



December 22, 1993

Dr. Douglas Stamps
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Subject: Additional Information Concerning the ALWR Report
"Qualification of PARs for Combustible Gas Control in ALWR s,"
April 8, 1993

Dear Dr. Stamps:

In response to your telephone request for additional information on the subject document, we are pleased to enclose the answers to your questions. We understand this information will be useful in performing Sandia's review of the PAR report requested by the NRC. As a part of the additional information, we include an ANS paper by Wolff and Sliter that expands on the approach and rationale in the ALWR report for how the PAR approach addresses the possibility of local hydrogen concentrations that might exceed the average concentration in the containment for short time periods.

Feel free to call Dr. George Sliter at 415-855-8699 if you need any clarification or further information.

Very truly yours,

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ALWR ANSWERS TO QUESTIONS ON PARs
FROM
SANDIA NATIONAL LABORATORIES

December 21, 1993

[Note that almost all of these questions focus on hydrogen conditions and PAR performance related to application in PWRs and not BWRs. For inerted BWRs like the ALWR SBWR, PARs perform their DBA and severe accident function by keeping oxygen levels less than the flammability limit of about 4 vol%. This function is not as challenging for a PAR system compared with hydrogen control in postulated severe accidents in PWRs.]

1. Page 26, third paragraph. How are contaminant levels measured in the tests and how do they compare with actual expected severe accident levels?

The contaminants are smoke/soot from burning oils and electrical cables, elemental iodine, and carbon monoxide.

Smoke/Soot Neither the quantity of smoke particles that the PAR model was exposed to from burning oils and electrical cables directly below the unit (see Fig. B.17) nor the quantity of contaminant that settled onto the catalyst pellets and cartridges was measured. However, it was observed that the cartridges were heavily coated with oily film and soot after removal from the half-hour fire. Surely the contamination included a significant level of hydrocarbons that condensed on the initially cool catalyst pellets. This exposure and contamination is viewed as being much worse than would be expected in an actual accident in which the fire is not nearly as close to a PAR and for which burn products would be much more diluted than in the test.

Elemental Iodine Three grams of solid crystalline iodine were heated in a plate two inches below a PAR model in a test compartment volume of 10 m³. (The ALWR PAR report mistakenly identified the iodine as being in liquid form.) If the sublimed elemental iodine vapor were allowed to diffuse into the open volume (and not plated onto the PAR) the concentration would have been 0.3 g/m³. This is about the same as estimates of released iodine in advanced PWRs (0.30 g/m³ for AP600 and 0.33 g/m³ for System 80+). Although the concentration of iodine in the plume of elemental iodine vapor to which the PAR model in the test was exposed was not measured, it was certainly orders of magnitude greater than expected in worst case accident exposures. The test results showed no effect on depletion rate at 4 vol%, and a small effect at lower concentrations (see Fig. B.18 in the report, which was inadvertently referred to as Fig. B.17 in the fifth paragraph on page 55).

Carbon Monoxide A PAR model was tested in an atmosphere containing 1 vol% carbon monoxide. This was the maximum concentration allowed by test personnel safety considerations. The maximum concentration of CO from core/concrete interactions is expected to be from 2 to 3 vol%. The performance test with the lower concentration is considered to be sufficient because (1) it showed no reduction in PAR depletion rate (see the attached plot of hydrogen concentration with and without CO; this plot was inadvertently omitted from the report -- it should be referred to in the sixth paragraph on page 55 as Fig. B.19), (2) CO was depleted by recombination at the 1% level (gas chromatography measurements of samples extracted from the chamber during the test showed that the concentration of CO decreased by one third as the hydrogen concentration decreased from about 4 percent to about 1 percent; (3) there is no known physical reason why a threefold increase in concentration would significantly increase poisoning effects of CO or decrease the efficiency at which it is recombined, and (4) peak CO concentration would occur late in an accident scenario after much hydrogen and oxygen has been already been recombined.

2. Page 27, Section 3.3. Can a PAR act as an igniter at hydrogen concentrations greater than the 10 vol% for which it was shown by test to not ignite the atmosphere?

Hydrogen concentrations greater than 10 vol% could not be tested, because the experimental facility available was not designed for the loads from a possible burn of gas mixtures richer in hydrogen than this. Furthermore, testing at higher levels was not viewed as an important need because it was felt that for severe accidents the exposure of PARs to hydrogen concentrations greater than the maximum eventual peak average of 10 vol% for any length of time is highly unlikely even for large release rates.

In response to this question, a further basis for the premise that the PAR would not act as an igniter for best-estimate severe accident hydrogen release and mixing scenarios will be discussed here.

It is conceivable that the PAR could act as an igniter either by the hot outer surface of its steel enclosure or by ignition of the gas stream at the hottest region inside the PAR and propagation of the flame front downwards to ignite the outer ambient gas mixture at the bottom entrance. (The flame front from a potential ignition would not propagate upwards because it would not propagate into the depleted exit plume.)

Sandia research has concluded on the basis of ignition experiments in a free volume that self ignition of a 4.5 vol% hydrogen/dry air mixture (oxygen about 5 vol%) can occur at a temperature of 600°C. Under certain circumstances this concentration and temperature can exist within the PAR.

In order for the outside surface of the box to ignite the surrounding gases, it would have to reach a temperature of at least 935°C. Because this surface is cooled by the ambient atmosphere it would reach such a temperature only after internal temperatures were very high. Therefore, if ignition can occur, it would

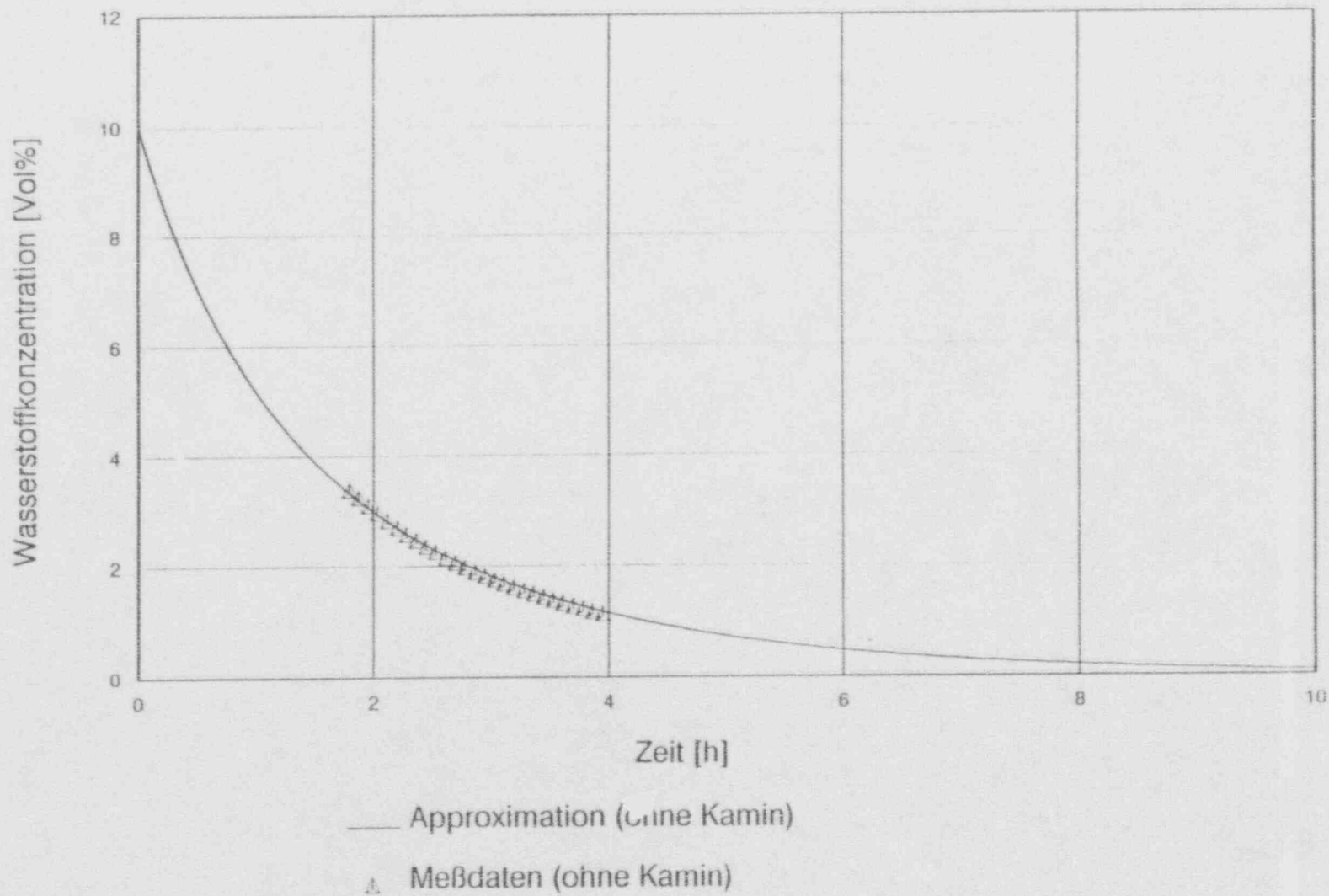


Bild 7-8: ⁰⁻¹⁹ Vergleich der Approximationsfunktion mit den Meßdaten; Versuch M: 1.2.3 (CO)

be the potentially ignitable conditions on the inside of the PAR that would govern the onset of ignition.

It should be noted that a temperature greater than 600°C is most likely needed to produce ignition within a PAR because of the very small volume of gas involved in relation to the free volumes in the Sandia research data. Also, propagation of a flame front may require greater temperatures because (1) the fine wire mesh surrounding the pellets acts as a barrier to flame propagation (a mesh was used to prevent the light source on early miners' hats from igniting the atmosphere) and (2) more severe conditions than in a free volume would be needed to produce downward flame propagation in the 1-cm-wide confined gas channel within the PAR because in the PAR a flame would have to propagate against a flow and into a cooler gas.

Nevertheless, since exhaustive experimental data is not available at this time, we examine (1) the range of conditions outside the PAR that are needed to produce the internal conditions given above and assumed to cause ignition and (2) the circumstances under which such conditions could be reached and how likely such circumstances are in severe accident scenarios.

Closed compartments:

Consider a compartment that is relatively closed to the open volume of the containment (or that has been purposely closed by means of the "PAR venting" design measure described in the attached ANS paper). We take as an example the AP600 IRWST gas space. The volume of this gas space varies, depending on water level, between 73 m³ (2700 ft³) and 220 m³ (8100 ft³).

A simple analysis can be made of the conditions in this volume, and the release compositions and rates required to produce these conditions. The temperature of the gas stream through the PAR increases 80°C for each 1 vol% of hydrogen that is recombined. (It can be assumed that the peak temperature of the gas is only slightly less than the peak temperature reached on the catalyst surface at some height within the PAR). Assuming an atmospheric temperature of 80°C, the concentration of hydrogen at the entrance of the PAR necessary to produce an internal peak temperature of 600°C and a corresponding concentration of 4.5 vol% is $4.5 + (600 - 80)/80 = 11\%$. Actually, it would take an entrance concentration of 12 vol%, because of the dilution contributed by steam created by the recombination. The oxygen content at the entrance has to be about 9 vol% to give about 5 vol% at the potential ignition location.

Starting from ambient temperature, it would take about three minutes for the PAR to overcome its thermal inertia and reach peak temperature. This then is taken as the thermal response time of the unit.

The analysis calculated the injection flow rate R₁ needed to reach 12 vol% hydrogen concentration in the compartment and the flow rate R₂ that would inert the volume by reducing the oxygen concentration below 9 vol%. For injection rates lower than R₁ the PAR would recombine at a rate great enough to prevent reaching 12 vol%. For injection rates greater than R₂ the concentration of oxygen would be reduced to levels that inert the internal mixture before the PAR

could reach 600°C. Ignitable conditions would be produced only if the average release rate from the time of initial release were maintained between these limits long enough for the PAR to act as an igniter.

The conditions quoted above can be reached for a volume of 73 m³ and a release with no steam only if the release rate of hydrogen stays for more than three minutes in the range of R₁ = 0.01 kg/sec and R₂ = 0.02 kg/sec (for 220 m³, R₁ = 0.01 kg/sec and R₂ = 0.05 kg/sec). This window of injection rates shrinks to zero as injection steam content increases to 35 vol%. Furthermore, any prior steam or hydrogen release would reduce the size of the window.

These results demonstrate that it is highly improbable to ever reach an ignition caused by PAR in an IRWST gas space during severe accidents.

Open containment volume:

For a large open volume, we are concerned only with injection rates great enough to cause one or two of the several PARs deployed in the open volume to be exposed to greater than 12 vol% for some time. To reach the postulated internal conditions for self ignition with downward propagation in a PAR, the entrance of the device must be exposed to a gas mixture falling into the following range of conditions for a minimum duration of about 3 minutes:

Steam content <35 vol%, temperature > 80°C, air with non-depleted oxygen content, and the following volume fractions:

- impossible to have high release rates with no steam
- steam = 0.20, 0.12 < H₂ < 0.3, the rest air
- steam = 0.10, 0.12 < H₂ < 0.4, the rest air
- steam = 0.00, 0.12 < H₂ < 0.5, the rest air

With a PAR placed sufficiently far from potential release points, these concentrations are unlikely to occur and remain for 3 minutes at the PAR location. This will need to be verified by detailed system design including analysis of gas mixing and hydrogen dilution for the relevant severe accident scenarios.

3. Page 32, 3rd paragraph. How was the flow rate through the PAR determined for different hydrogen concentrations?

In tests with hydrogen concentrations up to 3 vol%, anemometers were used to measure exit velocities and flow rates. These devices did not work at higher velocities. For the range in which velocities were measured, it turned out that flow rates calculated on the basis of measured depletion (i.e. a certain flow rate is needed to remove a known mass of hydrogen) matched the measured values. Flow rates were therefore calculated from measured depletion rates for concentrations greater than 3 vol%.

4. Page 35, middle bullet at middle of page. At what surface temperature does the surface of the catalyst oxidize?

Oxidation of palladium occurs at a continuously increasing rate with increasing temperature but remains small/insignificant even at high temperature. The rate of weight loss at 600°C is 10^{-7} g/cm²/hr and at 1400°C is 10^{-4} g/cm²/hr (ASM Metals Handbook, Volume 13).

5. Page 37, 2nd full paragraph. At what temperature does palladium oxidize carbon monoxide? What effect do concentrations of CO greater than the 1% used in the test have on PAR performance?

See answer to question 1.

6. Page 37, Wetting (and page 54, Wetted Catalyst in Saturated Steam). What is the maximum rate of spray onto a PAR for which it can still function?

Catalyst surfaces cannot function if the gases to be recombined cannot reach the surfaces because they are totally wetted (submerged or deluged with spray). A model PAR was sprayed with water for one hour and then tested while being sprayed at the same rate (the rate was not reported). These conditions were intended to represent a PAR wetted by heavy condensation and then called upon to function in a heavily condensing atmosphere. A test was not performed to determine the maximum spray rate for which a PAR can still function. There are no containment sprays in the AP600. If containment sprays are deployed during a severe accident such as in the System 80+, their effect would have to be examined in light of the test data with sprays. Either analysis using the empirical data would show that the PAR system would perform adequately even with the spray or the PARs would have to be rigged with a spray protector (umbrella).

7. Figure 5.2a. Why are no PARs indicated/located in the reactor cavity for the System 80+? (Two PARs are shown in the central region of the containment in Figure 5.2b.) A count of PARs in Figure 5.2a gives 42, not 40, even without the two "missing" PARs.

PARs are not deployed in the reactor cavity of the System 80+ because the cavity has a small free volume, most of which is isolated from the containment open volume by bellows between the reactor vessel (near its top) and the shield wall. The two PARs shown in the central region of the containment in Figure 5.2b are installed near the top of the dome open volume. They were inadvertently not shown in Fig. 5.2a. With the addition of these two "missing" units, a count of the PARs in the figure would give 44, not 40. To give the 40 PARs required by the simplified analysis, only 16 (not 20) PARs would be equally spaced at 22.5 degree intervals around the outside of the crane wall. Remember that locations for PARs shown in this report are shown for illustrative purposes only -- more in-

depth study by designers would be needed to select trial locations that would then be evaluated for adequacy by code analysis.

8. Figure 5.3b. What is the rationale for location of PARs above pools in the SBWR? Is a quarter-size PAR located at each sparger in pool?

Quarter-size PARs would simply be located at equal spacing above pools in the SBWR. No attempt would be made to place a PAR at each sparger location. PARs work best when (1) located at a distance from gas injection points sufficient to dilute pure released gases with ambient gases and (2) spaced uniformly and at locations that allow maximum mixing from forced convection produced by the PARs. For maximizing recombination, it is counterproductive to place PARs too close to expected release points.

9. Figure 5.3c. What is the rationale for the 2 PARs indicated in this figure?

These are two full size PARs located on each side of the open volume of the drywell. It was judged that the volume is small enough and open enough so that mixing and depletion of oxygen from these 2 PAR units is adequate.

10. Page 45, 5th paragraph. GRS has their catalyst plates stacked in an inerted box to avoid contamination during plant operation and automatically are unfolded and lowered during an accident. Did NIS consider doing this? Why was it not done?

Yes, NIS did consider placing catalyst cartridges in an inerted enclosure to avoid contamination during operation. It was decided not to do this because (1) the unprotected design avoids the complex and potentially unreliable mechanisms needed to deploy the catalyst when needed (the GRS design activates an opening and unfolding process upon a signal from temperature and pressure sensors built into the recombiner unit); (2) the NIS design has an immense reserve catalyst surface area that was expected to be resistant to contamination; this design has orders of magnitude more catalyst surface area than the plate design of GRS -- this expected resistance of the pellet design has been confirmed by test (apparently, the GRS designers wished to eliminate the need for testing for contamination).

11. How were hydrogen concentrations measured in an air/steam environment (this is usually difficult)?

Two methods using two different sensing devices were used in each experiment. The first used a gauge to measure the total pressure in the chamber. The saturation temperature was then determined on the basis of steam tables and the measured temperature. A gas sample was extracted and allowed to condense. The measured pressure of this sample was the partial pressure of hydrogen. This partial pressure was converted to the partial pressure at room temperature. The

concentration of hydrogen was then calculated from the concentration of hydrogen in the sample (from gas chromatography) multiplied by one minus the ratio of saturation pressure and total pressure. The second method used a sensing device for measuring the heat conduction of a gas sample and comparing to a calibration curve of known hydrogen concentrations. In all tests there was good agreement between the two methods.

12. Page 55, 5th paragraph. Exactly what was the formulation of the "liquid iodine" below the model? Does elemental iodine form when this liquid iodine evaporates? How was iodine in the plume of evaporated liquid iodine measured? How does the test amount compare with that expected in an accident?

See answer to question 1.

13. Page 57, 2nd full paragraph. This paragraph needs clarification. What was the partial pressure of air in test MC-3. If it was 0.5 bar, explain how this condition was achieved and determined?

A continuous readout of pressure was available. Before adding hydrogen, a 50/50 mixture of air and steam at 1 bar was created based on measured temperature and a steam table. As hydrogen was added to reach the desired level, the pressure of 1 bar was maintained by venting. The concentration of hydrogen at the start of the test was measured as in question 11. With this process the partial pressure of air had to be less than 0.5 bar.

14. Page 57, first paragraph of section C.3. Is 12 m³/hr an appropriately scaled hydrogen injection rate compared to expected rates in plants?

No, this rate is much lower than that expected in some accident scenarios. Higher hydrogen concentrations could not be tested, because the Battelle experimental facility was not designed for the loads from a burn of rich hydrogen gas mixtures. It was not intended that this flow rate be scaled to the expected injection rates in plants. The objective of these tests was mainly to measure the depletion performance of full-size PARs in a steam environment and to test the structural integrity of the PAR under hydrogen deflagration. It was realized that another objective, to determine PAR performance with distribution and mixing in multiple compartments, would be achieved, but only for injection rates and concentrations that would be lower than possible injection rates and local concentrations in some plant accidents. In terms of the injection, distribution, and mixing regimes discussed in the answer to question 19 below, this test series does not address Regime I (injection and initial mixing into a single compartment), but does address Regimes II and III (distribution and mixing in compartments and larger open volumes) to the extent allowed by the configuration and strength of the Battelle facility. It was felt that the levels of

hydrogen introduced in the tests were adequate to obtain the desired performance objective concerning these two regimes.

15. Page 57, last paragraph. What room does the data in Fig. C-10 apply to? If it applies to all the rooms, how was the measured curve derived?

The variable plotted in this figure is the average concentration of all the rooms included in the experiment. It was created electronically by combining the signals from all rooms (the blips in the curve are electronic disturbances of some sort).

16. Page 58, first paragraph. It is stated that for prototype test MC-2, "The delay was the time for the catalyst reaction to deplete the condensed steam before the reaction could continue." The previous sentence seems to imply that this happens only because the hydrophobic coating was no longer active. Wouldn't condensed steam have to be depleted even if the coating was active? Would this delay be characteristic of a PAR without hydrophobic coating?

It is true that this delay occurs only for a catalyst without a hydrophobic coating (or one for which the coating has been deactivated by damage). The delay is that required to boil off water clinging to or absorbed by the catalyst pellets. (Note that the delay is about one half hour for the less than 1 vol% mixture to which the PAR was exposed during the delay -- the delay would be less for higher concentrations.) There was almost no delay observed in test in which a hydrophobic coating was present to dramatically reduce water clinging and absorption (i.e. there was little condensed steam to boil off). It is for this reason that it may be best to use pellets with hydrophobic coating. The cost-effectiveness of applying the coating should be examined as part of the final design and qualification of a PAR system.

17. Page 58, last paragraph. Do the "different geometries" for which the empirical constants were corrected related to the PAR geometries or to the room geometries?

They relate to the PAR geometries and not the room geometries. The correction was needed simply to adjust for the different inlet areas for the two model sizes. To be clearer the sentence should read "To compare the functions obtained from the two different experiment types, the depletion rates must be corrected for the different inlet areas." Also, the figure referred to in the last sentence should be D.1 and not C.14.

18. Page 60, first paragraph. Does the "this" in the last sentence refer to not knowing that there were asymmetric injections or to not knowing (or the code not being able to model) the strong convection current produced by the injections? Once the feature of asymmetric injections was introduced into the

code solution, how many adjustments needed to be made in the solution method to give the desired prediction of measured results?

The "this" referred to not knowing that there was going to be injections at all during the test. When the original calculation was made, it was planned to run the experiment after preinjection of steam, so that no steam injections were included in the analysis. However, it was found that steam had to be injected during the test in order to keep the pressure at 1 bar as steam condensed. For the post-test calculation, this test condition was introduced into the mathematical model and the results shown in the report were generated by the code with no further calculations involving adjustments of the solution method.

19. Section C.5. Was the Gothic code run in a lumped parameter or finite difference mode (if the latter, what was the grid size?) Also, considering the notorious uncertainty of Gothic-type codes for accurately predicting hydrogen distribution (e.g. in the HDR tests) and the fact that the Battelle multicompartment model containment tests used to benchmark the code has a scale factor of four less than full scale, what rationale can be used to conclude that code calculations together with engineering evaluations of mixing and PAR performance are adequate for designing a PAR system for a passive ALWR?

The Gothic code was run in the lumped parameter mode. It is mainly this feature or limitation that has led to the well known fact that the code can not accurately predict certain thermal hydraulic parameters in certain three dimensional geometries under certain conditions. For example, the Gothic code and similar lumped parameter codes significantly underpredicted concentrations of hydrogen in the upper parts of the HDR containment for a test in which hydrogen was injected in the central region and stratification played a significant role during the distribution process. For this reason, it is important for the designers to consider this limitation when using the code to design and evaluate a PAR system. The degree of reliance on code predictions should vary with the various regimes of hydrogen release and distribution. There are three regimes that need to be treated separately when formulating acceptably sound engineering approaches for designing a PAR system.

The first, Regime I, involves the initial release, mixing, and distribution into one compartment or volume. It is so small that characteristic mixing times of gas plumes are of the same order as the response time of igniters and are significantly shorter than the response time of PARs. During this phase, it is intended that an igniter would ignite ignitable mixtures but a PAR would not have had enough time to recombine any significant amount of hydrogen released at intermediate or large rates. Also during this phase, the code cannot predict the mixing and distribution within the volume, but can give a reasonable estimate of average parameters as they build up. This regime was not modeled in the

Battelle multicompartment tests because the facility could not support the release of large amounts of hydrogen at high rates.

The second, Regime II involves transport of gases out of the first compartment, either into other small compartments or into a large open containment volume. The regime includes only the compartments and not the large open volume itself. For this regime the adequacy of the code to predict PAR performance and hydrogen distribution among compartments was confirmed by comparison with measurements from the Battelle multicompartment tests. (The difference of a factor of four between the volume per PAR in these tests and in a plant is not viewed as being great enough to invalidate this conclusion.) For this regime, the code can provide an adequate basis for evaluating the adequacy of a PAR system (numbers, sizes, and locations) that has been initially configured on the basis of test experience, engineering judgment, and simplified calculations.

Regime III involves transport and mixing of hydrogen into the large containment open volume. It is in this regime that potential code inaccuracies and the unavailability of full-scale mixing experiments require that code design calculations be augmented by other factors and approaches. (Note however that the uncertainties in the code calculations are expected to decrease in the presence of forced convection from the PARs which will tend to dominate over buoyancy and natural convection effects.) As indicated in the PAR report, PARs in the open volume will be distributed uniformly (i.e. in approximate proportion to the free volume in an area) and placed to maximize convection flow while avoiding regions in which peak counter flows from natural convection are expected (or predicted by code calculations). Uncertainties in code predictions for Regime III can be addressed by both adding margins of conservatism to the predicted peaks in hydrogen concentration and by appealing to the fact that the overall depletion rate of the PARs in the open volume has little dependence on gas distribution because regions of lower concentrations with slower depletion are balanced by regions of higher concentrations with faster depletion.

20. If glow plugs were used instead of PARs, is it acceptable that a station blackout would render them ineffective?

No. PARs offer the advantage of not depending on AC power, nor any other power source.

21. What were the maximum concentrations with and without steam tested in the prototype facility?

The maximum concentration of hydrogen in the prototype tests was 4.8 vol%. All prototype tests had roughly 50 vol% steam. The maximum concentration of hydrogen in the model tests was 11 vol%.

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

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ABSTRACT

A key aspect of the worldwide effort to develop advanced nuclear power plants is designing to address severe accident phenomena, including the generation of hydrogen during core melt progression (metal-water and core-concrete reactions). This design work not only resolves safety concerns with hydrogen, but also supports the development of a technical basis for simplification of off-site emergency planning.

The dominant challenge to any emergency planning approach is a large, early containment failure due to pressure excursions. Among the potential contributors to large and rapid increases in containment pressure is hydrogen combustion. The more improbable a containment-threatening combustion becomes, the more appropriate the argument for significant emergency planning simplification. As discussed in this paper, catalytic recombiners provide a means to passively and reliably limit hydrogen combustion to a continuous oxidation process with virtually no potential for containment failure in passive advanced light water reactors (ALWRs).

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 (in addition to safety) design simplicity, maintainability, and preference for passive components that do not have moving parts and do not rely on active power sources or support systems. These principles have led to adoption of the passive autocatalytic recombiner (PAR) as the preferred approach required by U.S.-utility and international ALWR participants for controlling combustible gases in ALWRs.²

PARs perform their function passively, sucking atmospheric gases containing hydrogen and oxygen at the bottom of a steel box-like device and blowing out water vapor from recombination at the top. Inside the device, recombination occurs at the surface of porous palladium-coated ceramic pellets used as a catalyst. 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 of combustible gases in a containment. Hydrogen in PWRs (or oxygen in inerted BWRs) begins to be recombined as soon as it is introduced. The recombination rate of a number of PARs distributed throughout a containment volume keeps the average concentration of hydrogen (or oxygen) below regulatory limits based on representative release rates. 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.

This paper gives a brief description of the design and qualification of PARs and how they would be implemented in *passive* ALWRs. (If this application appears sufficiently *cost-effective*, PARs could be considered for *nonpassive* ALWRs or operating plants.) The paper then contrasts the PAR approach with conventional hydrogen control systems based on igniters.

Although the PAR concept is applicable to control of combustible gases released during both design basis accidents and severe accidents in both PWRs and BWRs, this paper concentrates on the PAR system design for mitigation of severe accidents in PWRs. (A PAR system designed to meet combustible gas control requirements for severe accidents will assure that combustible gas concentrations for design basis accidents will remain well below flammability limits at all times. The Appendix gives a brief description of PAR application in a BWR.)

DESIGN AND QUALIFICATION OF PARs

The candidate design of a PAR system used for the ALWR feasibility study discussed in this paper is the pelletized 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.³ (Note that there are other catalytic recombiner designs that could perform the functions; these other designs are also candidates for selection by ALWR plant designers.)

The NIS/RWE PAR device shown in Figure 1 is a "molecular diffusion filter" (not the more conventional fixed-bed particle 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 spherical catalyst pellets having 1-cm-wide open flow channels between the cartridges. 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 sucked 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.

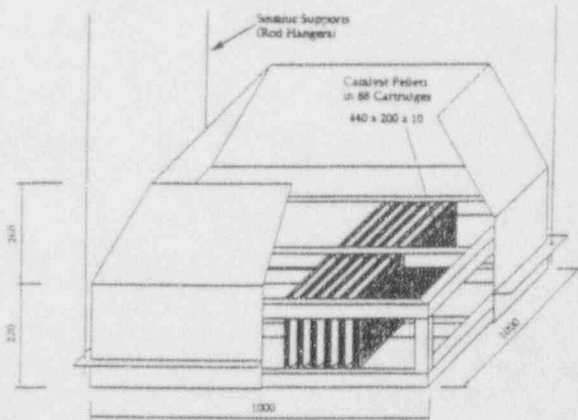


Figure 1 - Drawing of the Prototype PAR Device (Dimensions are in cm.)

Design optimization, extensive determination of performance characteristics, and qualification of the PAR device has been realized through a three-phase test program performed by NIS and Battelle⁴ that included screening tests of various catalysts, model tests to characterize performance, and full-size prototype tests in a multicompartiment model containment.

A best fit to the model and prototype test data gave the empirical curves of PAR depletion rate as a function of hydrogen concentration of the gas entering the device in Figure 2. These values of depletion rate were used for the benchmarking mixing and distribution code calculations and the simplified depletion analysis of a containment discussed in the next section. Note that on the basis of test results designed to examine the effect of poisons, such as iodine and carbon monoxide, on the performance of the PAR catalyst system it is justified to conclude that they do not significantly reduce the performance of PARs given by the curves in Figure 2.^{2,3}

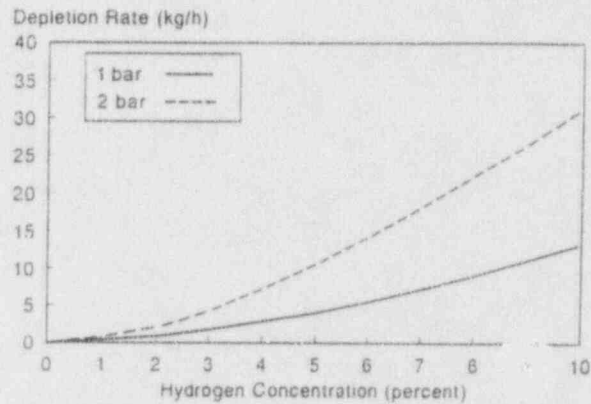


Figure 2 - Experimentally Determined PAR Depletion Rate as a Function of Hydrogen Concentration (1 bar = no steam, 2 bar = 50% steam)

APPLICATION OF PARs IN ALWR CONTAINMENTS

A simplified, conservative analysis has been used to investigate the feasibility of applying the PAR concept to plants. The analysis assumes a uniform gas distribution averaged throughout the containment volume and, therefore, treats only the global aspect of hydrogen control (i.e., ensuring that global concentrations do not exceed regulatory limits, thereby ensuring that the containment can perform its function even during severe accidents). More sophisticated thermal-hydraulic computer codes (such as the COBRA-NC/GOTHIC code) will eventually be used by designers to perform detailed analyses of specific plant applications. These analyses will treat both global and local aspects of hydrogen control. Regarding local aspects, the overall approach must prevent any situation producing a local detonation (or flame acceleration near detonation) that compromises the safety functions of structures or equipment in a local region or compartment. In the following paragraphs, we (1) describe the simplified analysis and results of a PAR plant application, (2) discuss the factors that justify use of the simplified analysis for this feasibility study of global performance, and (3) discuss the factors and measures that

the PAR concept relies upon to address the possibility of local detonations.

Conservative Simplified Analysis

The first step in the analysis is to specify the total amount and rate of hydrogen release into the containment. The Code of Federal Regulations^{5,6} gives clear guidance concerning generated/released quantities of hydrogen to be considered. In accordance with 10CFR50.34(f), which addresses the concern of global detonation, the total hydrogen quantity generated/released during a severe accident must be calculated from a reaction of 100% of the active fuel clad material. Also, the average uniform concentration in the containment building shall never exceed 10% hydrogen.

An envelope of the hydrogen release rates as determined in PRA best-estimate severe accident analysis for a variety of scenarios was estimated to perform the simplified design analysis.² It was assumed that all hydrogen is released within one hour and twenty-five minutes (50% of total hydrogen quantity in the first 10 minutes, 25% in the next 35 minutes, and the rest in the next 50 minutes).

To illustrate the approach used for the simplified analysis, a sketch of the assumed hydrogen release and calculated hydrogen depletion for a severe accident scenario in a typical ALWR PWR containment is shown in Figure 3. The upper curve shows the hydrogen concentration in the AP600 containment that would result from

release in accordance with the release assumption described above without any hydrogen depletion. The conservative assumption of no steam content is made. The lower curves give the calculated hydrogen concentration for different numbers of PAR devices installed in the containment. For the first 10 minutes, the simplified analysis assumes there is no depletion. This is a conservative treatment of the startup time during which hydrogen may have not reached some PARs and other PARs may be heating up, not yet working at full efficiency. Recombination is assumed to begin only after 10 minutes. From this time on, the depletion is calculated using a time-step-average hydrogen depletion rate (from Figure 2 assuming no steam content and ambient pressure) determined iteratively. The number of PAR devices determines the peak hydrogen concentration. This peak concentration (which is allowed to be as high as 10% in a best-estimate analysis) occurs between about one half and one and a half hours. With one PAR per 3000 m³ of containment volume, hydrogen recombination prevents the volume average concentration from exceeding 10%. Following termination of hydrogen release, the step calculation is continued. Several hours after the start of the accident, the atmosphere is inerted by the action of the PARs. Within 24 hours, only small amounts of hydrogen would remain.

The analysis shows that with just enough PARs deployed to keep global concentrations below 10 vol%, the atmosphere could be flammable at most only for a few hours. During this relatively short period, inadvertent ignition is acceptable because important systems, structures, and components are designed for the loads resulting

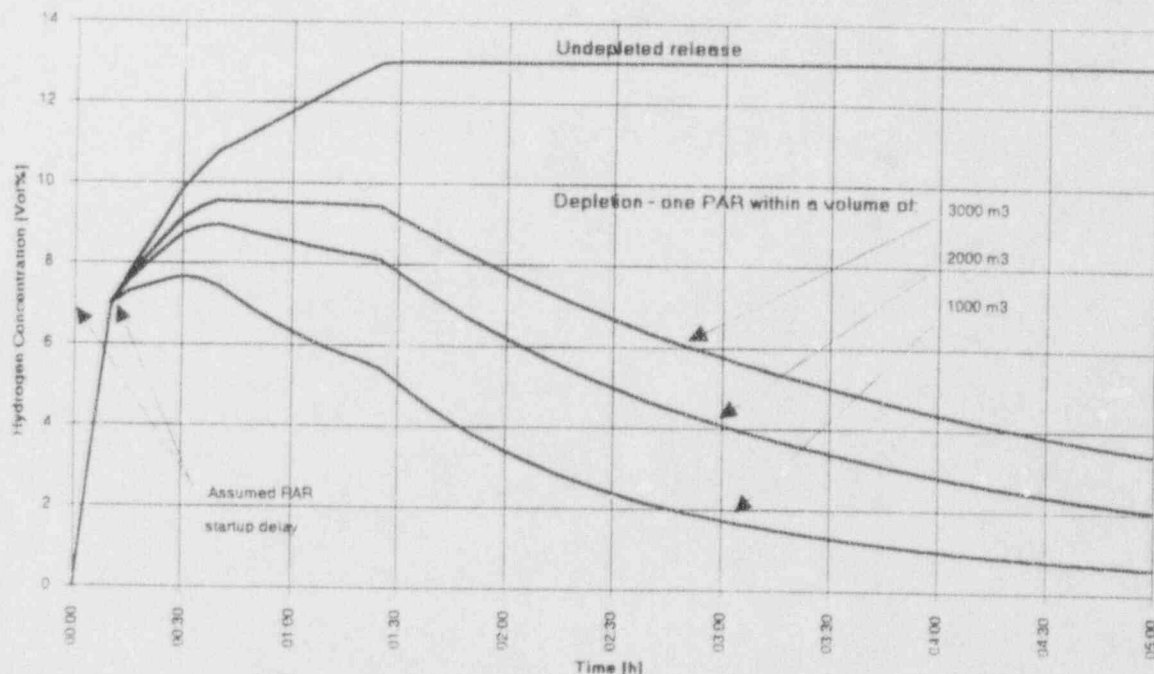


Figure 3 - Sketch of a Typical Assumed Hydrogen Release and Calculated Hydrogen Depletion for a Severe Accident Scenario in a PWR Containment

from a hydrogen burn of such a gas mixture. However, it is important to recognize that, in view of the several sources of conservatism in this simplified analysis, it is likely that hydrogen concentration will remain below even the flammability limit at all times for many severe accident scenarios. The following reasons are the basis for this expectation:

- It is conservative to assume that the total hydrogen would be generated in less than two hours (50% in only 10 minutes). Any stretching of the generation over longer times would reduce maximum concentrations. This statement is valid even for a less probable scenario in which fuel would exit the vessel and have a chance to react with concrete leading to additional generation of hydrogen. Such generation would occur later when most of the original release is already recombined.
- It is conservative to assume zero steam content, because (1) a large fraction of the water inventory will be released in the form of steam prior to any hydrogen generation; for each 10% of steam the maximum hydrogen concentration reduces by $\approx 1\%$; a steam content $\geq 50\%$ inerts the atmosphere for any concentration of combustible gases, and (2) it is virtually impossible (especially with the high release rates assumed) for the molten core to function as a 100% effective hydrogen generator, chemically reacting with all steam before the steam has a chance to leave the zone of the molten core.

The simplified analysis of hydrogen depletion was applied to the containment of the Westinghouse AP600 PWR. For a containment volume of $48,144 \text{ m}^3$ and a total hydrogen release of 635 kg, 20 PAR devices were found to control the peak volume average hydrogen concentration to no greater than 8.5%.^a

Uniform Global Concentrations

Here, we review features of hydrogen release and mixing in the presence of PARs to justify the assumption of uniform global concentrations inherent in the simplified analysis.

The momentum of released gases together with the prevailing natural circulation produced by large temperature gradients will initiate gas mixing (these global temperature gradients result from high temperatures associated with the accident and passive cooling of the containment dome in the AP600). Hydrogen will reach the nearest PAR devices within a few seconds following release. This can be recognized by noting that the

maximum distance of the nearest device to any potential release location is less than about 10 to 15 m^1 and the release velocity is expected to be well above 10 m/sec . (For AP600, the gas exit velocity would reach $\geq 60 \text{ m}/\text{sec}$ for a hydrogen release rate of 0.5 kg/sec , even assuming a fairly large release area of 1 ft^2 .)

After starting, the PAR device also acts as a "passive fan" strongly supporting gas mixing in the containment atmosphere. For example, twenty PAR devices exposed to air containing 4% hydrogen create a gas flow of about $18,000 \text{ m}^3/\text{hr}$. For 10% hydrogen, twenty PAR devices create a circulation of about $30,000 \text{ m}^3/\text{hr}$. This is the same order of magnitude as the capacity of one of the two circulation fans used to ventilate the AP600 during normal operation—about $50,000 \text{ m}^3/\text{hr}$ (31,000 scfm). Even at 1% hydrogen concentration, the twenty devices create a flow of $6,700 \text{ m}^3/\text{hr}$. Thanks to this strong self-mixing of PARs, in addition to the strong thermal currents present in an accident scenario, the distribution of gases in the containment can be considered to stay practically uniform starting shortly after the release of hydrogen and for as long as hydrogen and oxygen continue to be present in the atmosphere. Once established, the strong mixing also minimizes the extent of the local region at the point of reactor coolant system leak or break that by definition will have high concentrations of hydrogen.

The feature of good mixing to produce a reasonably uniform distribution of hydrogen has been demonstrated experimentally in the Battelle multicompartment test facility and theoretically using the validated COBRA-NC/GOTHIC code. Since all analysis is based on conservatively considering noncondensable gases only, steam condensation could not lead to any situation that is not covered by the design and needs no further consideration. Note also that the overall depletion rate of PARs distributed fairly uniformly 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. This gives us confidence that the simplified analysis is an adequate means for estimating the required number of PARs.

Local Concentrations

Although the simplified analysis described above made the conservative assumption that there is no depletion during a 10-minute startup stage for the PARs, the assumption would be over conservative if applied for estimating concentrations in an individual compartment, since a PAR near the break location would see hydrogen immediately and begin depletion. On the other hand, the fact that there are regions of the open volume of the containment and its compartments with higher concentration of hydrogen is inherent in the simplified analysis assumption of a uniform average concentration. That is, the simplified analysis does not address potentially high local concentrations of hydrogen. Here, we review factors and

^a The larger-volume containment ($90,200 \text{ m}^3$) of a nonpassive PWR, the ABB-CE System 80+, was found to need 40 PARs to keep the peak concentration to 8.1% with a total hydrogen release of 1,126 kg. Note that neither this result nor the result for the AP600 correlates with the curves in Figure 4 because slightly different parameters were used in the calculations for the figure.

measures used by the PAR approach to resolve the concern for the possibility of local detonations.

Hydrogen release into the free volume of the containment building will occur at the location of the primary system break which originally caused the accident and/or at a location such as a relief valve where the primary system was opened for depressurization. Since such a release could contain pure hydrogen produced by the metal/water reaction, it is not possible during dilution to avoid either a local region with hydrogen concentrations well above 10 vol% or a standing flame in the vicinity of hydrogen entry.

In such locations, a stream of hydrogen and steam will be released and will dilute into the free volume of the containment building driven by the momentum of the release with support from natural and PAR-enhanced convection. For many accident scenarios, the release stream would contain 50% or more of steam, so it would not be flammable. If the steam fraction of the release is less than 50%, flammable gas concentrations may exist in local areas for the short time it takes dilution into the free volume to take place. Effective mixing and minimization of the size of regions of high concentrations at entry locations will be promoted by designing compartments with boundaries having a large percentage of their surface open.

Although the initial release of steam-rich mixtures of hydrogen into air may lead to an inert atmosphere, steam condensation may eventually produce a flammable mixture in a compartment. The likelihood of this is reduced by the reduction of hydrogen both by mixing and diffusion to adjacent free volumes and by PAR recombination during the inert period.

Although, as discussed above, it is highly unlikely that pure hydrogen with no steam is released, let us examine such a case. For small release rates, the arrangements of PAR units within individual compartments will keep the average local hydrogen concentration below 10%. For large release rates, the compartment would be quickly inerted due to oxygen purging by the intruding hydrogen. Oxygen that would enter later due to diffusion or mixing would be recombined by the PAR unit or units, avoiding conditions that would allow local detonation. It is only relatively unlikely intermediate release rates of uninerted hydrogen that could both locally overload PARs and allow oxygen to be present.

Thus, although detonable local regions (average local hydrogen concentration greater than 10%) cannot be totally excluded, they are extremely unlikely to occur. If analysis shows that they could occur during a significantly great time interval, two ALWR design measures minimize the probability of local detonations. First, designs will avoid compartment configurations (e.g., long, narrow regions with obstacles and small net openings) that could support flame acceleration sufficiently to form a local detonation. Second, designs will minimize possible

sources of inadvertent ignition in the compartment, with special attention to avoid the high-energy ignition sources needed to initiate detonation.

The above factors and measures, supported by the results from detailed thermal-hydraulic analyses of PAR effectiveness, will probably lead to the conclusion that the probability of a local detonation is acceptably low. If there are still local regions where such a conclusion cannot be made with sufficient certainty the following two alternative measures can be explored.

The first alternative would be to design such regions [e.g., the condensation pool (IRWST) gas space in a PWR] to have what we will call "PAR venting." This involves closing the compartment to the open containment volume except for a vent or vents with PAR devices installed in them. In this design approach, combustible gases in the compartment are controlled in the following way. The vents require all gas transfer (out or in) to pass through the PARs. An additional PAR installed within the compartment is sufficient to control the hydrogen concentration for small release rates. For intermediate and large hydrogen release rates, rapid inerting of the compartment would occur mainly from oxygen purging through the vent as pressure buildup in the compartment is relieved. This would be assisted to some extent by recombination in the PAR device within the compartment. After achievement of inerting, hydrogen would be released through the vent and dilute into the open containment volume. Following termination of hydrogen generation, the hydrogen content of the compartment would recombine slowly with oxygen entering through the PAR in the vent.

The second alternative can be applied whether or not PAR venting is used. This alternative relies on the ability of structures and components in and around a region or compartment to withstand a local detonation. Analysis and/or test data would be used to predict the short-duration pressure spike from a local detonation and evaluate its effects to ensure that it would not produce an unacceptable level of structure or equipment damage or failure. The successful outcome of such an evaluation will be enhanced by (1) the limited energy available in a detonation in a localized region, (2) the acceptability of large deformations so long as the function of affected structures in an accident situation is not compromised, and (3) the small number of equipment items that (a) are needed to perform a safety function during a severe accident, (b) are not rugged enough to survive a local detonation, or (c) cannot be relocated to a region with an acceptably low probability of local detonation.

COMPARISON OF COMBUSTIBLE GAS CONTROL SYSTEMS

As a result of lessons from the Three Mile Island accident, operating nuclear power plants with relatively small containments have been backfitted with additional systems to control combustible gases produced during and after design basis and severe accidents. In contrast with

the PAR approach, conventional AC-powered igniter systems in existing U.S. power plant applications rely on deliberate local or global deflagration to limit global hydrogen concentration below detonable limits for severe accident scenarios. As a noninerted mixture of hydrogen is released into the containment, igniters burn hydrogen as soon as flammable mixtures reach an igniter location. If the released mixture is inerted with more than a 50-vol% concentration of steam, an igniter can begin to burn hydrogen only after steam condensation produces a noninerted mixture.

Most of these systems employ electrical igniters inside the containment and thermal recombiners inside or outside the containment. Because of their limited capacity, the thermal recombiners are used only to prevent hydrogen produced by radiolysis during a design basis accident from reaching flammable concentrations (about 5 vol%) and to assist in the removal of unburned hydrogen after an accident. Igniters are needed for noninerted containments in the event that the hydrogen produced by metal/water reaction in a degraded core accident would exceed the flammability limit. Controlled burning at or above this limit aims at preventing global concentrations from exceeding detonable limits (a volume average >10 vol%). Such detonations could compromise the integrity of the reactor containment structure.

PARs function even for hydrogen concentrations below the flammability limit or in hydrogen-rich steam-inerted mixtures. This attribute reduces the probability of producing flammable concentrations of hydrogen. However, if flammable concentrations are reached, inadvertent ignition from electrical devices or hot surfaces may lead to local or global deflagration. Therefore, the containment and other important equipment are designed for resulting mechanical and thermal loads from deflagrations of hydrogen concentrations as great as 10 vol%.

PARs limit global hydrogen concentrations below detonable limits during severe accidents (and below flammable limits during design basis accidents), entirely eliminating the need for AC- or DC-powered igniters and AC powered thermal recombiners. PARs remove residual hydrogen after an accident. They are less expensive to purchase and maintain than systems relying on two types of devices.

SUMMARY AND CONCLUSIONS

The PAR approach relies mainly on distributed recombination to prevent global detonation. PARs remove almost all hydrogen after the accident. Local detonation is addressed by (1) demonstrating its acceptably low probability (steam inerting, strong mixing, compartment design, and minimization of ignition sources), (2) redesigning potentially problematic compartments to be isolated from the open containment volume with PAR vents, or (3) by assuring survivability (i.e., that compartment structures and equipment can accommodate a local detonation).

In conclusion, the PAR approach is viewed as meeting regulatory requirements for hydrogen control while being simpler, easier to maintain, and more cost-effective than conventional igniter/thermal recombiner systems. Thus, the PAR approach is more in keeping with the design philosophy of the ALWR program. Upon acceptance of the PAR approach by the U.S. Nuclear Regulatory Commission and proper application (including detailed thermal-hydraulic and, if needed, structural analysis by designers), the issue of hydrogen control during severe accident scenarios in ALWRs will have a cost-effective resolution. This resolution is a key element of the technical basis for simplification of off-site planning.

REFERENCES

1. Advanced Light Water Reactor Utility Requirements Document, Executive Summary, EPRI (1990).
2. "Qualification of Passive Autocatalytic Recombiners for Combustible Gas Control in ALWR Containments," EPRI ALWR Program (1993).
3. U. WOLFF, "Control of Hydrogen Concentration in Reactor Containment Buildings by Using Passive Catalytic Recombiners," 2nd ASME/JSME International Conference on Nuclear Engineering (ICONE), San Francisco, California (1993).
4. 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).
5. 10CFR50.34(f), "Additional TMI-Related Requirements," Subparagraph 50.34.(f)(1)(xii).
6. 10CFR50.44, "Standards for Combustible Gas Control System in Light-Water Power Reactors."

APPENDIX—APPLICATION OF PAR CONCEPT IN INERTED CONTAINMENTS

For preinerted containments as in BWRs 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. 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 (or oxygen from other sources, if any) to assure that flammability conditions will never be reached.

Application of the conservative simplification analysis for the passive ALWR BWR (General Electric SBWR) showed that 2 standard size plus 8 quarter size PAR devices would assure that following the release of hydrogen, the oxygen concentration will be well below 4 vol%. The PAR can also be employed to remove residual post-accident hydrogen by the controlled gradual injection of oxygen if to the containment.