ALWR
ADVANCED LIGHT WATER REACTOR

February 15, 1994

Mr. James H. Wilson
US Nuclear Regulatory Commission
1 White Flint North M.S. 11 H3
11555 Rockville Pike
Rockville, MD 20852

Subject: Passive Autocatalytic Recombiners for Boiling Water Reactors

Dear Mr. Wilson:

Enclosed is a paper titled "Passive Autocatalytic Recombiners (PARs) for Combustible Gas Control in SBWR Advanced Light Water Reactors". This paper will be presented in April to the ANS ARS 1994 International Topical Meeting on Advanced Reactor Safety. Note that a similar paper, focused on PWR usage, was included in our letter to Dr. Stamps dated December 22, 1993.

We believe these papers may serve as useful support for the ongoing review of PAR suitability which the NRC is doing in response to our April 8, 1993 submittal.

Sincerely,

Edmund T. Rumble

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ALWR Program
ER/L1/lk

cc: Document Control Desk
Dr. D. Stamps, Sandia National Laboratories

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Presented at ANS ARS '94 International Topical Meeting on Advanced Reactor Safety, Pittsburgh, Pennsylvania, April 1994.

PASSIVE AUTOCATALYTIC RECOMBINERS FOR COMBUSTIBLE GAS CONTROL IN SBWR ADVANCED LIGHT WATER REACTORS

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ABSTRACT

This paper summarizes the technical bases for using a passive autocatalytic recombiner (PAR) system as a favorable alternative to an igniter system as an adjunct to pre-inerting for combustible gas control in General Electric's Simplified Boiling Water Reactor (SBWR) during both design basis and severe accidents. PAR devices use catalytic coatings to turn molecular hydrogen and oxygen into water vapor. They are self-starting and self-feeding, even under cold and wet conditions. Buoyancy of the hot gases they expel at the top of vertical flow channels in the PAR sets up natural convective flow currents that promote mixing of combustible gases in a containment. Oxygen in the inerted SBWR containment atmosphere begins to be recombined as soon as hydrogen and oxygen from radiolysis or hydrogen from metal-water reaction is introduced. After discussing design and qualification features of two similar PAR designs, the paper focuses on their application for the SBWR containment. Simplified analysis based on measured depletion capacities for full-size and scale models of the two PAR designs have shown that the combination of pre-inerting, free-volume dilution of oxygen in the SBWR containment and several strategically located PAR devices can keep the concentration of combustible gases below flammability limits with a large margin. Results of a cost study show that the life-cycle cost of the PAR approach is roughly a third of that using igniters as an adjunct to pre-inerting.

I. INTRODUCTION

Passive ALWRs are under development by General Electric, Westinghouse, U.S. and international utilities, the Electric Power Research Institute (EPRI), and the Department of Energy.[1] Basic design principles include safety, design simplicity, maintainability, and preference for passive components that do not rely on active power sources or support systems. These principles have led to adoption by U.S. utilities, international ALWR participants, and General Electric (GE) of the passive autocatalytic recombiner as the preferred approach for the SBWR containment.[2]

An early design decision for the SBWR was to use pre-inerting (as in today's BWR Mark Is and IIs) instead of igniters (as in Mark IIIs) to control hydrogen from metal-water reaction in a degraded core accident. With pre-inerting, it is oxygen from post-LOCA radiolysis that needs to be controlled. Utility requirements for ALWRs disallow the use of containment purge and re-inerting systems. Therefore, igniters were selected originally to control radiolytic oxygen in SBWR accident scenarios.

The containment oxygen concentration history begins at inerted pre-DBA values (typically 4 vol%) and slowly increases over time. Igniters—whether of the glow-plug or spark type—produce controlled low-energy burns as the combustible gases rise to flammability limits. The containment is designed to accommodate these small controlled burns, which by their recombination action preclude burns of higher concentrations that could challenge containment integrity. But with the advent of PARs, even these designed-for, controlled burns are eliminated as recombination can and will take place at concentrations well below flammability limits.

PARs perform their function passively, drawing in atmospheric gases containing hydrogen and oxygen at the bottom inlet of a sheet metal housing and blowing out water vapor from recombination at the top. Inside the device, recombination occurs at a catalyst surface. PARs are self-starting and self-feeding, even under cold and wet conditions. Buoyancy of the hot gases they create sets up strong convective flow currents that promote mixing and homogenization of oxygen and hydrogen in the containment. These gases begin to be recombined as soon as hydrogen is introduced into containments as a result of a design basis or degraded core accident. As discussed in this paper, the recombination rate of a number of PARs distributed throughout the SBWR containment volume keeps the average concentration of oxygen well below the flammability limit. Since PARs have no moving parts and require no external energization, they require no operational procedures and are easily maintained. This is projected to lead to greater life cycle cost-effectiveness, which is also a goal of passive ALWRs.

Because the results of the feasibility study[2,3] were sufficiently positive, the ALWR program has requested NRC review and approval of the PAR concept. This paper gives a brief description of the design and qualification of PARs and how they would be implemented as an adjunct to pre-inerting to control combustible gases released during both design basis accidents and severe accidents in *passive inerted* ALWRs, namely, GE SBWRs. Wolff and Sliter[4] described how PARs would be implemented in *passive non-inerted* ALWRs, namely, the AP600, under development by the Westinghouse Corporation.

The PAR approach is also applicable for severe accidents in *non-passive* ("evolutionary") ALWRs, but utilities stopped short of requiring its use in these designs lest the change have a negative impact on their design and certification schedules. If the PAR approach to combustible gas control is accepted by the regulator and is projected to be sufficiently cost-effective, it could be considered as well for evolutionary ALWRs.

II. DESIGN AND QUALIFICATION OF PARs

There are two PAR designs believed to have the requisite performance characteristics and degree of test qualification needed to be candidates for application in SBWRs. Both the NIS and Siemens designs are described below. Although the ALWR feasibility study[2] was performed for the NIS design, any catalytic recombiner design that can be qualified to function as required could be selected by GE for implementation in the SBWR.

A. NIS Design

One candidate design for the PAR system discussed in this paper is the pelletized catalyst design developed and qualified in Germany by the NIS Company in cooperation with Degussa (catalyst supplier), the Battelle Institute (test laboratory), and the Technical University, Munich (analysis). Its development has been sponsored by the German utility RWE Energie, which is a participant in the ALWR Program.[5]

The NIS PAR device shown in Figure 1 is a "molecular diffusion filter" (not the more conventional fixed-bed particle catalyst filter, in which gases are forced through the interstitial spaces between catalyst particles). The device consists of 88 flat, rectangular cartridges containing a total of about 30 kg of hydrophobic spherical catalyst pellets, with 1-cm-wide open flow channels between the cartridges. The total weight of a full-size PAR is about 170 kg. The immense surface area of the palladium-coated outer layer of the porous ceramic pellets acts upon diffused gas molecules, while heavier particles or aerosols in the atmosphere flow through the open channels with little plugging of the pellet surfaces. The gas flow is drawn in at the bottom of the device, recombined while passing through the flow channels, and funneled into a chimney blowing the heated gas through a square hole at the top.

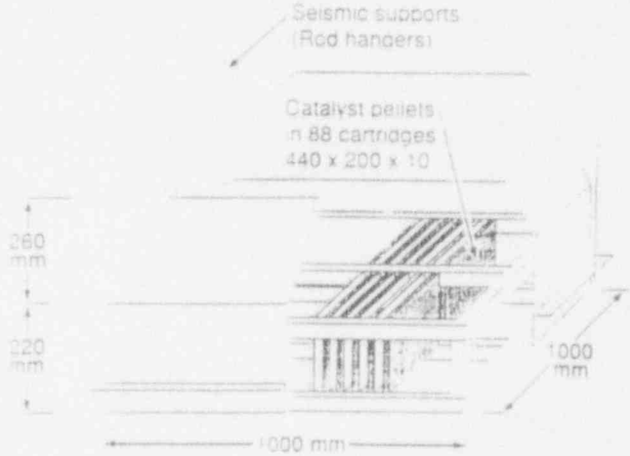

Figure 1. Drawing of the Prototype NIS PAR Device

Structural supports for a PAR device can be customized to suit a size and installation location. The size of the devices can be varied as indicated in Figure 2. For devices in an open space, a convenient moment-free support technique would be to hang them from their four corners on rods from above, as indicated in Figure 1. If the potential exists for the freely hung device to impact nearby components during earthquakes, some form of lateral bracing would be provided. The device can also be supported from beneath or attached to a wall (see, for example, the quarter-capacity unit on the right side of Figure 2).

Performance/qualification testing. Design optimization, extensive determination of performance characteristics, and qualification of the NIS PAR device has been realized through a three-phase test program performed by NIS and Battelle[5] that included screening tests of various catalysts, model tests to characterize performance (including under adverse conditions), and full-size prototype tests in a multicompartment model containment.

The performance of PARs was determined primarily by means of 41 tests on PAR models with full-height catalyst cartridges and an 11 x 11 cm cross-sectional flow area. An additional 8 tests in a large multicompartment concrete containment model confirmed the performance of a full-size PAR prototype and demonstrated the ability of the PAR to withstand burns of up to 10 vol% hydrogen without structural damage.

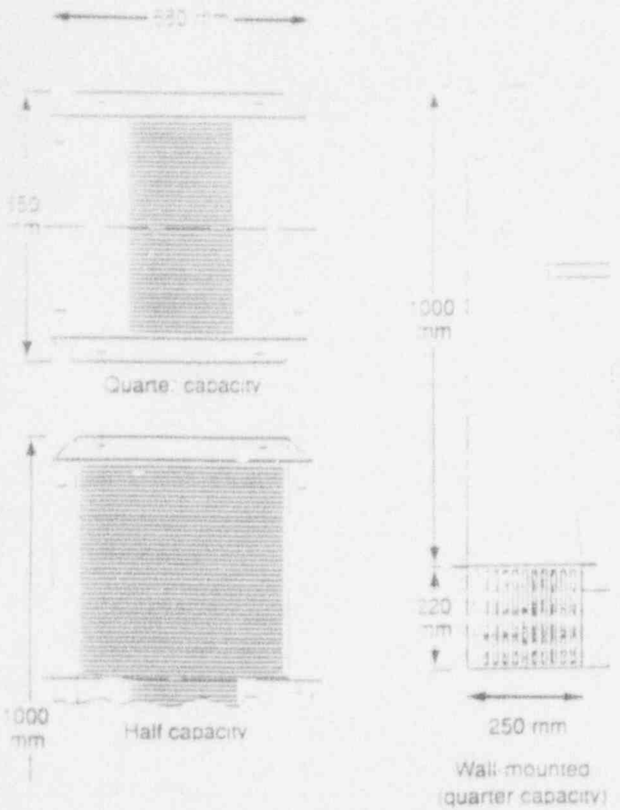

Figure 2. Sketch of Half-Capacity, Quarter-Capacity, and Wall-Mounted Quarter-Capacity NIS PARs

All but one of the model experiments were performed under conditions typical of severe degraded-core accidents in PWRs: pressures up to 2 bars, temperatures up to 125°C, and steam concentrations up to 50 vol%. Hydrogen concentration was about 3 vol% in most tests, up to 11 vol% in some. In addition to the tests with PWR-like conditions, one test was performed with 20 vol% hydrogen, 70 vol% steam, and 10 vol% air to simulate more the inerted SBWR condition. The atmospheric conditions for the model and prototype performance tests of the NIS design are displayed in the ternary diagram in Figure 3.

In each experiment, the following measurements were made: temperature rise in the catalyst material, convection flow velocity, and hydrogen concentration and gas temperature at entrance and exit. In addition, the history of hydrogen concentration, pressure, and relative humidity in the test chamber was measured. From these data the depletion rate and startup behavior of the models were determined.

A best fit to the model and full-size test data gave the empirical curves of NIS PAR depletion rate as a function of hydrogen concentration of the gas entering the device in Figure 4. Note that the depletion rate increases

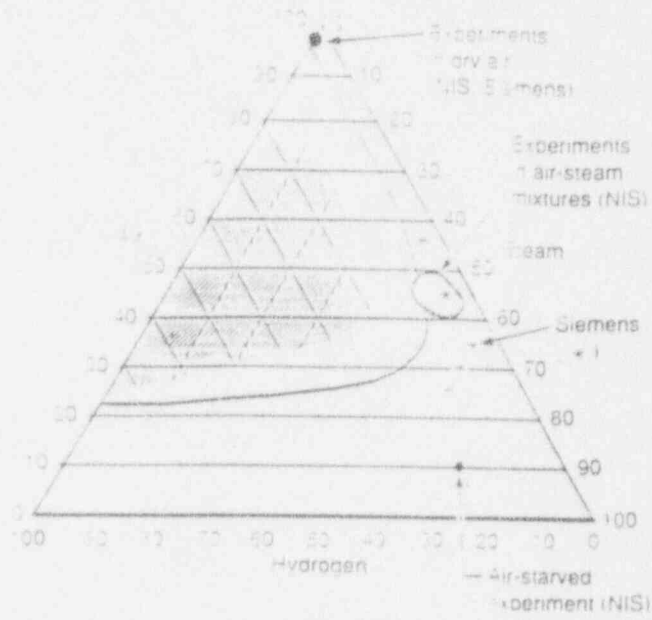

Figure 3. Ternary Diagram Showing Atmospheric Conditions for PAR Tests

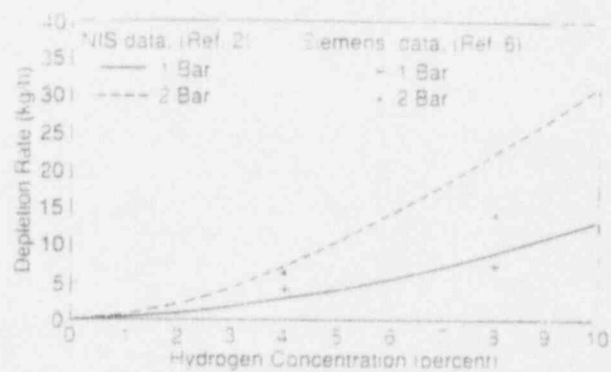

Figure 4. Experimentally Determined PAR Depletion Rates (1 bar = no steam, 2 bar = 50 vol% steam)

with increasing concentration and with increasing pressure.

The depletion rates in Figure 4 are primarily for tests in oxygen-rich gas mixtures. In the test with 20 vol% hydrogen, 70 vol% steam, and 10 vol% air (2 vol% oxygen) at 2 bars, function of the catalyst was confirmed for an oxygen-starved atmosphere. The measured hydrogen depletion rate was 2 kg/h, corresponding to an oxygen depletion rate of 16 kg/h. This compares favorably with the hydrogen depletion rate of 2.3 kg/h for 2 vol% hydrogen (or oxygen) at 2 bars from the oxygen-rich data in Figure 4. Therefore, the simplified analysis below uses the depletion rates for oxygen-rich mixtures in Figure 4 for both oxygen- and hydrogen-rich mixtures.

Note that on the basis of results from several model tests designed to examine the effect of inhibitors (such as sprayed water) and poisons (such as iodine, carbon monoxide, and soot from cable and oil fires) on the performance of the PAR catalyst system, it is justified to conclude that they do not significantly reduce the depletion rates of PARs determined from the tests without adverse conditions.

In summary, test data for the NIS PAR support the following features of the PAR approach (as indicated in the following subsections these features are shared to a large extent by the Siemens design):

• PARs are ruggedly constructed and can be installed to meet seismic qualification requirements.

• Small-sized versions of PARs can be installed in cramped areas.

• PARs begin the controlled catalytic recombination of hydrogen and oxygen upon exposure to these gases even at room temperature. They function for concentrations below the flammability limit or in hydrogen-rich and steam-inerted mixtures.

• PARs generate substantial convection currents by distributed forced ventilation (e.g., each full-size NIS device creates a gas flow of about 335 m^3/h for an oxygen or hydrogen concentration of 1 vol%). This promotes gas mixing, homogenizing the atmosphere and eliminating stratification.

• Performance of the catalyst is virtually unaffected by all of the known poisons that were selected for experimental investigation.

• Catalyst material is not measurably degraded or consumed as it functions and is not subject to long-term aging degradation (except perhaps for some contaminant buildup that could be cleaned by maintenance). Nevertheless, a surveillance program is proposed.

B. Siemens Design

Another candidate design of a PAR that could used for combustible gas control in the SBWR is the one developed and qualified by Siemens in Germany.[6]

A drawing of the device is shown in Figure 5. The operating concept of this device is similar to that of the NIS design. The recombiner consists of a metal housing designed to promote flow, with gas inlet on the bottom and gas outlet at the top. Numerous parallel thin-walled stainless-steel plates with a hydrophobic catalytic active coating are arranged vertically in the lower part of the housing. The basic design is configured for mounting on a vertical surface such as a compartment or containment wall or other structure.

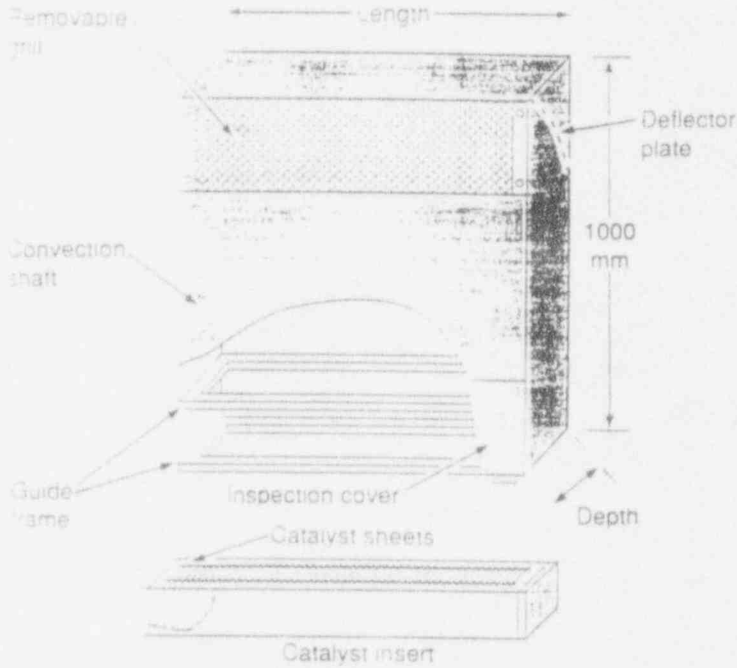

Figure 5. Drawing of the Siemens PAR Device (Available sizes -- Length(mm)/Depth(mm): 150/150; 400/150; 1000/150; 1500/300)

Development tests were conducted to optimize the configuration so that a maximum rate of recombination is achieved with a housing of minimum size. To allow flexibility in the arrangement of devices in the various compartment areas of a containment, the recombiner is available in sizes from 30-120 kg in weight (see caption of Figure 5).

Performance/qualification testing. In addition to development tests on model and full-size Siemens devices, an extensive test qualification program was conducted to measure their depletion rate under a range of hydrogen concentrations, steam/ pressure conditions, and various potential adverse conditions (see Figure 3). Some tests were conducted in the same Battelle multicompartment facility used for testing the NIS prototype. Qualification tests of the Siemens design to German requirements were conducted under an independent testing organization, TÜV. Measured depletion rates of the Siemens device are shown in Figure 4. Note that, even though the active cross-sectional area of the full-size Siemens design is about half that of the NIS design, the measured depletion rates are roughly the same, except for the case of high hydrogen concentrations with steam.

It was also successfully demonstrated that the depletion rate of the Siemens device is not significantly affected by impurities expected to be present during plant operation or in the containment atmosphere following an accident. The following potential catalyst inhibitors or poisons were included in the testing: fumes from welding and solvents, water, steam, elementary iodine, carbon monoxide, boric acid, methyl iodine, and oil or cable fire.

C. Aging Under Operational Conditions

Catalytic recombiners are constructed of metals and other materials whose physical properties do not change significantly under long term exposure to operating temperature and radiation environments in containment. For the Siemens design this fact was confirmed by accelerated aging tests. Because PARs have no significant aging mechanisms that cannot be tracked by in-service inspection, they are expected to have a qualified service life equal to the life of the plant—60 years for the SBWR.

Preventive maintenance. The only potentially significant aging degradation mechanism for catalytic recombiners is one that can be tracked by in-service inspection—that is, fouling of the catalyst cartridges due to settling or plateout of contaminants that might be present in the atmosphere of the containment during operation. Although such fouling is almost certain not to occur because of the normal precautions taken to keep the containment environment reasonably clean, a preventive maintenance program will be implemented to ensure that PAR devices are able to perform their safety function for their entire service life. This program will consist of periodic visual inspection of the catalyst surfaces in all of the recombiners in the system, supported by sampling surveillance performance tests.

Periodic visual inspections of the catalyst surfaces will be made during each refueling outage. If dust is observed, the catalyst cartridges or plates can be cleaned off with a vacuum or air hose.

In addition, periodic surveillance tests of catalyst performance will be conducted. A representative catalyst cartridge or plate will be removed from some PARs and taken out of the containment during refueling outage. (These will be replaced by new or renewed elements.) The removed specimens will be placed in a standard laboratory performance test apparatus at each station. A controlled flow of air containing a known quantity of hydrogen would pass through the specimen container. The measured temperature increase of the exiting gas after a specified time from start of gas flow would indicate whether any degradation of catalytic reaction (in comparison with baseline tests of new specimens) has taken place.

III. APPLICATION OF PARS IN SBWR CONTAINMENT

The first step in the design of any combustible gas control system is the determination of combustible gas generation. The Code of Federal Regulations[7,8] gives guidance concerning generated/released quantities of hydrogen and oxygen to be considered. In accordance with 10CFR50.34(f), advanced reactors must address combustible gas effects for a severe accident that releases an equivalent amount of hydrogen as would be generated from a 100% fuel clad metal-water reaction and the post-accident atmosphere must not support detonation. For design basis accidents, the average concentration of combustible gases must not reach the flammability limit. To meet regulations for design basis accidents, PARs need to be classified and qualified as safety-related.

For the pre-inerted containment of the SBWR, the time dependence of hydrogen release during severe accidents as well as the total quantity released are not of interest for the design of combustible gas control systems. The containment atmosphere at the start of an accident would have the maximum allowable pre-inerted oxygen concentration of 4 vol%. Any massive hydrogen release will only further reduce the relative oxygen concentration well below flammability limits. The only task for PAR devices is to consume the slowly generated radiolytic oxygen to assure that flammability conditions will never be reached. Therefore, loads from burning of combustible gas need not be considered in the design of the SBWR containment.

A simplified conservative analysis has been used to determine the required number of PARs distributed in the drywell and wetwell of the SBWR.[a] The analysis shows that only two PARs are needed to control oxygen for a design basis or severe accident. Therefore, before discussing the analysis, we give the rationale for the number of PAR devices tentatively selected for the SBWR. Note that, since the recombination rate for a full-size Siemens PAR is roughly the same as for an NIS PAR (see Figure 4), the determination of the number of PARs needed and the safety margin discussed below applies to both designs.

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[a]This analysis is essentially the same as that reported in Ref. 2 and leads to the same number of PARs in the combustible gas control system, but some of the parameters (e.g., the radiolysis gas release rates in accidents) have been updated with the latest information from GE for the analysis reported here.

A. Number and Location of PARs

Engineering judgment has been used to select the number and location of PARs in the SBWR. To give a reasonably uniform distribution of recombiner capacity throughout the containment, two full-size PARs for the wetwell and 8 quarter-size PARs (2 full-size equivalents) for the drywell are located as indicated in Figure 6.

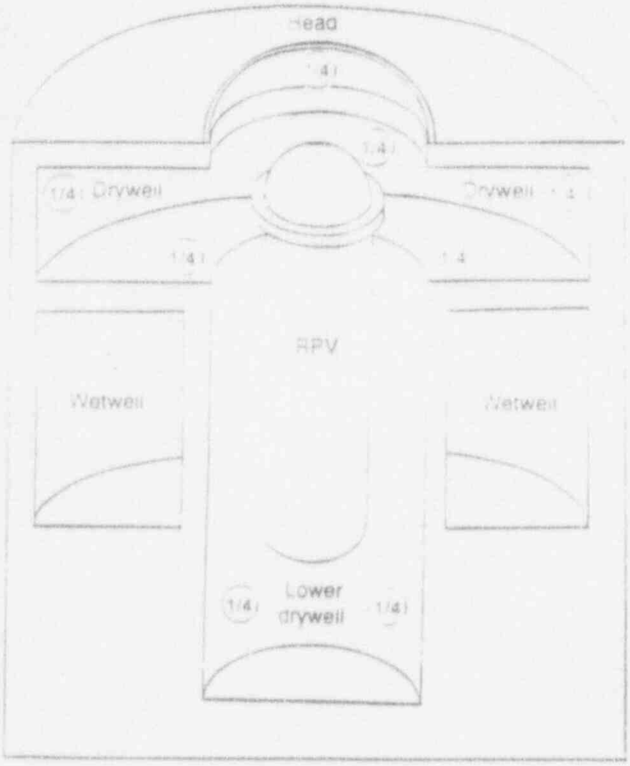

Figure 6. Preliminary Locations of PAR Devices (2 Full-Size and 8 Quarter-Size) in the Drywell and Wetwell of the SBWR (5 Quarter-Size PARs Distributed Around Drywell).

B. Simplified Conservative Analysis

The analysis assumes a uniform gas distribution averaged throughout the containment volume. For the SBWR, this assumption is valid because of the relatively low oxygen release rates and long times during which mixing can take place by diffusion and by natural convection; with PARs this mixing is enhanced by the forced convection produced once the recombination process within the PARs is established. Note also that the overall depletion rate of PARs distributed throughout the containment free volume has little dependence on actual hydrogen distribution, because regions of lower concentrations with slower depletion are balanced by regions of higher concentration with faster depletion (see Figure 4). This provides additional confidence that the simplified analysis with the uniform distribution assumption is adequate for estimating the required number of PARs.

The analysis also conservatively considers non-condensable gases only (i.e., no steam). With this assumption, steam condensation could not lead to any situation that is not covered by the design and needs no further consideration.

The containment atmosphere at the start of an accident is assumed to be at the maximum allowable pre-inerted oxygen concentration of 4 vol%. Any release of hydrogen into the containment from metal-water reaction during a DBA or a severe accident will reduce the relative oxygen concentration. The only task for the PAR system is to consume the additional oxygen slowly generated by radiolysis in the core (or in any effluent that has been released into the containment) at a rate sufficient to ensure that the initial oxygen concentration does not increase. This will ensure with margin that flammability conditions will never be reached.

During a severe accident assumed to have a completely degraded core, a preliminary estimate of the 72-hour average generation rate of radiolytic oxygen for the SBWR is 7.5 kg/h. This average continues to decrease as time proceeds, but the 72-hour average is used conservatively to determine the PAR capacity needed to prevent an increase in the initial oxygen concentration. Recombination of oxygen at this rate is equivalent to recombination of hydrogen at 7.5/8 = 0.94 kg/h. From Figure 4, the depletion rate of hydrogen for one PAR at 1 bar (with the conservative assumption of no steam) and 1.8 vol%[b] hydrogen is about 0.7 kg/h. Since the capacity of 4 equivalent PARs is then 2.8 kg/h, we see that they have about three times the capacity needed to keep oxygen from increasing above its initial concentration. The excess capacity of the 4 PARs is even greater for controlling oxygen in a DBA, for which the radiolysis rate is smaller and the PAR depletion rate may be greater (because the initial oxygen concentration is higher with less release of hydrogen from metal-water reaction).

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[b] A complete metal/water reaction of 100% of the clad would produce a hydrogen release of about 1000 kg. This amount of hydrogen assumed to be released immediately into a total free volume of the drywell and the wetwell of about 9300 m^3 decreases the initial 4 vol% of oxygen to 1.8 vol%. We enter the measured depletion curves in Figure 4 with an equal value of hydrogen concentration (1.8 vol%) because recombination within the PAR is governed by diffusion just as for the combustion limits of about 5 vol% for *both* hydrogen and oxygen indicated in the ternary diagram in Figure 3.

In summary, we can conclude from the simplified analysis (with the greatly conservative assumption of no steam) that four full-size equivalent PAR devices distributed throughout the SBWR containment would ensure oxygen levels during either a DBA or severe accident are maintained well below the flammability limit.

After an accident, PARs will eventually reduce the mixture of combustible gases to one where the concentration of the limiting (less prevalent) reactive gas in the containment is essentially zero. PARs can also be employed to remove residual postaccident hydrogen by the controlled gradual injection of air into the containment.

IV. PAR COST STUDY

A cost study was performed to examine the life-cycle economic feasibility of the PAR concept. This cost study generated estimates of costs for PARs versus the originally envisioned igniter-based combustible gas control system for the SBWR. (Although the study was made only for the NIS PAR design, a similar conclusion would likely be reached for the Siemens design.) Costs were categorized as capital costs (in today's dollars) and O&M costs (in man-hours per refueling cycle). NIS provided the estimates of capital cost for PARs. GE and equipment suppliers provided the estimates of capital costs of the igniter-based design. Quality assurance costs were not included in the study (they would be about the same for different combustible gas control systems).

The table below summarizes the results of the study.

System	Capital ($1000)	O&M (Man-H/Cycle)
Original Igniter System	482 (42 igniters)	64
PAR System	165 (4 equiv. PAR units)	24

The following paragraphs give information on how the costs were estimated.

A. Cost of PAR System

1. Capital Costs. Capital and engineering costs are estimated to be:

Capital Cost for a full-size PAR Unit = $20,000

Engineering Cost = $75,000

Although most of the engineering cost can probably be shared by all of the plants in an SBWR family, we conservatively will retain it as a per-plant cost.

The estimated $100,000 cost for generic seismic and environmental qualification of PARs to U.S. standards can be expended once for all PARs in a family. Therefore it is not included in the per plant capital costs.

The total estimated installed cost of the 4 "equivalent" PARs, engineering costs, and the $10,000 cost of surveillance test equipment is $165,000. This does not include potential savings in battery size reduction.

2. O&M Costs. Because very little specific data was found to be available to use as a baseline for O&M costs, O&M time estimates are based on judgments and operational insights from utility personnel as to what would be considered reasonable in terms of man-hours to perform the required inspections and tests.

The O&M costs for PARs are based on the inspection and plant laboratory performance surveillance testing described earlier. Due to the 60-year design life of PARs, no replacement costs are anticipated. The total estimated man-hours per cycle for inspection/testing of the PAR system is 24. This assumes that the inspection is done by 2 technicians of 10 (2-full-size, 8-quarter-size) PARs that are reasonably accessible and includes the changing of 5 catalyst cartridges (16 man-hours) and that the testing is done by 1 technician on 5 catalyst cartridges and includes setup and knockdown time (8 man-hours).

B. Cost of Igniter System

1. Capital Costs. The original SBWR design for combustible gas control was an inerted containment combined with 2 divisions of 21 safety-related igniters each. The igniters were glow plug or spark type wired to remote batteries backed by AC power. The total estimated installed cost of the 42 igniters, including engineering, is $482,000. The cost of the additional battery power needed is not included. As for the PAR system, the cost of qualification is not included.

2. O&M Costs. The surveillance/preventive maintenance program for the original SBWR combustible gas control system consisted of a visual inspection of each igniter, a system functional test for each division of igniters, and an infrared temperature measurement and resistance to ground test of each igniter at each refueling cycle.

The total estimated man-hours per cycle for inspection/ testing of the igniter system is 64. This assumes that the inspection is done of 42 igniters that are reasonably accessible by 2 technicians (32 man-hours), the functional test is done by 1 operator and 2 technicians taking 4 hours per igniter division (24 man-hours), and the resistance check is done by 2 technicians with circuits centrally located taking 2 hours per division (8 man-hours).

In summary, the above estimates indicate that initial and operating costs of PARs are roughly a third of the costs of the originally-envisioned igniter-based adjunct to pre-inerting.

V. SUMMARY AND CONCLUSIONS

PARs are consistent with the ALWR design philosophy, being simple and passive in nature (no need for electrical or other support systems, therefore, invulnerable to loss of off-site power). Extensive performance testing of two designs has demonstrated a long list of desirable attributes, including functioning in a steam-inerted atmosphere and resistance to potential adverse conditions and catalyst poisons.

A simplified conservative analysis has shown that a PAR system assures the inerted conditions that exist at the onset of an accident in an SBWR will never be lost and there will be no deflagration during design basis or severe accidents. Four full-size-equivalent PAR units control the oxygen to well below 4 vol% for both design basis and severe accidents. A cost study indicates capital and O&M costs roughly a third of those for an igniter-based system.

Thus the PAR approach meets regulatory requirements for combustible gas control while being simpler, easier to maintain, and more cost-effective than conventional systems. Upon acceptance of the PAR approach by the NRC and implementation by the designer using a more detailed and in-depth design and analysis process than discussed in this paper, the issue of hydrogen control in SBWRs will have a cost-effective resolution.

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5. U. Behrens, M. Seidler, and U. Wolff, "Hydrogen Mitigation using Catalyst Modules," *Proceedings of a Workshop on Hydrogen Behavior and Mitigation in Water-Cooled Nuclear Power Reactors*, Brussels, March 1991, 286 (1992).

6. R. Heck, G. Kelber, K. Schmidt, and H. J. Zimmer, "Hydrogen Reduction Following Severe Accidents using the Dual Recombiner/Igniter Concept," *SMiRT 12 Post Conference Seminar: Containments of Nuclear Reactors*, Karlsruhe, Germany, August 1993.

7. 10CFR50.34(f), "Additional TMI-Related Requirements," Subparagraph 50.34.(f)(1)(xii).

8. 10CFR50.44, "Standards for Combustible Gas Control System in Light-Water Power Reactors."