style-type: none"> <li>•capacity and self-start limits are unaffected by 480 kGy <math>\gamma</math>-radiation to catalyst materials</li> </ul>

(continued...)

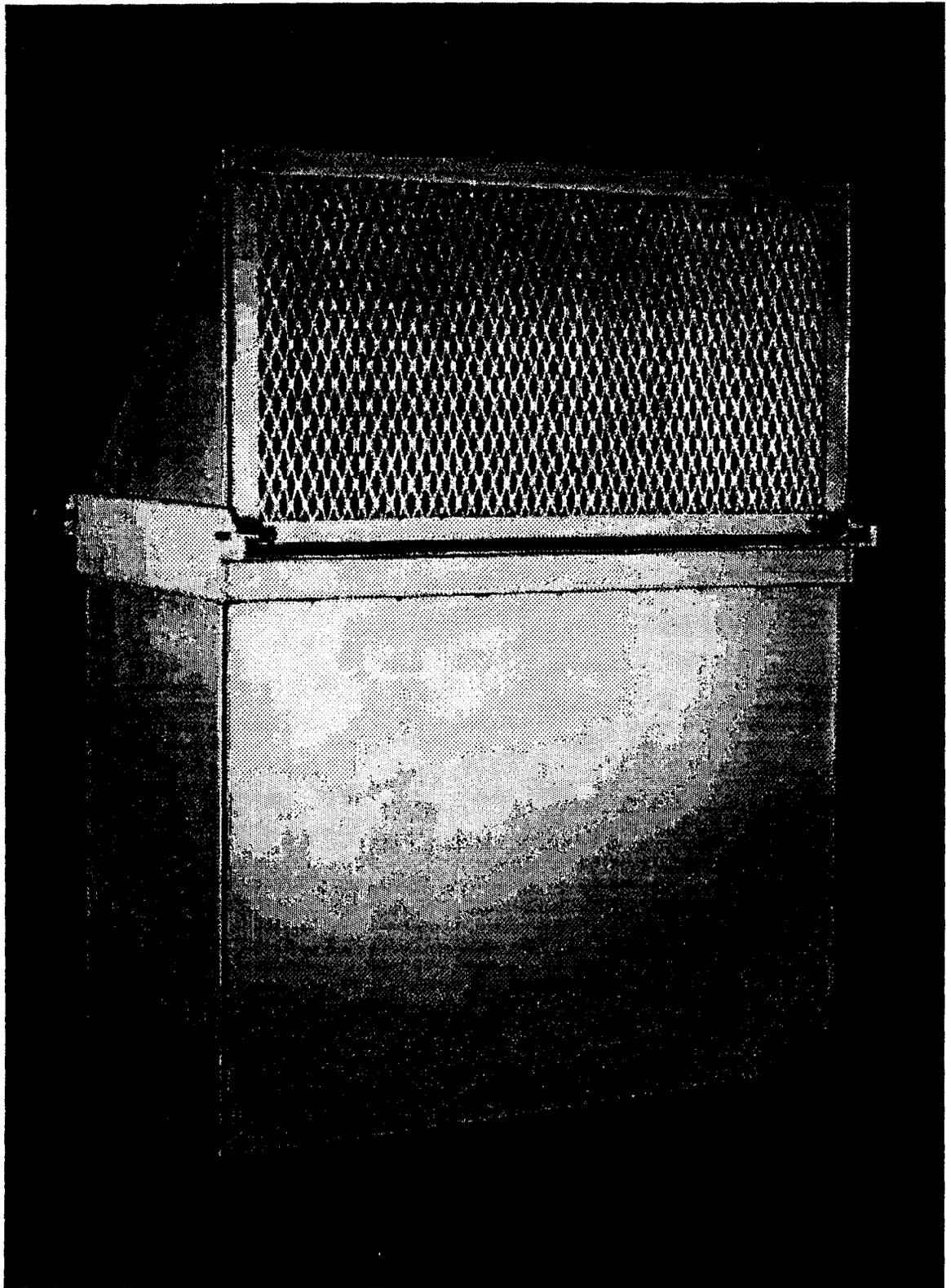
TABLE 2 (concluded)

effect of deliberate exposure to H <sub>2</sub> burn	3	<ul style="list-style-type: none"> <li>•catalyst performance unaffected by 10% and 14% H<sub>2</sub> burns</li> </ul>
operating temperature limit	4	<ul style="list-style-type: none"> <li>•performance unaffected after operation at 700°C in 20% H<sub>2</sub>/6% O<sub>2</sub></li> </ul>
resistance to poisoning and fouling		
- boric acid	1	<ul style="list-style-type: none"> <li>• after soaking in saturated boric acid solution:                             <ul style="list-style-type: none"> <li>- self start limits unaffected</li> <li>- some reduction of capacity due to precipitate coating</li> </ul> </li> </ul>
- cable fires	2	<ul style="list-style-type: none"> <li>•after <u>heavy</u> sooting from a cable/kerosene fire:                             <ul style="list-style-type: none"> <li>- no effect on self-start</li> <li>- small reduction of capacity</li> </ul> </li> </ul>
- carbon monoxide	6	<ul style="list-style-type: none"> <li>•carbon monoxide is oxidized to carbon dioxide at approximately the same rate as hydrogen oxidation</li> <li>•hydrogen removal capacity is unaffected by carbon monoxide</li> <li>•self-start limit for hydrogen recombination increases to 2% H<sub>2</sub> with prior exposure to 2% carbon monoxide</li> </ul>
- methyl iodide	1	<ul style="list-style-type: none"> <li>•10<sup>-7</sup> M CH<sub>3</sub>I in the gas phase had no effect on the capacity. Self-start limit increases to 3% H<sub>2</sub></li> </ul>
- formaldehyde	1	<ul style="list-style-type: none"> <li>•no effect</li> </ul>
- benzene	1	<ul style="list-style-type: none"> <li>•no effect</li> </ul>
ageing	2	<ul style="list-style-type: none"> <li>•catalyst plates exposed to industrial atmosphere for 4 years exhibited no change in performance characteristics</li> </ul>

**TABLE 3**

**Summary of Experiments with Full-Scale Prototype Recombiner  
in the Containment Test Facility**

Type of Test	# of Tests	Result
Measurements of Capacity of H <sub>2</sub> Removal - hydrogen concentration - initial pressure - initial temperature - humidity - chimney height	12	<ul style="list-style-type: none"> <li>•capacity increases linearly with hydrogen concentration</li> <li>•capacity increases linearly with initial pressure</li> <li>•capacity is unaffected by initial temperature or humidity</li> <li>•capacity increases ~30% per metre of chimney height</li> </ul>
Measurements of Capacity of CO Removal	4	<ul style="list-style-type: none"> <li>•the molar rate of CO oxidation is approximately the same as H<sub>2</sub> oxidation</li> </ul>
Adverse Environments - cold, wet (25°C, 100% RH) - CO (1%, 2%, 4%) - I <sub>2</sub> (10 <sup>-7</sup> M, 10 <sup>-8</sup> M) - paint fumes (2 part, self-priming epoxy for nuclear containments, with Valspor thinner)	4 5 2 2	<ul style="list-style-type: none"> <li>•spontaneous self-start is observed at 1% H<sub>2</sub> under all environments tested</li> <li>•CO at 2% and 4% levels produces an increase in H<sub>2</sub> oxidation. Effect on self-start same as small-scale tests</li> <li>•molecular iodine at 10<sup>-7</sup>M did not affect self-start limits or capacity</li> <li>•fumes from 0.3 m<sup>2</sup>/m<sup>3</sup> freshly painted surfaces of epoxy paint produced no effect on self-start limits or capacity.</li> </ul>



**Figure 1. Picture of the Commercial Model Recombiner.**

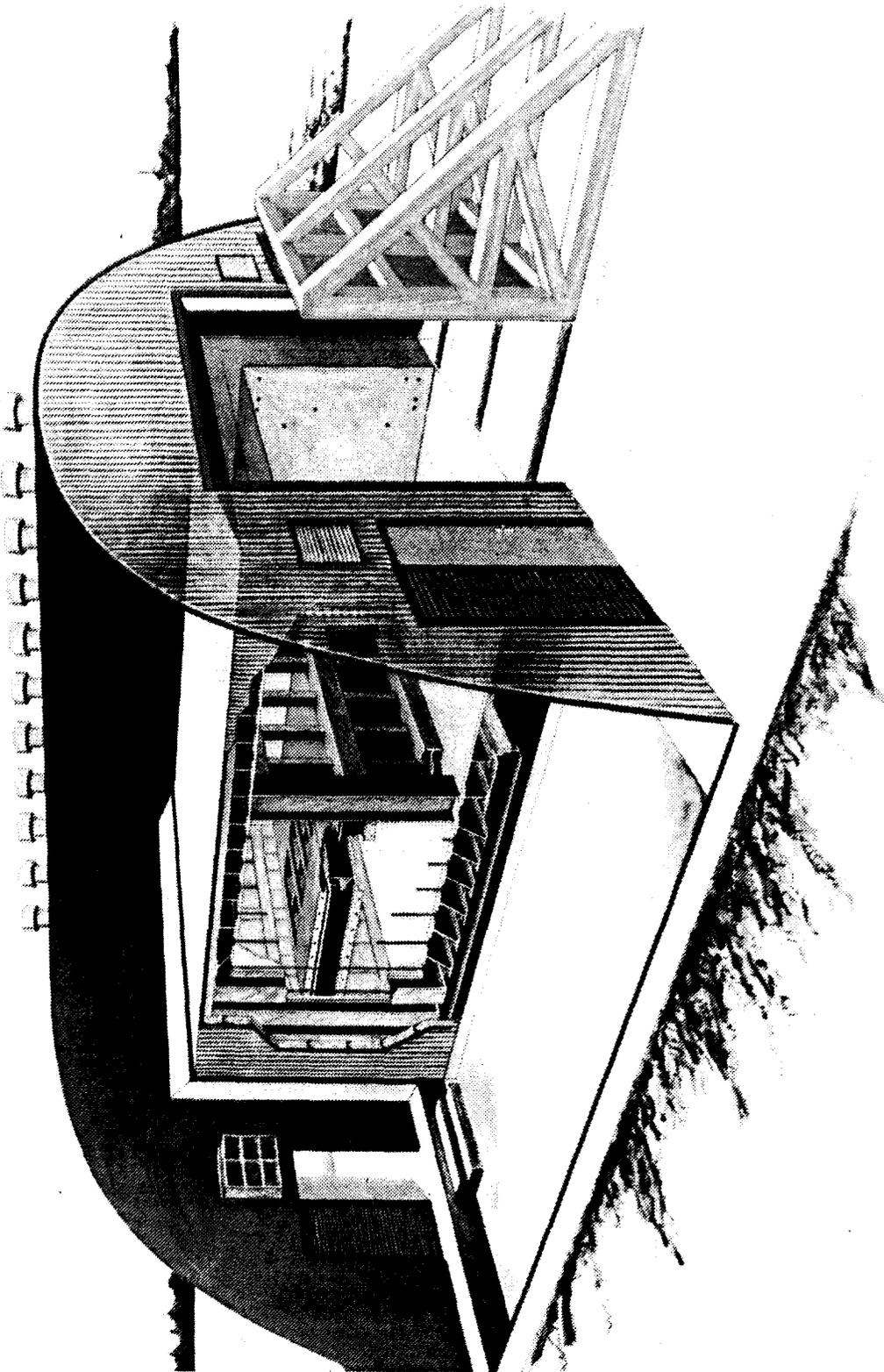
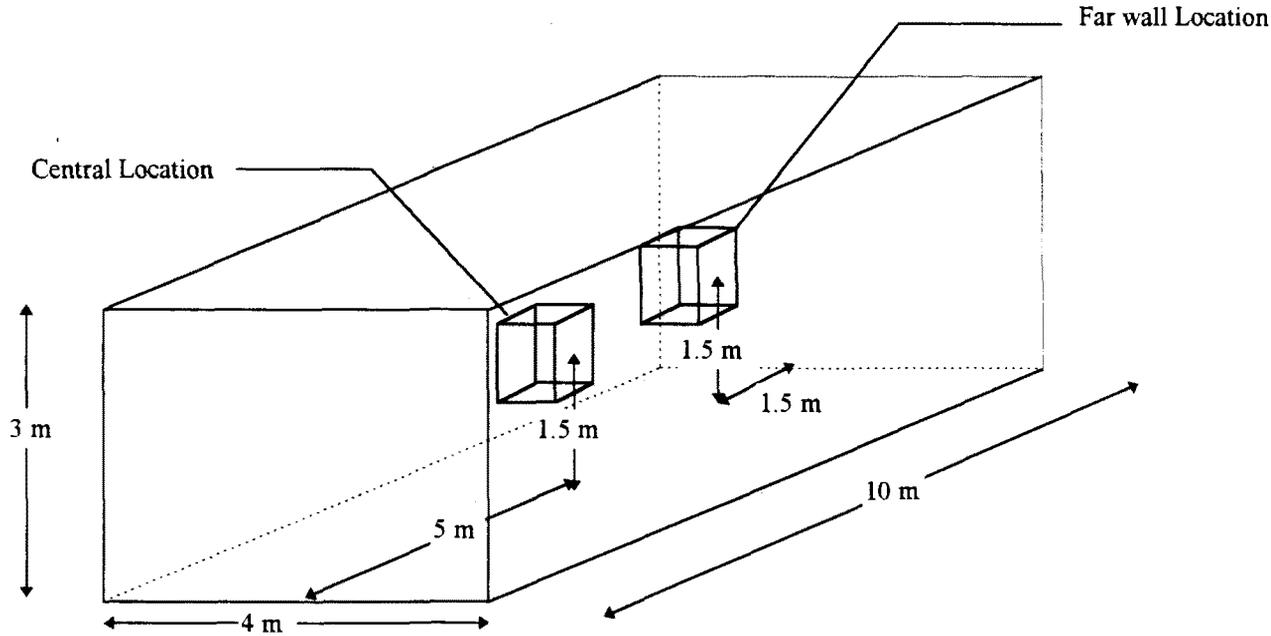
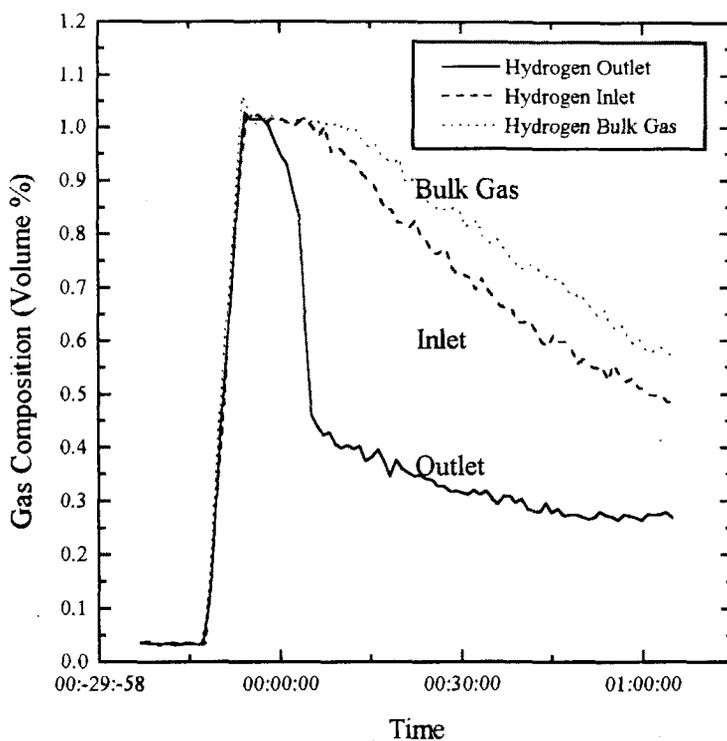


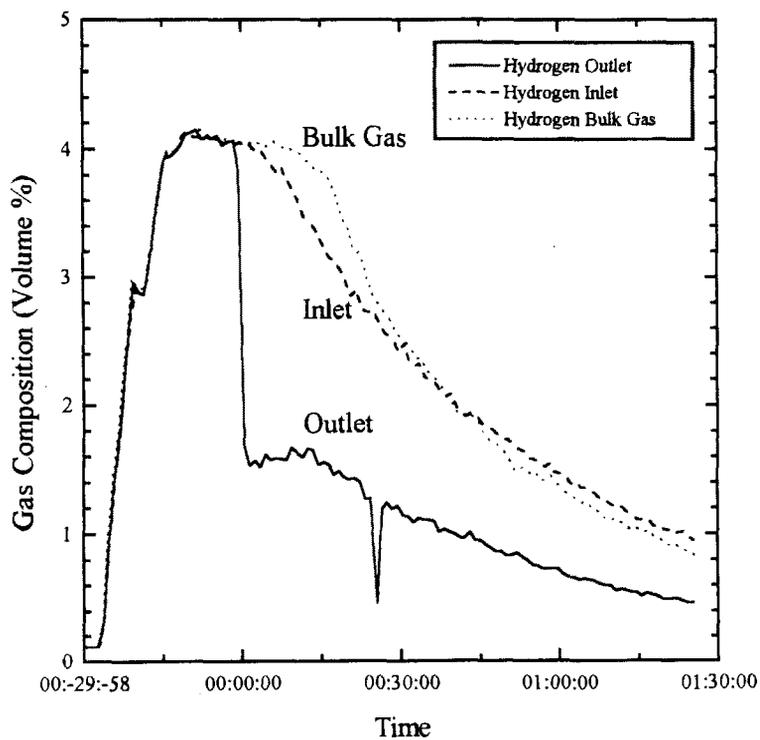
Figure 2. Schematic of the Large-Scale Vented Combustion Facility.



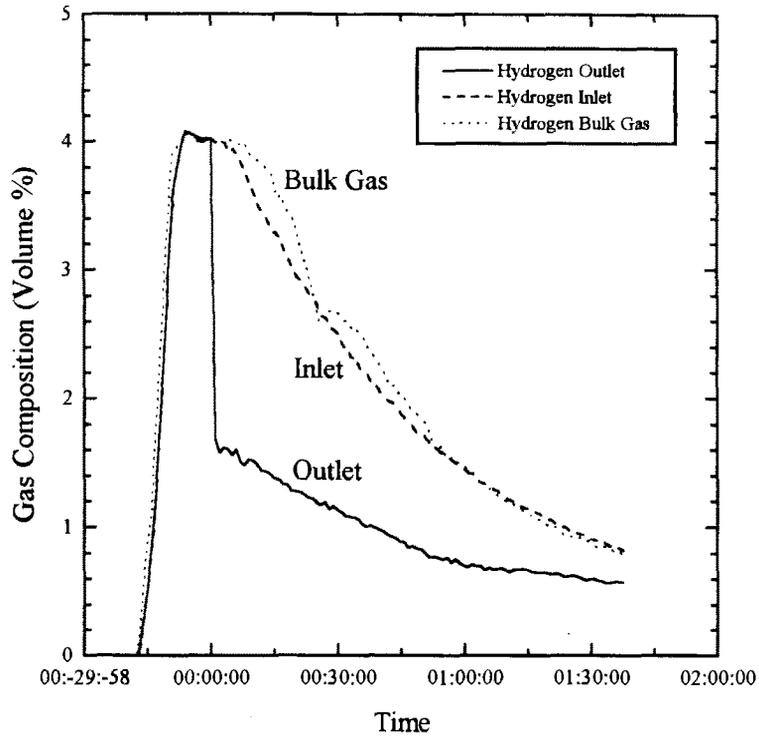
**Figure 3. Schematic of Combustion Chamber with Recombiner Locations.**



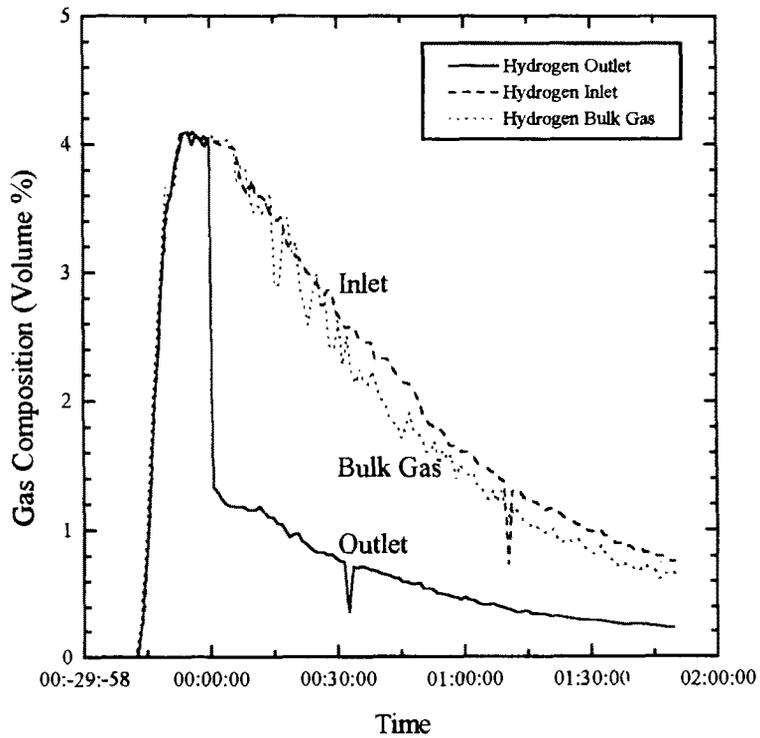
**Figure 4. Gas Analysis Results for Test Model in 1% Hydrogen, 5% steam, at 25°C. Recombiner at Central Location.**



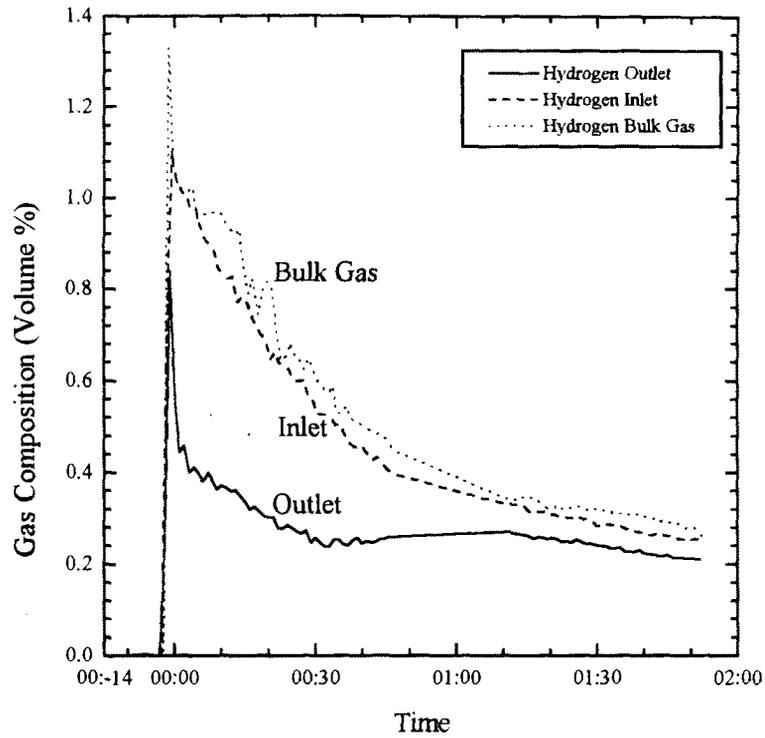
**Figure 5. Gas Analysis Results for Test Model in 4% Hydrogen, 5% steam, at 25°C. Recombiner at Central Location.**



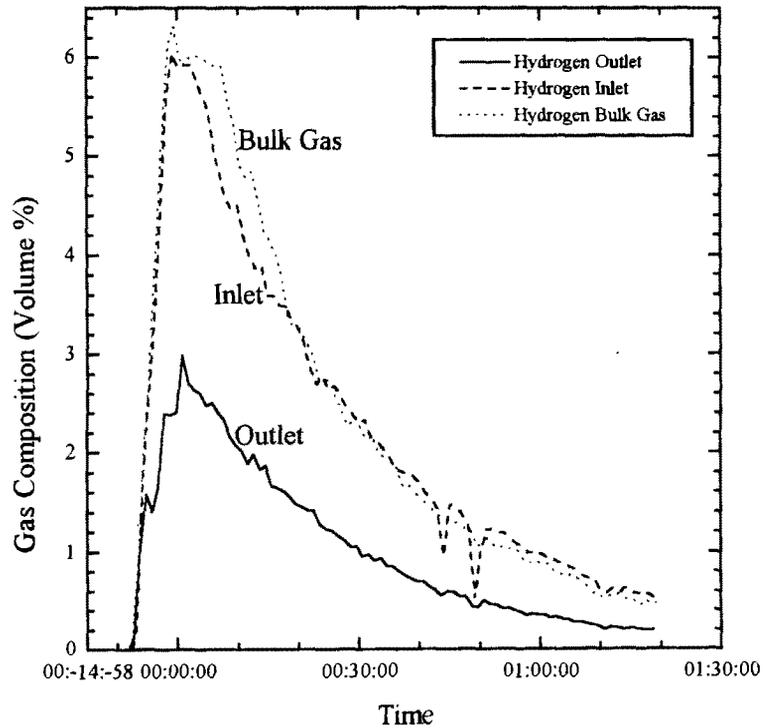
**Figure 6. Gas Analysis Results for Test Model in 4% Hydrogen, 5% steam, at 25°C. Recombiner at Far Wall Location.**



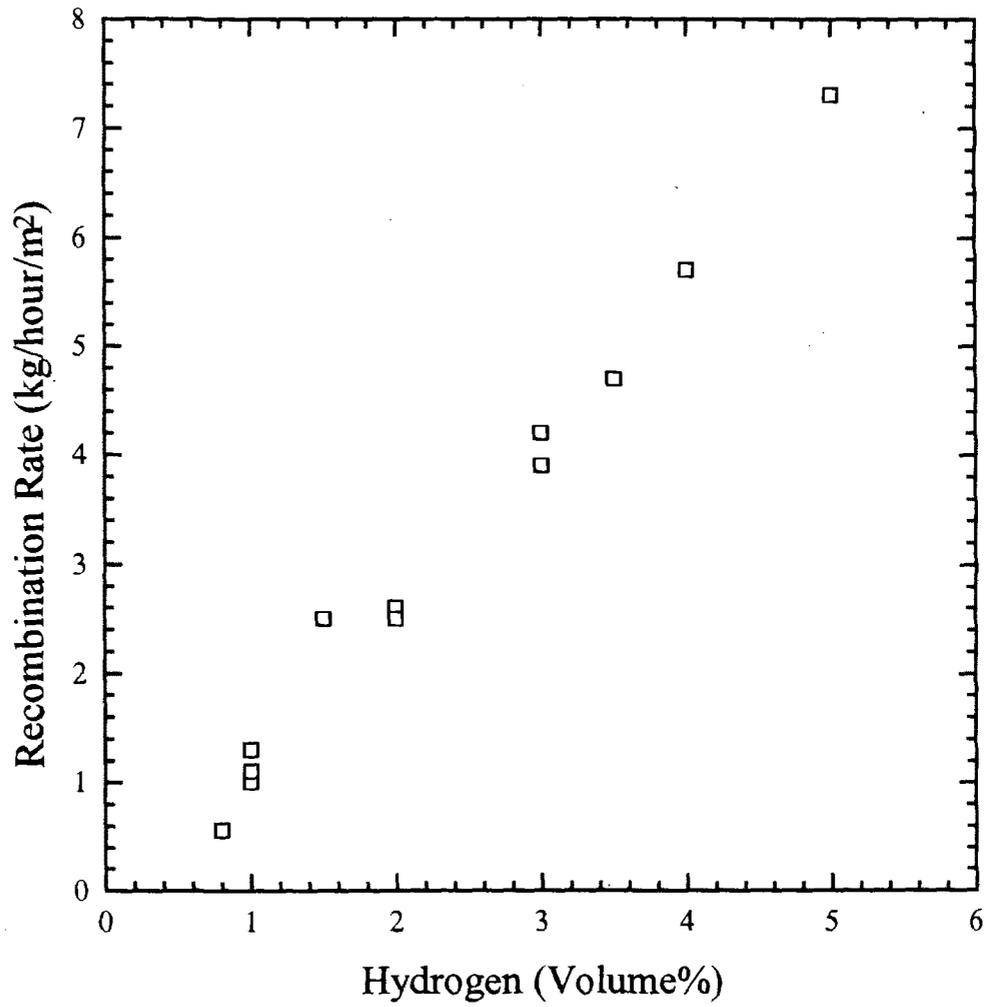
**Figure 7. Gas Analysis Results for Test Model in 4% Hydrogen, 5% steam, at 25°C. Recombiner at Central Location. Exhaust Duct and Inlet Gratings Attached.**



**Figure 8. Gas Analysis Results for Commercial Model in 1% Hydrogen, 5% steam, at 25°C. Recombiner at Central Location.**



**Figure 9. Gas Analysis Results for Commercial Model in 6% Hydrogen, 5% steam, at 25°C. Recombiner at Central Location.**



**Figure 10. Recombiner Capacity for 0.2 m<sup>2</sup> Commercial Model Recombiner.**