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6.1 CONTAINMENT AIR CIRCULATION FOR OPTIMAL HYDROGEN RECOMBINATION

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Abstract

An accepted first-line defense for hydrogen mitigation is to design for the hydrogen to be rapidly mixed with the containment atmosphere and diluted to below flammability concentrations. Then, as hydrogen continues to be produced in the longer term, recombiners can be used to remove hydrogen: recombiners can be located in forced-air ducts or passive recombiners can be distributed within containment and the heat of recombination used to promote local air circulation. However, this principle does not eliminate the possibility of high hydrogen concentrations at locations removed from the recombiners.

An improvement on this strategy is to arrange for a specific, buoyancy-driven, overall circulation of the containment atmosphere such that the recombiners can be located within the recirculation flow, immediately downstream of the hydrogen source. This would make the mixing process more predictable and solve the mass-transfer problem associated with distributed recombiners. Ideally, the recombiners would be located just above the hydrogen source so that the heat of recombination would assist the overall circulation. In this way, the hydrogen would be removed as close as possible to the source, thereby minimizing the amount of hydrogen immediately downstream of the source and reducing the hydrogen concentration to acceptable levels at other locations.

Such a strategy requires the containment volume to be divided into an upflow path, past the hydrogen source and the recombiner, and a downflow path to complete the circuit. The flow could be generated actively using fans or passively using buoyancy forces arising from the difference in density of gases in the upflow and downflow paths; the gases in the downflow path being cooled at an elevated heat sink.

Introduction

The conventional principle for hydrogen mitigation is to design for the hydrogen to be rapidly mixed with the containment atmosphere so as to be diluted below flammability levels. Then, as hydrogen continues to be produced in the longer term, recombiners can be located in forced-air ducts or passive recombiners can be distributed within containment to remove hydrogen and the heat of recombination used to promote local air circulation. However, this approach does not eliminate the possible existence of high hydrogen concentrations at locations removed from the recombiners. Multi-dimensional containment fluid-flow calculations are needed to guide the positioning of recombiners and to demonstrate that localized pockets of high hydrogen concentration can be successfully avoided.

Utilizing this principle of mixing and recombination, an improved strategy, using recombiners, is to arrange for a specific overall circulation of the containment atmosphere such that the recombiners can be located immediately downstream of the hydrogen source. This would make the mixing process more predictable and solve the problem of mass-transfer of hydrogen and air to distributed recombiners. Ideally, the recombiners would be located above the hydrogen source so that the heat of recombination would assist this overall circulation. In this way, the hydrogen would be removed as quickly as possible and as close as possible to the source, thereby minimizing the amount of hydrogen immediately downstream of the source and reducing the hydrogen concentration to acceptable levels at other locations.

Such a strategy requires the containment volume to be configured into an air upflow path, past the hydrogen source and the recombiners, and an air downflow path to complete the circuit. Thus containment baffles are required and are often available in the form of crane walls or walls which separate an outer accessible volume from an inner reactor vault. Steam generator enclosures could be used for the upflow path. The flow could be generated actively using fans or passively using buoyancy forces arising from the difference in density of gases in the upflow and downflow paths; the gases in the downflow path would be cooled at an elevated heat sink.

This paper describes how such a strategy can be applied to CANDU® reactors.

Passive Emergency Water System PEWS

A passive emergency water system is discussed in Reference [1] and can be applied to CANDU reactors as shown in Fig. 1.

The vented water pool in the containment dome is a general-purpose emergency heat sink. For a large CANDU, a volume of about 2000 m^3 provides, after boil off, a three-day heat sink. It serves as a heat sink for the steam generators, for the CANDU

CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL) moderator acting as an emergency-core-cooling (ECC) system, and for containment. Water from the vented pool is supplied to and returns by natural circulation from the tube side of the tube banks, located at an upper elevation within containment.

The tubes are inclined to the horizontal, so that there is a preferred flow direction for the water. Water is supplied from the pool via the header at one end, and heated water is returned to the pool via the header at the other end of the tube bank. In the longer term, a boiling steam/water mixture is returned to the pool.

The containment itself is divided into an inner and an outer region, as shown in Fig. 1. Such is normally the case in contemporary CANDU containment designs, the outer region being accessible during normal operation and not connected to the inner region. However, a connection is required in this design, at least during accidents, to permit a natural circulation flow of gases up through the steam generator enclosure and down through the accessible region. The flow is induced by the difference in density of the hot gases (air, steam and hydrogen) rising from a break in the reactor coolant pipes and the gases cooled in passing across the elevated tube banks. The large elevation difference between the heat source, near the reactor, and the heat sink, at the tube bank leads to enhanced natural circulation flows of containment gases. The flows are directed by using the internal wall as a baffle which eliminates mixing between downflowing and upflowing streams.

A reduced long-term containment pressure is achieved with a high rate of heat transfer from the containment gases to the water-cooled tubes. A large heat transfer coefficient follows not only from the enhanced flow velocities but also from the high heat transfer coefficient for flow across a tube bank as compared to the coefficient for flow tangential to a surface such as a vertical containment wall.

Hydrogen Mitigation

The enhanced natural circulation flow within containment permits improved hydrogen mitigation. Hydrogen mitigation can be accomplished by directing flow to the source of the hydrogen and locating catalytic hydrogen recombiners in the stream of mixed air, steam and hydrogen. If the recombiners are located at low elevation in an upward flow of this stream, the heat of recombination acts to augment the buoyancy-induced flow.

Figure 1 shows hydrogen recombiners located in the CANDU steam-generator enclosures. The intent is to blank off any alternative flow path bypassing the recombiners so that the entire recirculating air flow is available for hydrogen mitigation. This greatly increases the effectiveness of recombiners as compared to the conventional strategy of dispersing recombiners throughout containment and relying on local convective flows for supply of air to each recombiner. LOCA calculations, using the GOTHIC code, show air and steam flow rates which would dilute hydrogen concentrations to below flammable concentrations of 4% in the steam generator enclosure, even at the inlet of the recombiners. This calculation assumes a worst case impairment of the emergency coolant injection system to maximize hydrogen production and assumes that all such hydrogen enters only one of four steam generator enclosures. Higher local concentrations can be expected upstream of the recombiners and nearer the break but with the recombiners located so close to the break, the mass of hydrogen is small. This residual problem of hydrogen combustion in the region near the hydrogen source may require bounding or more sophisticated calculation of the effects of such ignition. Igniters might be employed in this region to limit the effects of a sudden deflagration.

Catalytic hydrogen recombiners located in a strong flow of air can have single-pass efficiencies above 80% [2] leading to small exit hydrogen concentrations. This leads to small hydrogen to air ratios in the stream at exit from the recombiners and precludes the need for any additional recombiners.

Passive CANDU-6 Application

The feasibility of these ideas, when applied to a passive CANDU containment, was demonstrated in simulations using a series of simplified GOTHIC models of a passive CANDU-6 containment. As discussed above, the containments of contemporary CANDU reactor designs are divided into an inner, non-accessible region and an outer, accessible region. In the case of the passive design they are connected, at least during loss of coolant accidents. The outer region can be arranged to include such regions as the containment dome. This was assumed in the GOTHIC code simulations which placed the dome in series with the other regions of the recirculating flow path. The objective was to show that the global long term containment behavior, such as pressure, temperature and hydrogen transients, under the worst-case scenario LOCA with impairment of the emergency coolant injection system and all decay heat being released to containment, is acceptable. Although this exercise was based on a CANDU-6 containment, with passive features such as the PEWS and elevated tube banks, similar results can be obtained for other CANDU containments that would employ such passive concepts, scaled accordingly.

The containment was divided into five principal regions, shown in Fig. 2: the upflow region (generally the fueling machine vaults and steam generator enclosures), the containment dome, the elevated tube bank region, the downflow region, and the remainder of containment. The circulation loop is completed by the downflow region being connected to the fueling machine vaults near the floor level. The hydrogen recombiners, when modeled, were located at the top of the steam generator to ensure that all possible hydrogen sources are below them (i.e. upstream in the air circulation loop). Some design changes in pipe location will likely allow the lower, more favorable location of the recombiners, shown in Fig. 1, near the bottom of the steam generators. Overall containment circulation is passive and driven by the buoyancy difference in the upflow and downflow regions, resulting from heat removal through steam condensation at the elevated tube bank. During hydrogen release this flow would be further assisted by heat generation from the recombiners, however, this effect is minimized in the model due to the high location of the recombiners.

Fig. 3 shows the break and total hydrogen inflow into the bottom of one of the fueling machine vaults (including break flow and recirculation) and the return air and steam flow rates from the downflow region into the same fueling machine vault. With a maximum hydrogen inflow of 360 moles/s and an air and steam return rate of 7200 moles/s a simple calculation shows that the maximum hydrogen concentration (well mixed) at the inlet to the recombiner would be 5 % with no recombination. If all the hydrogen can be recombined, only the break hydrogen flow must be considered in the break vault, leading to an expected fueling machine vault hydrogen concentration of below 2%. These bounding cases are shown in Fig. 4. Figure 5 shows the transient hydrogen concentrations, as predicted by GOTHIC with a recombiner model, at the inlet of the recombiners for various recombiner efficiencies, including the case of no recombiners. The recombiners are predicted to have a dramatic effect on hydrogen concentrations, even at a low assumed efficiency.

PWR Application

The idea for an elevated PEWS and hydrogen recombination within a defined recirculation flow could be applied to advanced PWR containments. The separation of the containment into an upflow and a downflow region would be done using existing walls or additional baffles, thereby directing an air-rich mixture towards the hydrogen source to facilitate recombination. Location of the recombiners in the upflow path, just upstream of possible break locations, would minimize the mass of hydrogen and optimize the recombiner efficiency, if high air flow rates can be ensured by the overall, passive recirculation or by fans.

Conclusion

Optimal hydrogen mitigation can be achieved in water-cooled nuclear reactors by arranging for an overall circulation of the containment atmosphere that directs a mixed flow of air, steam and hydrogen through recombiners located immediately downstream of the hydrogen source. In CANDU reactors, the recombiners can be located in the steam generator enclosures and the overall circulation can be achieved passively or with fans.

For passive water-cooled reactors, use can be made of inner walls which can act as baffles to direct a natural circulation flow loop of containment gases. If fans are employed, ducting can be chosen to take the flow from an air-rich region to the region of the hydrogen source to close the flow loop.

References

1. Spinks, N.J., "A Passive Emergency Heat Sink for Water-Cooled Reactors with Particular Application to CANDU Reactors", 4th International Conference on Nuclear Engineering, Vol 2, p. 297, March 1996.
2. Koroll, G.W., D. Lau and W.R.C. Graham, "Catalytic Removal of Hydrogen in Humid Hydrogen-Air Gas Streams," CEC Hydrogen Behaviour and Mitigation in Water-Cooled Reactors, Brussels, Belgium, p. 317-323, March 4-8, 1991.

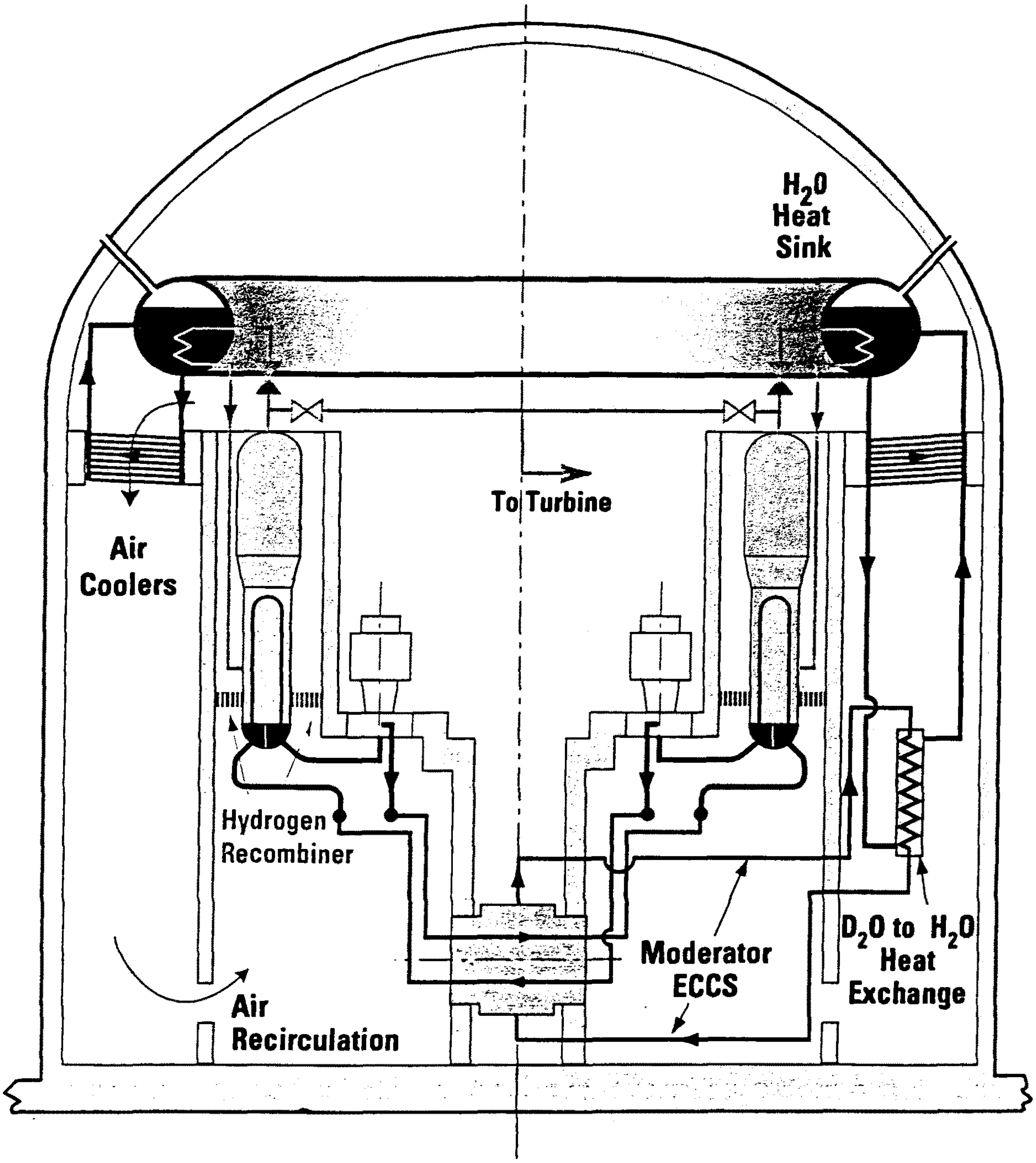

Figure 1. CANDU Containment with Passive Emergency Water System

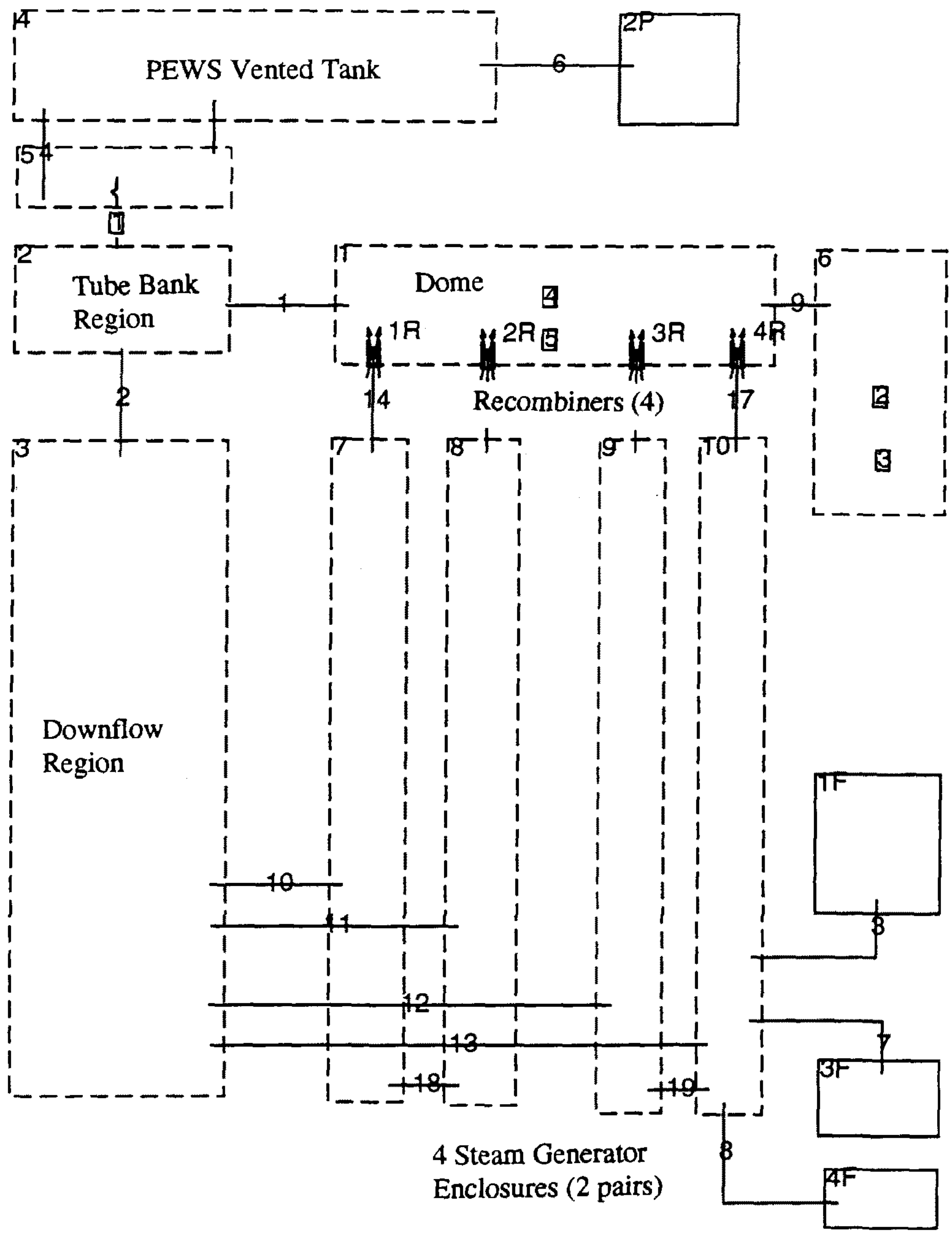

Figure 2. GOTHIC Model of Passive CANDU Containment

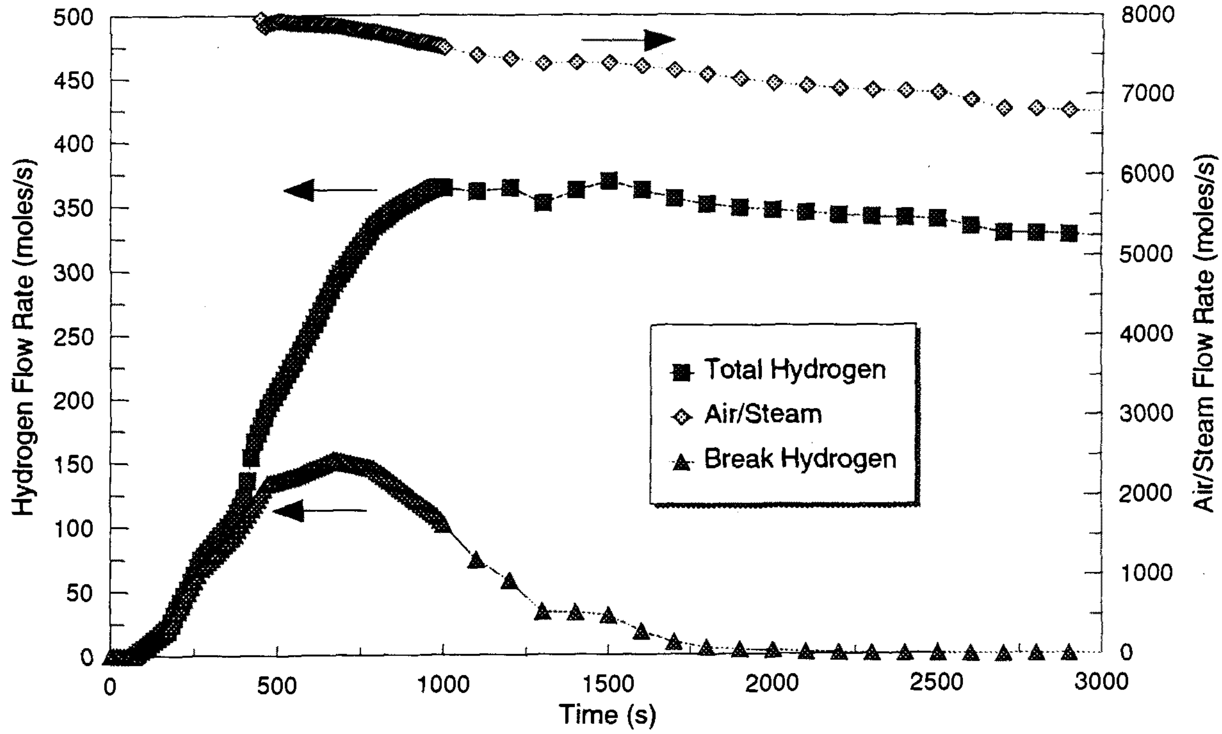

Figure 3. Hydrogen and Steam/Air Flow Rates into Fuelling Machine Vault

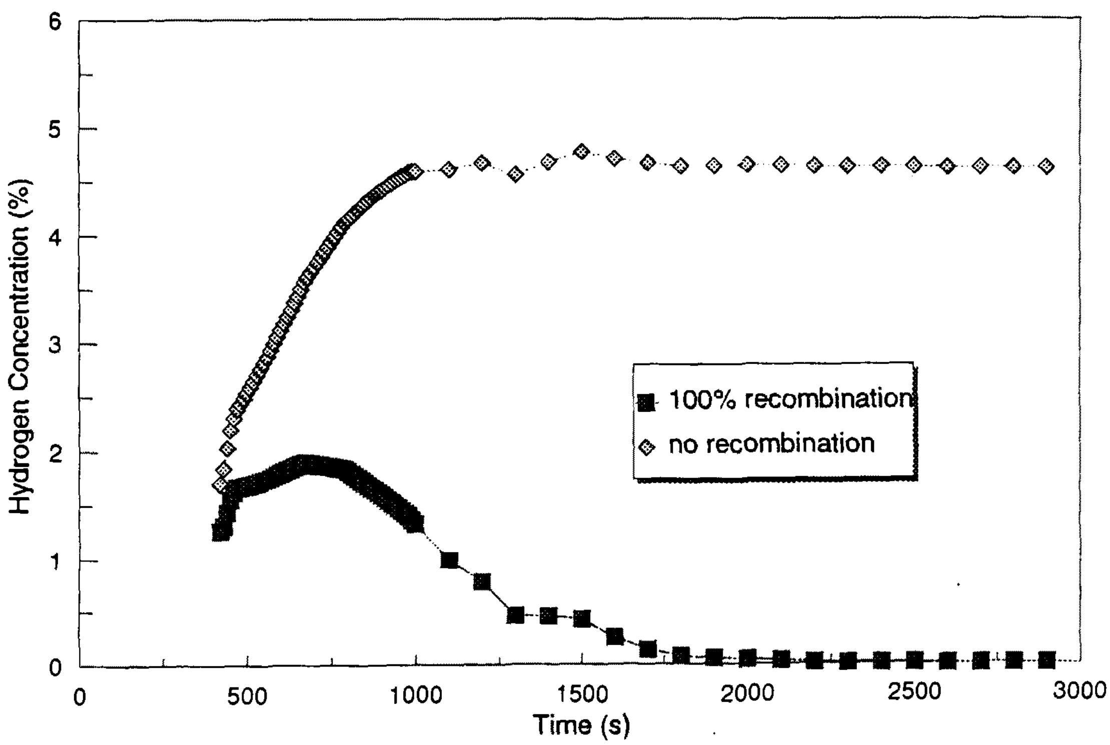

Figure 4. Hydrogen Concentration in Fuelling Machine Vault

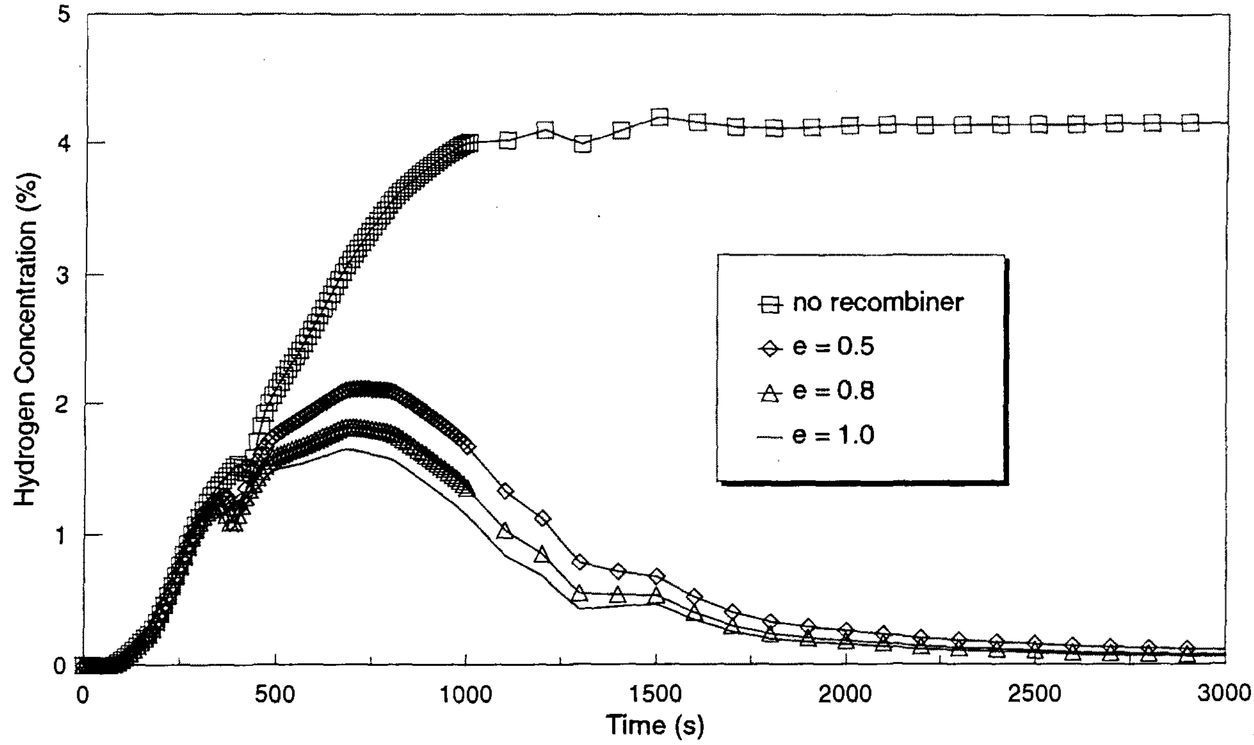

Figure 5. Fuelling Machine Vault Hydrogen Concentration with Various Recombiner Efficiencies