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6.3 PARs FOR COMBUSTIBLE GAS CONTROL IN ADVANCED LIGHT WATER REACTORS

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Abstract

This paper discusses the progress being made in the United States to introduce passive autocatalytic recombiner (PAR) technology as a cost-effective alternative to electric recombiners for controlling combustible gas produced in postulated accidents in both future Advanced Light Water Reactors (ALWRs) and certain U.S. operating nuclear plants. PARs catalytically recombine hydrogen and oxygen, gradually producing heat and water vapor. They have no moving parts and are self-starting and self-feeding, even under relatively cold and wet containment conditions. Buoyancy of the hot gases they create sets up natural convective flow that promotes mixing of combustible gases in a containment. In a non-inerted ALWR containment, two approaches each employing a combination of PARs and igniters are being considered to control hydrogen in design basis and severe accidents. In pre-inerted ALWRs, PARs alone control radiolytic oxygen produced in either accident type. The paper also discusses regulatory feedback regarding these combustible gas control approaches and describes a test program being conducted by the Electric Power Research Institute (EPRI) and Electricité de France (EdF) to supplement the existing PAR test database with performance data under conditions of interest to U.S. plants. Preliminary findings from the EPRI/EdF PAR model test program are included. Successful completion of this test program and confirmatory tests being sponsored by the U.S. NRC are expected to pave the way for use of PARs in ALWRs and operating plants.

Introduction

It has long been recognized that during and following a design basis loss of coolant accident, relatively small amounts of hydrogen and oxygen can be released to the containment of a nuclear power plant. To mitigate such releases, U.S. Nuclear Regulatory Commission (NRC) regulations [1] require combustible gas control (CGC) systems to prevent volume average concentrations from reaching combustible levels. Almost all these systems in today's plants include electrically powered thermal recombiners. The surveillance and maintenance of these devices, some of which are quite complex, can be a significant operations and maintenance (O&M) cost burden.

The accumulation and uncontrolled burn of hydrogen in the Three Mile Island 2 (TMI-2) accident in 1979 focused attention on the hydrogen produced by metal-water reactions in a degraded core accident. Since then, great strides have been made in understanding the generation and control of combustible gases produced during severe accidents [2, 3]. In compliance with expanded regulatory requirements in this area, certain types of non-inerted U.S. operating plants have installed electrically powered igniter systems to control hydrogen buildup under postulated beyond-design-basis accidents (severe accidents), to prevent potential detonations at average uniform concentrations greater than 10 vol %.

PAR Description. During the past decade, a new, simpler device called a catalytic recombiner or passive autocatalytic recombiner (PAR) has been developed for cost-effective control of combustible gases [3]. PARs are stainless steel sheet metal boxes open at the top and bottom and containing many vertical flat catalytic cartridges or plates with open gas flow channels between them (PAR units from two suppliers are shown in Figs. 1 and 2). The PAR is a molecular diffusion filter in contrast to the fixed-bed particle

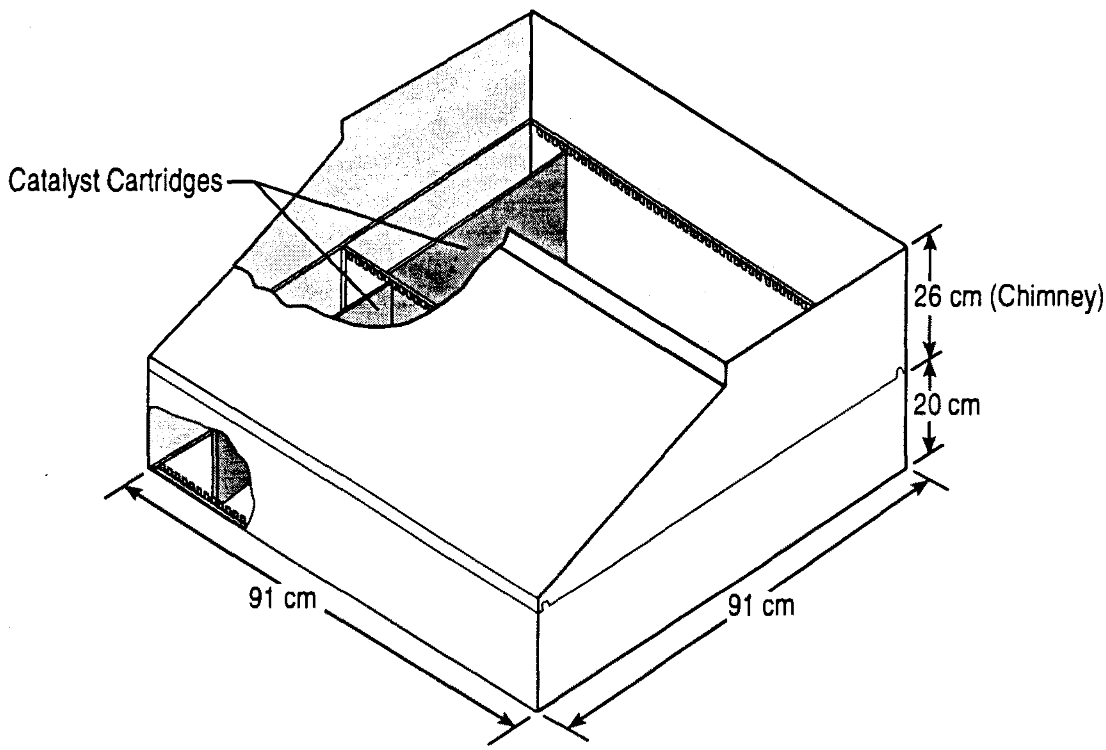

Figure 1 NIS PAR Unit

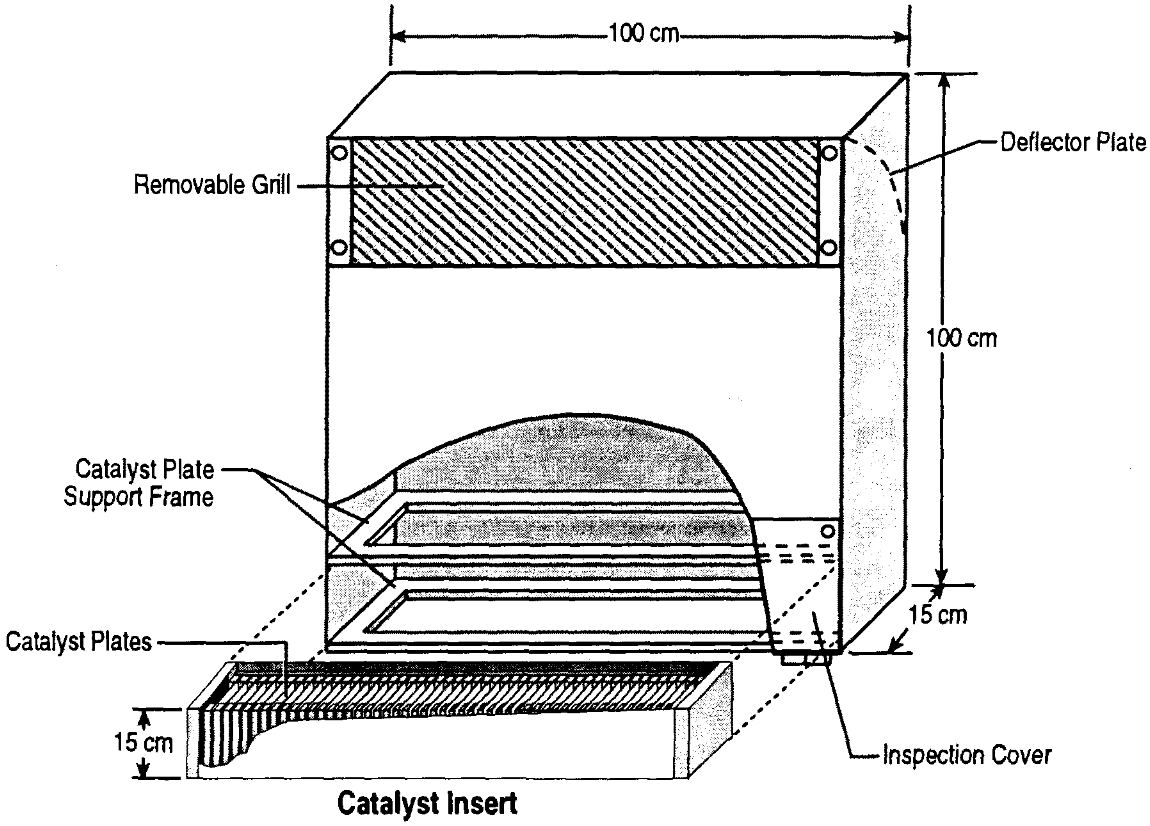

Figure 2 Siemens PAR Unit

filter configuration used in many industrial catalyst applications. During an accident the platinum or palladium catalyst in the PAR recombines hydrogen and oxygen in the flow channels to steam, which rises and is expelled from the top of the units due to buoyancy, drawing gases from the containment atmosphere into the unit from below. A "chimney" can extend above the catalytic region to provide additional lift to enhance throughput and recombination capacity. Heated gases and water vapor exhaust at the top of the unit and mix with the containment atmosphere via natural and PAR-induced convection. Under dry room-temperature conditions, the catalytic recombination process starts up almost immediately at concentrations far below flammability levels. If the PAR is wet from spray or condensed steam, startup can be delayed while the heat of recombination dries the water on the catalyst. Initial wetness can be reduced by adding a hydrophobic coating on the catalyst elements. Recombination rate increases with increasing concentrations of combustible gases and is not retarded by steam. The convection currents produced by the PAR promote gas mixing, helping to eliminate stratification. Although the catalyst material is not consumed as it functions and is not subject to long-term aging degradation, periodic surveillance is needed to detect any potential functional degradation due to buildup of contaminants during operation.

Use of PARs in ALWRs. In 1992, the Electric Power Research Institute (EPRI) recognized PARs as a favorable alternative to active devices like igniters and electrical thermal recombiners for controlling combustible gases in passive Advanced Light Water Reactors (ALWRs). PARs are consistent with the ALWR design philosophy, being simple, maintainable, and passive in nature (no moving parts; no need for cooling or electrical power, therefore invulnerable to loss of offsite power). They require no operational procedures. In 1993, EPRI changed the ALWR Utility Requirements Document for passive plants [4] to require that PARs alone (without igniters) be used to control hydrogen buildup below flammable levels in design basis accidents (DBAs) and detonable levels during and after severe accidents in PWRs (i.e. the Westinghouse AP600), and to control oxygen buildup below flammability levels in the pre-inerted General Electric Simplified Boiling Water Reactor (SBWR).

Since 1993, EPRI and ALWR designers have been engaged in the process of obtaining design certification from the U.S. Nuclear Regulatory Commission (NRC) for the use of PARs in standard ALWR designs. This paper describes the technical and regulatory history and status of introducing PAR technology into ALWRs. It also presents the prospects for backfitting PARs into certain operating plants. Finally, it gives the status of EPRI research testing being performed to enhance the understanding of PAR performance.

Overview of PAR Development and Deployment

To the authors' knowledge, four commercial designs of PARs are available, two from Germany [5, 6], one from Canada [7], and one from Switzerland [8]. They are all based on the same general catalytic technology (molecular diffusion filter) described above. Both German designs have been extensively tested. The NIS design (Fig. 1) employs palladium-coated pellets with a polymeric hydrophobic coating and enclosed in screen-covered cartridges, while the Siemens design (Fig. 2) employs a platinum-based catalyst on steel sheets with no hydrophobic coating. An extensively tested commercial version of the Canadian design has recently become available. It is similar to the Siemens design, having platinum-coated steel sheets, but the platinum is matrixed in an inorganic wetproofing support. The Swiss design is similar to the NIS design in that it employs catalyst/hydrophobic-coated pellets embedded between sheets of wire "gauze." However, the catalyst is platinum and the pellet "sandwiches" are corrugated and stacked back-to-back to form an open cross-flow channel structure. The authors are not aware of published test data on the recombination performance of the Swiss PAR design.

To date there are no PARs installed in U.S. operating plants. During 1995 Siemens PARs were installed at Doel 1 in Belgium for control of severe accident hydrogen and are scheduled for installation at six additional nuclear units [9]. Plants in Germany are considering PARs along with igniters or post-inertization for combustible gas control systems [10].

Although more than one type of commercial PAR is available for inclusion in an ALWR CGC system, a specific type employing palladium-coated alumina pellets in cartridges and developed by NIS Ingenieurgesellschaft in Germany has been addressed in a generic EPRI PAR report to the NRC [11] and is being cited in passive plant safety analysis reports being submitted to the NRC for ALWR design certification. Once PARs are deemed as licensable via the design certification process, the final design of ALWRs can employ any type of PAR that meets design and safety functional requirements.

As required by the 1993 revision of the ALWR Utility Requirements Document [4], PARs alone can be used to control combustible gases for both design basis accidents (DBAs) and severe accidents in both non-inerted PWRs and pre-inerted BWRs. The following paragraphs describe generally how PARs alone might be deployed in ALWRs. Although based on test data and generic analyses for the NIS PAR reported in [11], the deployment scenarios would be similar for other PAR types.

Deployment in PWR ALWRs. The depletion rate of a PAR between 3 and 4 vol% hydrogen is typically greater than the radiolysis hydrogen generation rate in an ALWR PWR (e.g. a Westinghouse AP600 or ABB-CE System 80+). Therefore, for such plant designs one PAR would be adequate to maintain hydrogen levels below the DBA regulatory flammability limit of 4 vol% (dry) [11]. However, since safety-related components required to function in a DBA have to be single-failure-proof, two PARs would typically be needed to satisfy redundancy.

For severe accidents in PWRs, PARs have to control not only radiolytic hydrogen, but also the much greater amounts produced by metal-water reaction of the active fuel in a degraded core. Post-TMI regulations [12] require that hydrogen burns or detonations not compromise containment integrity, nor the ability of the plant to be brought to a safe shutdown condition. Global detonation is prevented by the requirement that the global average hydrogen concentration be less than 10 vol% (dry). ALWR containments are designed to withstand a global hydrogen burn up to 10 vol%. Local detonation in a compartment must either be eliminated by maintaining local average concentrations less than 10 vol% or be withstood by demonstrating that detonation loads will not cause failure of structures or equipment.

To keep global average hydrogen below 10 vol%, about 20 PARs are needed for a 600-MWt AP600 and about 40 PARs for a 1300-MWt System 80+. Keeping local concentrations below 10 vol% relies on designing compartments with boundaries having a large percentage of their surface open. Designs would also (1) avoid compartment configurations that support flame acceleration sufficiently to form a local detonation (e.g., long, narrow regions with obstacles and small jet openings) and (2) minimize the high-energy sources needed to initiate inadvertent ignition. If the possibility of local detonation could not be eliminated by design measures, it would have to be shown that a detonation would not cause unacceptable failure of structures or equipment.

A more detailed description of the use of PARs alone in ALWR PWRs is contained in [11, 13].

Deployment in BWR ALWRs. For BWRs with nitrogen-pre-inerted containments, it is oxygen and not hydrogen that needs to be controlled during and after an accident. PARs would control radiolytic oxygen during either a DBA or a severe accident (the hydrogen produced by metal-water reaction from a degraded core would only further inert the containment). Four full-size-equivalent PARs are distributed throughout the drywell and wetwell. (There are actually more than four PAR units, some of them being smaller than full size.) These PAR units also can function after an accident for removal of hydrogen prior to containment entry of either pre-inerted or non-inerted containments.

A more detailed description of the use of PARs in ALWR BWRs is contained in [11, 14].

Although PAR technology is applicable to both small passive ALWRs and large active evolutionary ALWRs, it is currently included only in the designs of passive ALWRs. Both evolutionary designs, the System 80+ and ABWR are interested in the benefits of PARs, but have received standardized final design approvals with other types of CGC systems. Both designs use electrically powered thermal recombiners for DBAs. For severe accidents, the System 80+ uses electrically powered distributed igniters to control hydrogen and the ABWR uses pre-inerting with nitrogen to control oxygen.

NRC Evaluation of Combustible Gas Control Using PARs Alone

In November 1994, the NRC issued the "Staff Evaluation of EPRI's Report dated April 8, 1993, "Qualification of PARs for Combustible Gas Control in ALWR Containments" [15]. The report had presented a summary of test data and simplified analysis to support the use of a PAR-only CGC system for both DBAs and severe accidents in PWR and BWR ALWRs.

The NRC evaluation stated that "The staff concludes, based on the information in EPRI's report, that PARs are acceptable devices for the control of combustible gas within ALWRs for the complete spectrum of DBA conditions." From a design-specific point of view, the evaluation stated further, "the staff will determine the acceptability of using PARs for DBA applications during its review of individual applications." Apparently the first statement meant that PARs are acceptable for DBAs from a generic technology point of view.

For severe accident applications, the evaluation stated that the following several issues need to be addressed further in order to gain NRC acceptance of PARs alone:

- Insufficient test data on PAR performance for hydrogen concentrations exceeding 6 vol%.
- Need for additional data on the potential effect of sulfur (from cable fires) and tellurium (as a core melt fission product) as catalyst poisons.
- Need for additional data on the effect of carbon monoxide (from core-concrete interaction) under BWR oxygen-deficient conditions.

- Need to perform parametric studies as part of a specific design analysis to determine how sensitive the PAR system would be to variations in severe accident hydrogen release rates.
- Insufficient test data on PAR performance in compartments with hydrogen concentrations that exceed 10 vol%.
- The potential for auto-ignition in hydrogen concentration exceeding 11 vol%.

With regard to the last three bullet items, the evaluation stated that "Igniters could be an option for those rooms in which locally high hydrogen concentrations are possible."

The evaluation also pointed out the need for a design-specific surveillance program to assure that plant operating conditions do not degrade the design function of the PAR. The surveillance program envisioned by PAR developers consists of simply removing sample catalytic elements during refueling outages and performing a benchtop acceptance test of their ability to recombine a measured amount of hydrogen.

ALWR Program Response to NRC PAR Evaluation

The NRC evaluation of PARs cleared the path to their use in passive ALWRs. During 1995, the designers of both the AP600 and SBWR adopted PARs to control combustible gases in DBAs. For the AP600 design, the PARs replaced electric thermal recombiners located inside the containment. For the SBWR, the PARs replaced electric thermal recombiners located outside the containment. Pre-inerting of the SBWR is still relied upon as the main means of controlling combustible gas in a severe accident (in a pre-inerted containment, PARs are simply relied upon to maintain radiolytic oxygen below the flammability limit as they do in a DBA).

For the control of hydrogen in a PWR severe accident, the NRC evaluation can lead to two paths regarding PAR application. One is to continue to pursue the PAR-only concept, which would require additional design analysis and testing to resolve the NRC-identified issues listed above. Although EPRI views this path as having a reasonable chance of success, the additional time and resources are not available in the ALWR program.

The other path for PWRs involves the adoption of an alternative to PARs-only for severe-accident hydrogen control. At present there are two alternatives under consideration, one preferred by the AP600 designers and the other by EPRI. The AP600 designer preference is to retain its original approach of using many distributed igniters to control severe accident hydrogen. Although the igniter system can meet regulatory requirements, EPRI prefers the alternative to PARs-only suggested in the NRC evaluation -- that is, PARs supplemented with a limited number of igniters. EPRI views this "PAR-based system" as technically superior to an all-igniter system for severe accident hydrogen control. The main technical advantage of the PAR-based system is that a large number of accident scenarios (those that do not result in high release rates) could be accommodated by the fully passive PARs, with no reliance on the igniters. There would be no concern for loss of electric power or for failure of the igniters to activate due to component degradation or operator error. Even in the unlikely event of such failures, in the majority of accidents (in which hydrogen is released at rates low enough to allow dilution, diffusion, and mixing to preclude high local accumulations), the PARs will gradually recombine the hydrogen and altogether eliminate burns. The igniters would come into play by burning hydrogen locally only in less-likely scenarios with high release rates that could overwhelm the recombination capacity of a local PAR. Such a PAR-based system would be more harmony with the passive plant design philosophy of accommodating accidents without the need for active components. To reflect this technical preference, EPRI has initiated a change in the Utility Requirements Document that would maintain distributed PARs as the principal means of control, but require a limited number of igniters, as needed, to preclude local accumulation of hydrogen as suggested in the NRC evaluation of the PAR-only approach. The resulting CGC system is similar to the German dual recombiner/igniter concept [10], except that it requires only a few igniters, while the German dual concept has many (enough to control hydrogen without the PARs).

As this paper is being prepared, EPRI is both (1) providing technical support to Westinghouse's design application using the igniter-based CGC system, which EPRI views as adequate for safety (a final NRC safety evaluation is expected this year), and (2) developing additional test data to address the list of NRC concerns about severe-accident application of PARs and thereby providing additional support for a PAR-based CGC system (distributed PARs with a limited number of local igniters) as an approach to severe-accident hydrogen control that could be adopted in PWR ALWRs in the future.

It should be noted that, with regard to relative life-cycle costs, the major savings are achieved by replacing high-capital-and-O&M-cost active thermal recombiners with simple passive PARs. The life-cycle costs of the current AP600 igniter-based CGC system and the EPRI-preferred PAR-based CGC system are not significantly different from each other.

Backfitting PARs in Operating Plants

All U.S. operating plants have the capability of depletion of radiolytic combustible gases in a DBA using thermal recombiners (including flame recombiners) located inside or outside the containment (one plant has an active catalytic recombiner located outside containment). Post-TMI beyond-design-basis combustible gas control is achieved either by volume dilution (large-volume dry containments) or by distributed igniters (ice condenser containments and non-inerted BWRs). Since the CGC systems of all operating plants are adequate for safety, a decision to install PARs as a replacement for existing CGC devices would be based purely on economics.

Thermal recombiners outside containments, whether permanently installed or transportable, require containment penetrations, isolation equipment, safety-grade electric power and control systems, and cooling. They require a significant amount of maintenance and testing. For some BWRs and PWRs, direct replacement of complex recombiner systems with simple PARs appears technically and economically beneficial.

Several U.S. operating plants are actively considering replacement of existing thermal recombiners with PARs. For straightforward replacement of DBA combustible gas control equipment in operating plants, PARs need to be environmentally and seismically qualified to U.S. standards.

In summary, PARs are being considered by several U.S. plants as a replacement for electrically operated thermal recombiners for DBA combustible gas control. In addition, PARs are being incorporated for control of radiolytic combustible gas in passive ALWR designs, and the possibility exists that the design approach for ALWR PWRs could change in the future to rely mainly on PARs for severe accident hydrogen control, using only a limited number of igniters to prevent the buildup of hydrogen to unacceptable levels in local compartments in which hydrogen is released.

EPRI/EdF Test Program Supporting U.S. Applications of PARs

To date, a substantial amount of development and testing has been completed by others on four PAR designs (see discussion above). Hydrogen depletion rates have been measured under a wide range of hydrogen concentrations, temperatures, pressures, and steam simulating postulated German and Canadian nuclear plant severe accident conditions. In addition, the effects of various inhibitors such as water and soot (the latter from cable and oil fire) and poisons such as iodine and carbon monoxide have been tested.

To improve the understanding of PAR performance for member-utility prospective users, EPRI has initiated a PAR test program in collaboration with Electricité de France (EdF) and its contractors, Commissariat á l'Energie Atomique (CEA). The test program is being conducted at the Cadarache research center of CEA and is scheduled to be completed in June 1996. The remainder of this paper presents a description of the test objectives, test facility, test scope, and preliminary findings.

The general objective of the EPRI/EdF PAR test program is to generate supplemental PAR performance data, which, together with existing test data, will provide a comprehensive technical understanding and confirmation of the expected performance of PARs under postulated DBA and severe accident conditions in both advanced and operating U.S. plants. The broadened range of parameters and conditions are intended to include those identified by the NRC evaluation of NIS test data to be insufficient to support a safety assessment.

In particular, the comprehensive data set will provide the basis for development and validation of analytical methods for predicting PAR hydrogen and oxygen depletion rate as a function of local combustible gas concentrations and ambient temperature, pressure, and moisture conditions. These methods also need to account for the possible reduction of depletion rate due to potential poisons and the possible delay in startup of recombination due to wetness from water spray or steam condensation.

Test Facility. The EPRI/EdF PAR Test Program is being carried out in the "KALI" facility of the CEA Cadarache research center near Aix en Provence, France.. Figure 3 is a sketch of the experimental arrangement. The 15.6 m^3 steel cylindrical test vessel is instrumented to measure

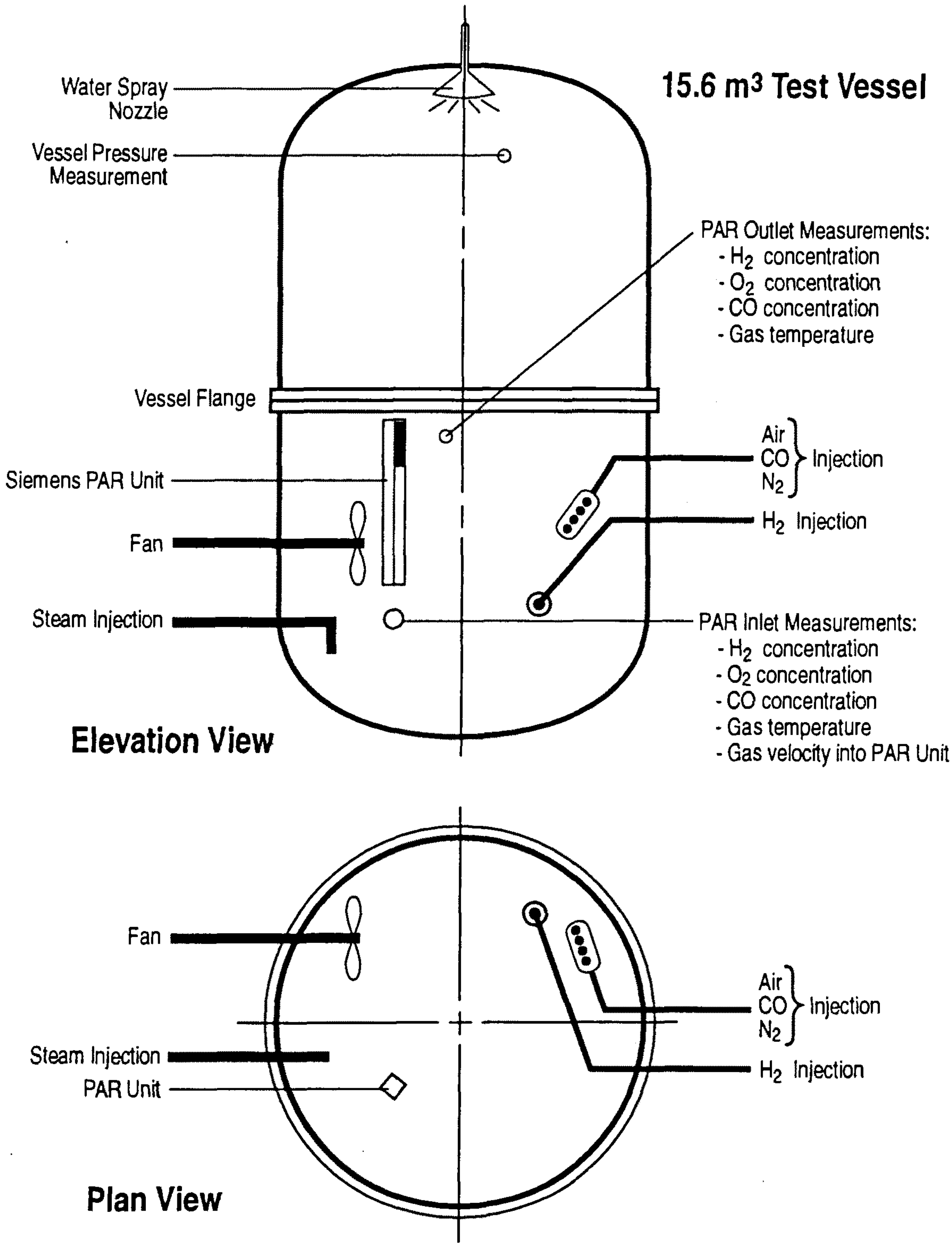

Figure 3 KALI PAR Test Facility Configuration

hydrogen, oxygen, and carbon monoxide concentrations, pressure, and gas temperatures (at two locations -- the PAR inlet and outlet). By intermittent operation of a mixing fan, vessel average concentrations of the various gaseous constituents are also measured at intervals during each test. In addition, PAR inlet gas flow velocity is recorded by an anemometer. Temperature histories are also measured at three locations on the catalytic elements within the PAR models. The facility includes the capability to inject heated air, water spray, steam, hydrogen, carbon monoxide, and nitrogen.

PAR Segment Models. Since the test facility cannot accommodate full-size PAR units, small-size "segment" models of two PAR types, NIS and Siemens, are being tested in the EPRI/EDF program. Segment models of NIS and Siemens PARs are shown in Figs. 4 and 5. The catalyst elements of NIS PARs are 20-cm-tall cartridges containing 4-to-6-mm-diameter porous ceramic spherical pellets coated with palladium and a thin hydrophobic outer layer. The faces of the 1-cm-thick cartridges consist of sheet metal with slots to permit diffusion of gases to the pellets. The catalyst elements of Siemens PARs are 15-cm-tall stainless steel plates coated with a platinum-based catalyst and ordinarily have no hydrophobic coating. Both models have 1-cm-wide gas flow channels between catalyst elements.

A PAR segment model maintains full-scale values for all key dimensions; i.e., PAR overall height, catalyst element height, and width and spacing between the catalyst elements. Only the length and number of catalyst elements are reduced from full-size values. Recombination rates are scaled up to full size by multiplying the recombination rate measured with the segment models by the ratio of full-size to small-size flow channel cross-sectional area. Using physical arguments confirmed by existing test data [10], it can be demonstrated that this approach for scale-up leads to conservatively low estimates of full-size recombination rates, in that proportionately more heat is lost to the ambient environment in the segment models than in full-size PARs.

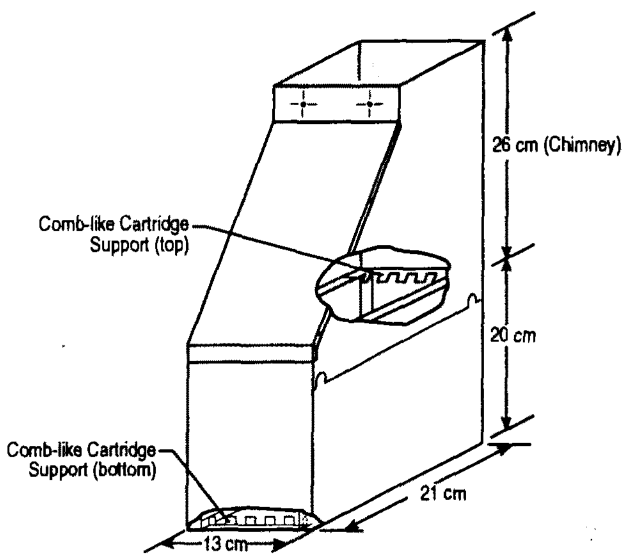

Fig. 4 NIS PAR Segment Model

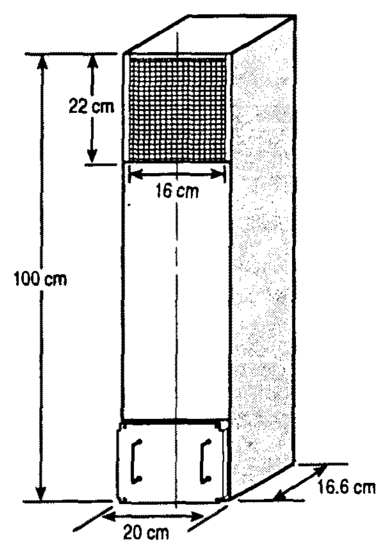

Fig. 5 Siemens PAR Segment Mode

The PAR segment models of both types are of essentially the same design and construction as the models and full-scale prototypes tested previously in Germany. Minor modifications in the NIS PAR models aim at simplifying fabrication and a minor modification in the Siemens model aims at improving start-up behavior at low ambient temperatures. The expectation that none of the modifications have a significant effect on recombination capacity will be checked in a test of each with conditions duplicating those in tests with the original design.

Test Procedure. Each test is conducted with a PAR model installed near the bottom of the vessel and halfway between the vessel centerline and wall (see Fig. 3). First, the test volume is temperature conditioned by means of heated air or steam. Then all gaseous constituents except hydrogen are added and well mixed with the fan. The data acquisition system is activated, followed by a relatively fast injection of hydrogen up to the target test concentration. Fan operation is continued for two minutes to ensure complete mixing and allow an accurate measurement of the initial volume average hydrogen concentration. Fan operation is then terminated allowing PAR heatup to establish convective flow through the PAR model. At ten-minute intervals, the fan is operated for one minute to allow measurement of test vessel average gas concentrations. Hydrogen, oxygen, and, where applicable, carbon monoxide concentrations are recorded continuously until no further change in combustible gas concentration is observed.

Test Matrix and Rationale for Selection of Test Conditions. Table 1 presents the matrix of tests planned to be performed on each of the two PAR model types. Test conditions were selected generally to represent both DBA and severe accidents in both non-inerted PWRs and inerted BWRs. The following effects/technical issues are addressed:

a) Low ambient gas temperature as may occur in some postulated accidents; e.g. low initial containment temperature or coolers remain in operation.

b) Effect of low hydrogen concentration (4 vol% and less) on PAR start-up time, especially in a DBA.

c) Effect of wetness on start-up time (the wetness would come from condensation for any plant type and also from sprays in plants equipped with them -- passive ALWRs do not have sprays). Much of the data obtained previously for wet PARs was under relatively high temperature conditions (50-100°C). The EPRI/EdF tests are exploring the cold (30°C) and very wet (water soak of 1 hour) initial conditions representing a limiting case for PAR start-up delay.

d) Effect of high hydrogen concentration (10 vol%), which is the regulatory upper limit with respect to volume average concentrations that may produce detonations in severe accidents.

e) Effect of ambient gas temperature.

f) Effect of ambient gas pressure.

g) Effect of steam as inertant.

Table 1 EPRI/EdF PAR Test Matrix

Test No.*	Plant Type Simulated	Initial Gas Temp (°C)	Initial Gas Pressure (Bar)	Initial Gas Composition (vol %)**					Remarks
				H_2	Air	Steam	CO	Excess N_2	
1	PWR	30	1.3	2	98	0	0	0	Low H2 conc (DBA)
2	PWR	30	1.3	2	98	0	0	0	Effect of wetness on start up ***
3	BWR	30	1.3	8	18	0	0	74	Effect of wetness on startup (low O2)***
4	BWR	30	1.3	8	18	0	0	74	Low O2 (BWR)
5	SIEM NIS	112 100	2.9 2.0	5 3.6	45 46.4	50 50	0 0	0 0	Repeat of test previously conducted in Germany on PAR developmental designs
6	PWR	30	1.3	4	96	0	0	0	Effect of initial H2 concentration (DBA)
7	PWR	100	1.3	4	96	0	0	0	Gas temperature effect
8	PWR	30	4.0	4	96	0	0	0	Gas pressure effect
9	PWR	119	4.0	4	46	50	0	0	Steam Effect
10	BWR	63	1.3	8	18	18	0	56	BWR wetwell conditions
11	BWR	115	4.0	4	10	44	0	42	BWR drywell conditions
12	PWR	30	1.3	4	93	0	3	0	Inject CO when H2 reaches 2.5%
13	BWR	30	1.3	8	18	0	3	71	Inject CO when O2 reaches 3 %
14	PWR	30	1.3	10	90	0	0	0	Effect of initial H2 conc (Sev Acc)
15	PWR	30	1.3	4	96	0	0	0	Potential poisons from US cable fire
16	BWR	30	1.3	8	18	0	0	74	Potential poisons from US cable fire

* Matrix to be tested separately for NIS and Siemens PAR units

** After H_2 injection. "Excess Nitrogen" means in addition to the nitrogen in air.

*** Sprays (without chemicals) to be activated (30 °C) for 1 hour and then terminated prior to H2 injection to ensure a fully wetted PAR

h) Effect of nitrogen inertant typical of a BWR.

i) Effect of low oxygen concentrations to simulate inerted BWR conditions.

j) Effect of potential poisoning from carbon monoxide that would be released from core/concrete interaction late in a severe accident.

k) Effect of potential poisoning from U.S. cable burn products such as carbon, sulfur, and hydrochloric and sulfurous acids (from chlorosulfonated polyethylene jackets).

l) Effect of minor differences between the PAR types in this program and original versions tested previously.

Previous testing in Germany has established the effect of fission product iodine on PAR depletion rate (the depletion rate is reduced, but not substantially enough to incapacitate the PAR's recombination function). Although not specified in the test matrix of Table 1, an additional KALI test on both PAR types to examine the effects of airborne tellurium (a fission product potentially poisonous to catalytic recombination) is being considered.

Preliminary Observations

At the time this paper was completed, testing of the Siemens PAR segment model was mostly completed and testing of the NIS PAR was in progress.

Figures 6 and 7 are typical examples, for the Siemens PAR, of measured histories of wet hydrogen concentration and PAR flow velocity variation within the test vessel, respectively. For this test the nominal initial conditions are 5% hydrogen, 45% air, 50% steam, 2.9 bar, and 112°C. Note from Fig. 6 that hydrogen recombination begins immediately following hydrogen injection and continues until the hydrogen concentration is reduced to approximately 0.25 vol%. Vessel average concentration is recorded at the end of each intermittent fan operation. This record will be analyzed to give PAR model depletion rate as a function of concentration.

The spikes in flow velocity exhibited in Fig. 7 are the result of intermittent fan operation and are not true PAR flow velocities. Accurate flow velocities (ranging from 0.2 to 0.4 m/s) are obtained between 1200 and 3700 seconds. The threshold for flow velocity measurement appears to be approximately 0.2 m/s. The output is zero for velocities below the measurement threshold.

Based on a preliminary quick look at the **Siemens PAR model data** obtained to date, the following observations are made (except where noted, results are for Siemens PAR models without hydrophobic coating). The term "start up delay time" denotes the time from the beginning of hydrogen injection to the time when a significant depletion of hydrogen or oxygen is observed.

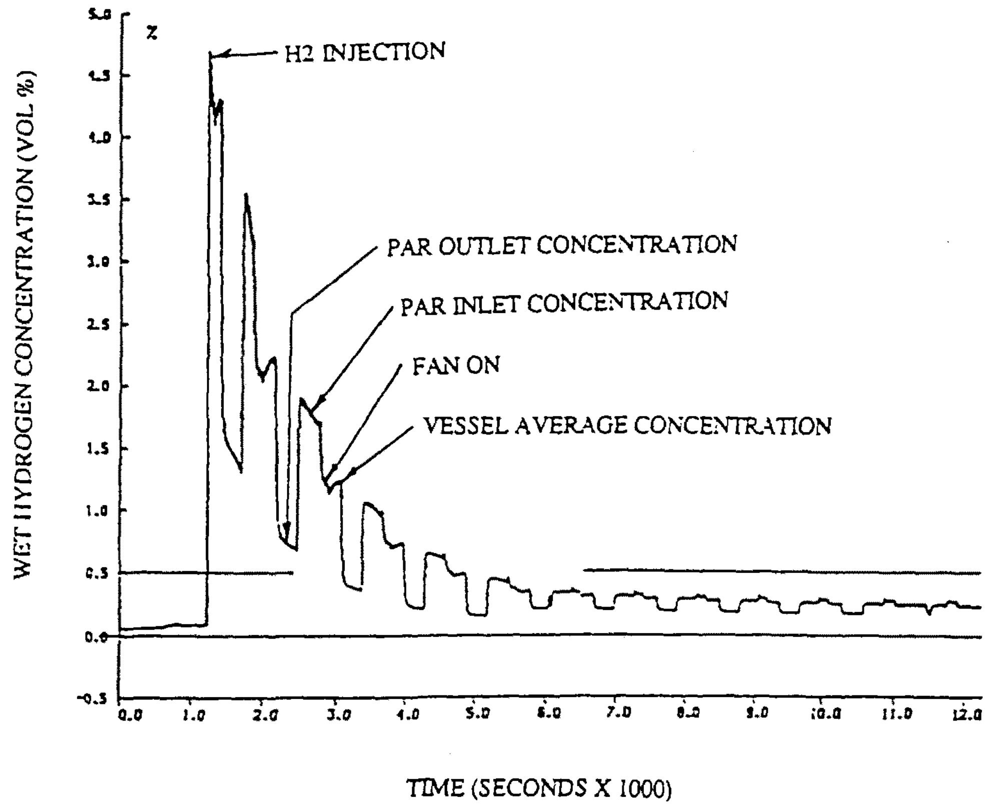

Figure 6 Hydrogen Concentration History (Test S5)

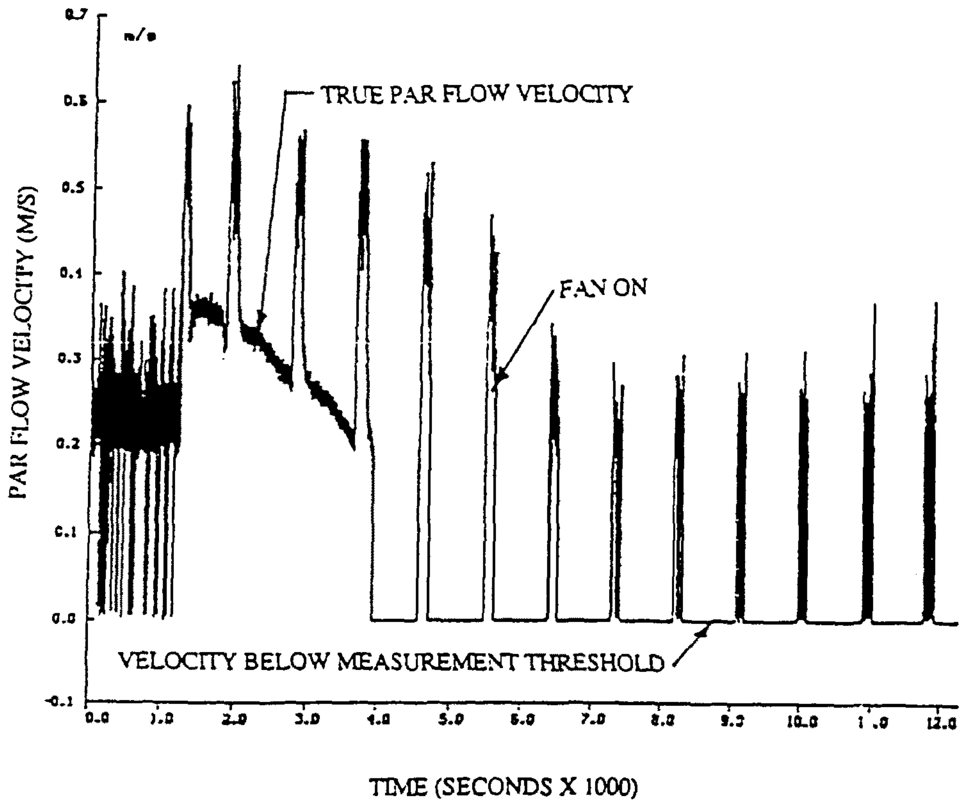

Figure 7 PAR Flow Velocity History (Test S5)

1) Under dry, cold (30°C) conditions, immediate PAR start up occurred at the lowest initial hydrogen concentration tested (2.0 vol%).

2) Once the PAR started up, recombination continued until the hydrogen concentration dropped below approximately 0.25 to 0.5 vol%.

3) Under warm (100°C) conditions in a steam-rich condensing environment with a hydrogen concentration of 4 vol% immediate PAR start up was observed.

4) Under cold (30°C) and very wet conditions (cold spray water applied for 1 hour prior to test initiation), PAR startup delays at low hydrogen concentrations can occur while water is being heated off. Under such initial conditions, a start-up delay of 45 minutes was observed at 3 vol% hydrogen and of more than 4 hours at 2.5 vol%. At 2 vol% no startup was observed after 5 hours and the test was terminated.

5) Under cold (30°C) and very wet conditions and at low BWR-inerted oxygen concentrations (3.8% oxygen, 8% hydrogen), PAR start up was observed after a 5-minute delay.

6) With hydrophobic coating applied to the catayst plates, start up performance was improved; i.e., at 2 vol% start-up occurred within 12 minutes.

Based on a preliminary quick look at the **NIS PAR model data** obtained to date, the following observations are made (note that the catalytic pellets in these tests had a hydrophobic coating).

1) Under dry, cold (30°C) conditions, immediate PAR start up occurred at the lowest initial hydrogen concentration tested (2.0 vol%).

2) Once the PAR started up, recombination continued until the hydrogen concentration dropped below approximately 0.25 to 0.5 vol%.

3) Under cold (30°C) and very wet conditions (cold spray water applied for 1 hour prior to test initiation), PAR start-up delays at low hydrogen concentrations can occur while water is being heated off. Under such initial conditions, a start-up delays of 5 minutes (at 2 vol% hydrogen) and 37 minutes (at 1 vol%) were observed.

4) Under cold (30°C) and very wet conditions and at low BWR-inerted oxygen concentrations (3.8% oxygen, 8% hydrogen), PAR start up was observed after a 5-minute delay.

The observed delays in PAR start up are of no consequence in a design basis accident because combustible gas production rates are extremely low and, without any mitigation, flammable levels typically are not reached for days.

Summary

PARs appear to provide a cost beneficial approach for controlling combustible gases during and after postulated accidents in ALWRs. Acting in combination with igniters or pre-inerting, PARs deplete hydrogen in non-inerted containment atmospheres and oxygen in inerted atmospheres, such that no detonations or uncontrolled burns take place that could cause failure of safety-related structures or components. Design certification of the AP600 is serving as the arena for gaining licensing acceptance by the U.S. NRC for PAR applications in ALWRs. It is expected that an application for backfit of PARs in an operating plant will be submitted to the NRC this year. The research office of the NRC is presently conducting a confirmatory test program on PARs at Sandia National Laboratory. It is anticipated that the extensive performance test data generated by PAR developers, complemented with the EPRI/EdF and NRC test data, will pave the way for licensing acceptance of PARs for combustible gas control in both ALWRs and operating plants by year end.

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