AREVA

Qualification and Testing of the U.S. EPR Passive Autocatalytic Recombiner

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
0	All	Original Issue

Contents

List of Tables

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Nomenclature

(If applicable)

Acronym	Definition
APC	Airplane Crash
BDBE	Beyond Design Basis Event
BWR	Boiling Water Reactor
CEA	French Energy Atomic Commission
DBA	Design Basis Accident
DBE	Design Basis Event
EDF	Électricité de France
IPSN	Institut de Radioprotection et de Surete Nucléaire
PAR	Passive Autocatalytic Recombiner
PWR	Pressurized Water Reactor
NPP	Nuclear Power Plant
SA	Severe Accident
TÜV	German Non-governmental Authority

1.0 INTRODUCTION

This document describes the test program for qualifying the AREVA NP Passive Autocatalytic Recombiner (PAR). The AREVA NP PARs (formerly known as the "Siemens" PARs) are used for hydrogen reduction following certain accident scenarios postulated for the U.S. EPR design.

The PAR tests were performed under a wide range of hydrogen concentrations, initial ambient gas temperatures and pressures, steam and nitrogen as inert gases, and potential poisons. In addition, the effects of wetness and low ambient temperature on PAR start-up were studied.

The Integrated Core-Melt-Simulation-Test Program in Cadarache (Section 2.0) is considered one of the most important test programs concerning poisoning, deposition, and contamination of catalyst in a post-accident atmosphere. During this program, the PAR was subjected to a realistic aerosol exposure generated by a molten core.

The tests address the effect of aerosols on the catalytic recombination and catalytic poisoning by fission products in a severe accident atmosphere.

The tests indicate no significant reduction in PAR performance.

The following sections describe the most important test programs, single tests, and results. A summary of the tested conditions and main results are provided in the figures at the end of each section and Appendix A. On the basis of the performed comprehensive tests, it is concluded that the PARs are tested and qualified to deplete hydrogen in the harsh environmental conditions that occur in Design Basis Accidents (DBA) and Beyond Design Basis Events (BDBE).

2.0 INTEGRATED CORE-MELT-TEST

A series of H_2-PAR tests were started in 1996 and continued until 1998 at the Cadarache Nuclear Centre to investigate and document performance of commercially available PARs. These tests are considered some of the most important tests to demonstrate the PAR function under severe accident atmospheric conditions. Électricité de France (EDF) and Institut de Radioprotection et de Surete Nucléaire (IPSN) concentrated their test activities on the AREVA NP PAR as a preselected type because of its compact size, poison resistance, and design depletion design rate. Most of the performed tests were done exclusively with the AREVA NP PAR.

2.1 Objective of the Test Program

The test program was designed to investigate the potential impact of vapor and fission product aerosols, resulting from core meltdown, on the effectiveness of the PAR. The thermal behavior of the catalyst was also studied.

2.2 Experimental Conditions

2.2.1 Test Facility

The H_2-PAR test design was made of a double terphane vessel ($\approx 8\ m^3$). This vessel was fixed on a stainless-steel plate with a diameter of two meters. A double plastic vessel was needed because the interstitial area was heated by thermal resistance located on the plate to allow for thermal insulation of the inner containment (see Figure 2-1). An induction furnace (Polyr), the catalytic recombiner (same type as used in the KALI H_2 experiments), and measuring equipment were installed inside the vessel (see Figure 2-2).

2.2.2 Pre-Tests for Adjusting the Test Facility

Pre-tests were performed prior to using the terphane test container to check for hydrogen permeability and the behavior due to of incidental deflagration. This facility is able to accept large hydrogen deflagration, up to the stoichiometric mixture, in a volume of 8 m^3, delimited by a plastic and transparent pocket. After the pre-tests were successfully performed, the test container was used for the H_2 PAR program. Its advantages were:

- Good control of steam saturation (the plastic container was able to adjust its total volume to all partial pressures with a constant total pressure of 1 bar).
- Video control.
- No cleaning and contamination problems (after use, the test container allowed for compact disposal).

2.2.3 Aerosols

To simulate a realistic source term, it was necessary to produce vapors and aerosols analogous to their generation from the reactor core. Production of vapors and aerosols coming from a crucible containing a mixture of 25 elements representing the fuel, the

[ ] The products generated in the test containment atmosphere were extensively qualified both physiochemically and quantitatively. The elements produced are in agreement with known values and with the values calculated by the Gemini code. The created pollution leads to an aerosols volume concentration of [ ] depending on the point in time, in which 25 corium elements are present. The median granularity of aerosols was approximately [ ] During operation and the cooling phase, the furnace was protected by argon scavenging.

Table 2-1 presents the 25 elements that were used to simulate the reactor core inventory.

Table 2-1: Chemical Elements Introduced in the Furnace

[ ]

2.2.4 The aim of Pre-Tests for Aerosols Characterization

The objective of the pre-tests was to determine if the aerosol production is representative for a realistic accident source in the containment. The following parameters were evaluated:

- Concentration and size of the aerosols (during heating, maturation, and sedimentation phase).
- Chemical element yield.
- Chemical forms (in this case, the results could be compared to other experiments).
- Comparison with the accident sequences.

Experiments were carried out to study these parameters.

2.2.5 Full-Scale Experiments with PAR

The main thermal hydraulic conditions were the following:

- Total pressure: [ ]

- Maximum atmosphere temperature: [ ]
- Saturated steam or dry air.
- Injected hydrogen volume fraction: [ ] percent by volume in dry air.

2.2.6 Results of PAR Performance after Exposure to Aerosols, Fumes, etc. from Molten Core Substitute

Before the qualification test series began, one test (E2Bis) was performed without exposure to aerosols to use it as benchmark for the following tests. Test number E14 was performed with aerosol generation but without a PAR to eliminate the hypothesis that hydrogen consumption is caused by aerosols and gases arising from simulated melting of the corium.

In all of the performed tests, the PAR depleted hydrogen in a sufficient manner,

[

] Tests E16 and E16Bis were performed to observe the effects of tests without CO. Previous tests used a graphite crucible, which generated CO. The crucible was replaced for tests E16 and E16Bis with a crucible that would not produce CO. The effect of CO on PAR performance was evaluated (see Section 7.0). Table 2-2 lists the performed PAR tests in the presence of molten core aerosols (except reference tests E2Bis, E3S, and E3S6), test condition, and overall results.

Table 2-2: Overview of Test Conditions and Results

[ ]

The summary of the qualification tests is shown in Figure 2-3. The graph depicts the aerosols injection and [

]

Figure 2-1: EDF / IPSN, H_2-PAR Test Facility

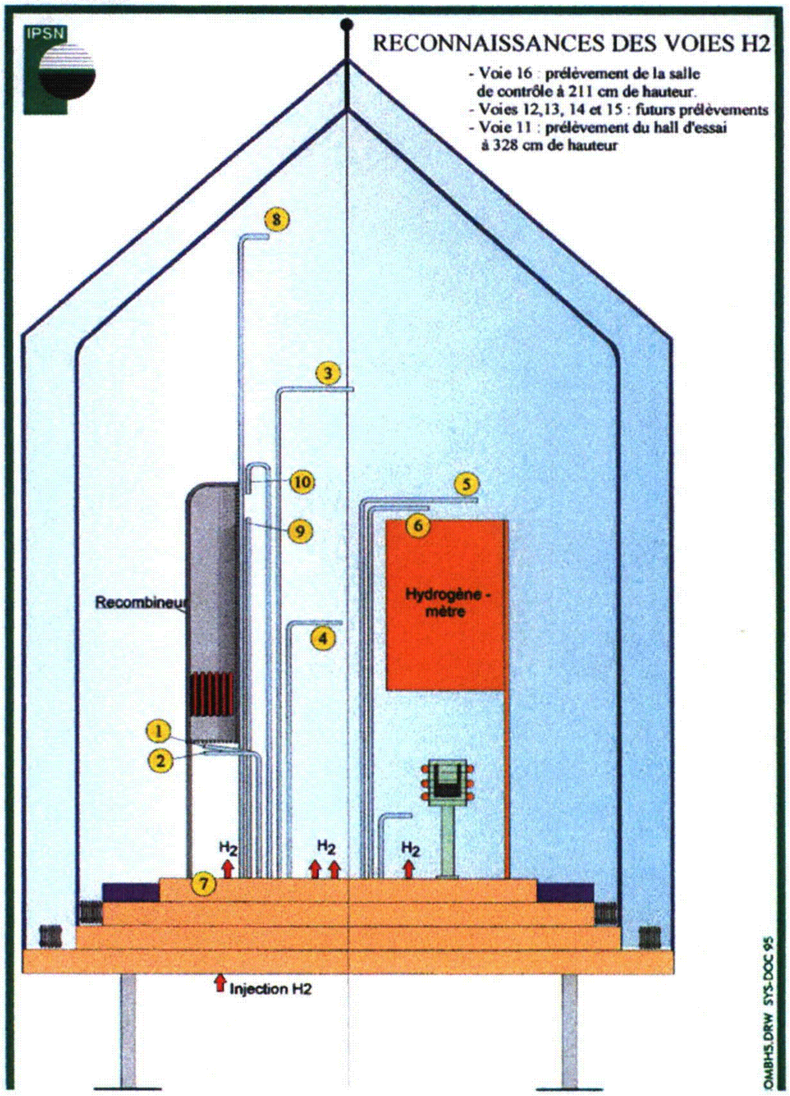

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Figure 2-2: EDF / IPSN, H_2-PAR Test, PAR Installation and Aerosol Generation Device inside the Test Vessel

Siemens- Recombiner FR1-150 with sensors for measurement

Induction furnace for aerosol generation

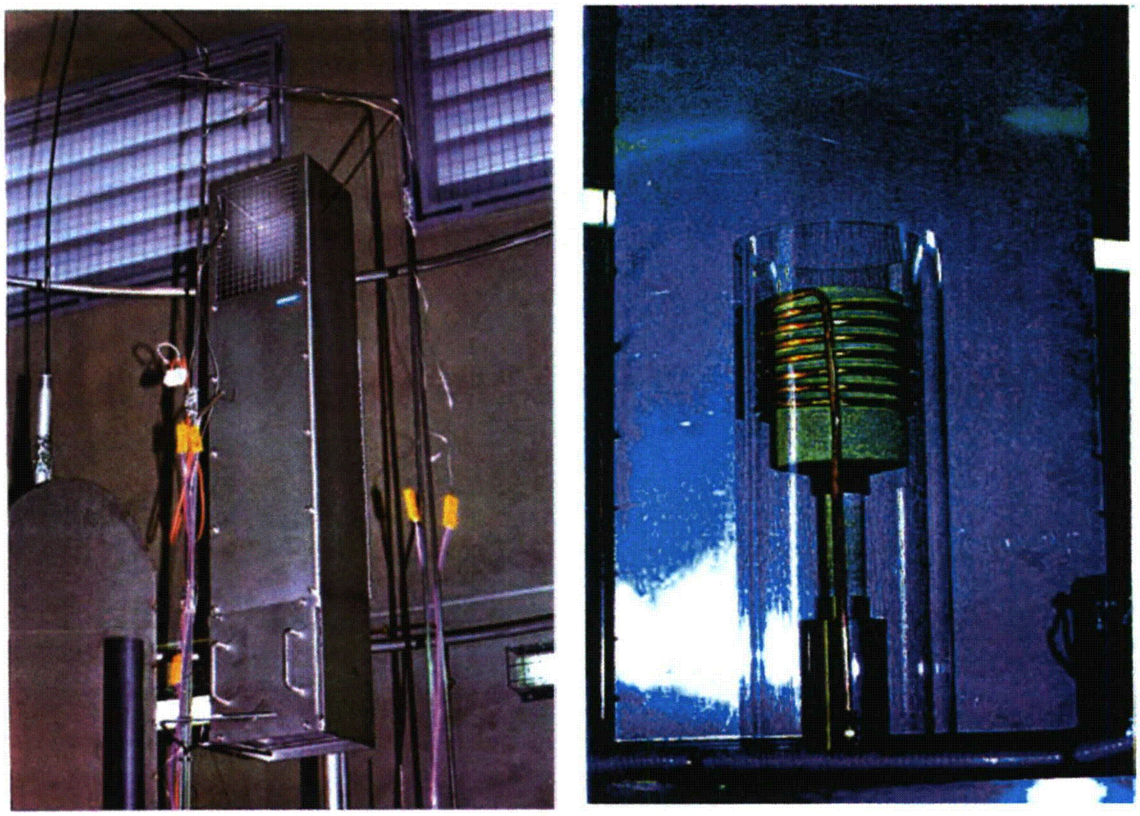


Figure 2-3: EDF / IPSN, H_2-PAR Test, Summary of the Qualification Tests

3.0 EDF H_2-KALI TESTS WITH SPRAY INCLUDING CHEMICALS

This program was exclusively performed with the PAR, by CEA (French Energy Atomic Commission) between 1993 to1995. The KALI-H_2 facility is located at the Cadarache Research Centre.

3.1 Objective of the Test Program

The objective of this test program was to study the effect of containment spray on the PAR efficiency.

3.2 Experimental Conditions

Twelve tests were performed with a specific range of temperature [ ] and dry hydrogen volumetric concentration, Y_{H2}, of [ ] percent by volume. During spray operation, the pressure was kept constant by regulation of steam input. The spray water was conditioned with [ ]

3.2.1 Test Vessel

For the test performance, the KALI spray test vessel was used (see Figure 3-1). The test vessel was a vertical axis cylinder (height of 5 m, internal diameter of 2 m) and had a volume of 15.6 m^3. The design pressure was 12 bar and the design temperature 200°C. The PAR was located close to the wall, at the bottom of the vessel to improve gas circulation (see Figure 3-2).

To simulate realistic conditions, a steam and hydrogen injection system and a spray system was used. Each system is described in detail in the following sections. The test matrices for the single tests are given in Table 3-1 and Table 3-2.

3.2.2 Steam Injection System

A steam generator, with a total power of [ ] injected saturated steam at the bottom of the vessel. One injection path was routed to the top of the vessel to maintain homogeneity. This system was used for the following reasons:

- To preheat the vessel structures by condensation.
- To reach the initial conditions for the experiments.
- To compensate during the tests for the heat losses by condensation on the inner wall of the vessel.

The mass of steam and pressure remained constant during the tests.

3.2.3 Hydrogen Injection System

Via a specific pressurized bottle, hydrogen was injected at the bottom of the vessel within less than [ ] to achieve H_2 concentrations between [ ] percent molar fraction (In steam conditions).

3.2.4 Spray System

Cold water [ ] was injected through a spray system with a specific mass flow rate [ ] and a specific size of droplets [ ] The spray water was subjected to a specific chemical treatment typical for a PWR. [

]

The vessel was also equipped with a fan to avoid any stratification during the hydrogen injection and to produce a homogenous mixture as a starting condition. The fan was stopped 45s after the beginning of the hydrogen injection.

Figure 3-2 presents the measurement locations in the KALI spray test facility. Temperature measurements were installed at three different locations in the vessel (T1, T2, T3), on the catalyst plate (T4), in the gas space just above the catalyst plate (T8), and at the inlet and outlet of the convection shaft (T6 and T7).

The velocity transducer (V) allowed measurement of the natural convection velocity at the inlet of the convection shaft. The overall pressure was measured by a gauge (P) located at the bottom of the vessel. The test matrix is shown in Table 3-1.

3.3 *Experimental Results*

[

]

3.3.1 *Conclusion*

The recombiner was subjected to 12 temperature cycles, including 10 hours of total spray [

]

Table 3-1: KALI Spray Test Facility—Initial Test Conditions

Table 3-2: KALI Spray Test Facility—Spray Test Matrix

[ ]

Notes:

* Homogeneity test without recombiner with [ ] (dry air)

** Redo of test no. 2

Figure 3-1: KALI Spray Test Facility

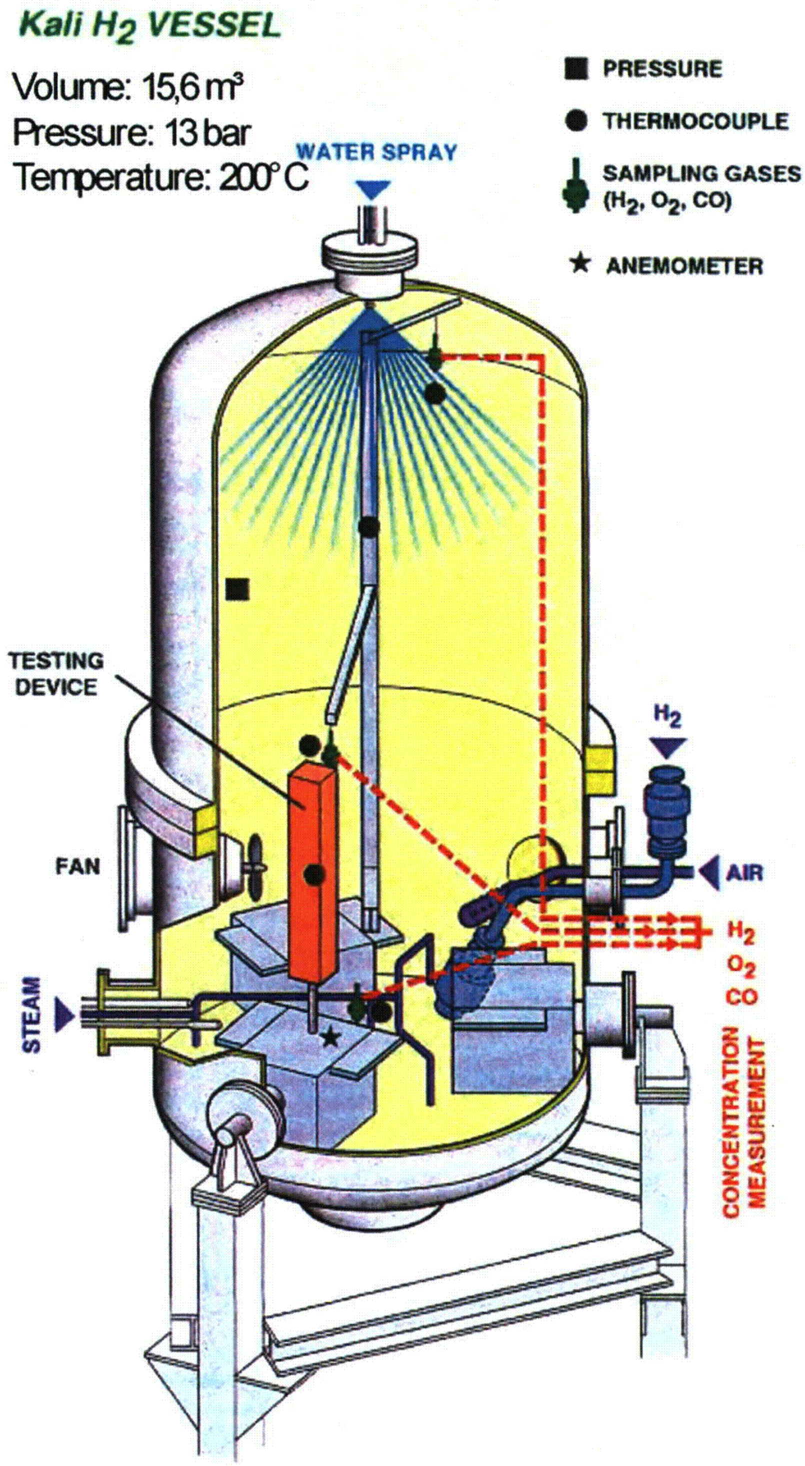


Figure 3-2: Instrumentation of KALI Spray Test Facility

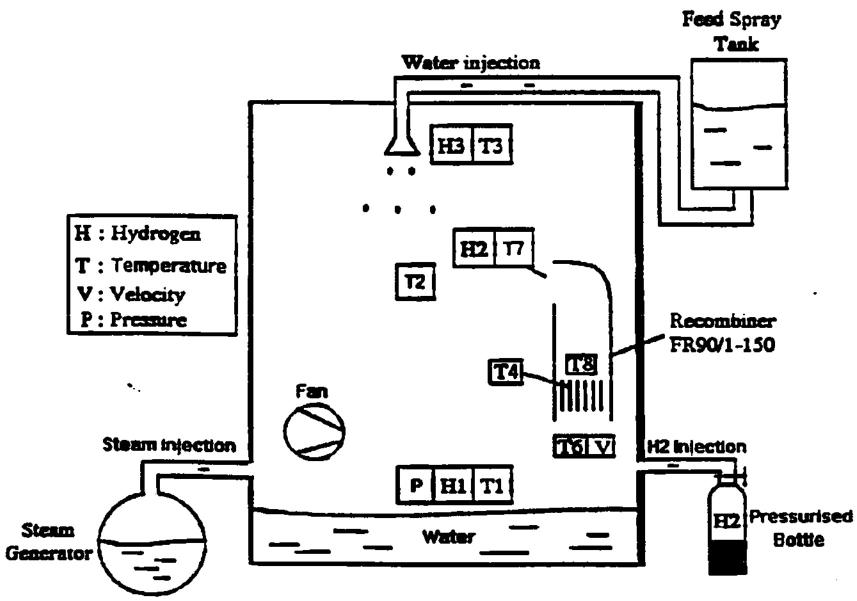
Commissariat a l'Energie Atomique Cadarache DEC/SECA/LTEA

Experimental apparatus and measurements

1) 15.6 M3 vessel of 2 m diameter and 5 m height

2) Measurements :

- In the vessel
- At the inlet of the recombiner
- At the outlet of the recombiner
- Inside the recombiner



ENS Class 1 Topical Meeting on "Research Facilities for the Future of Nuclear Energy"
BRUSSELS, June 4-6, 1996

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Figure 3-3: KALI Test, PAR Efficiency with / without Spray

4.0 PAR EFFICIENCY TEST UNDER CONTAINMENT SPRAY CONDITIONS

The PAR efficiency test under containment spray conditions was an additional test program to the already performed H_2-KALI tests. The aim of this test program was to study the effect on the PAR performance under containment spray conditions with a trisodiumphosphate (TSP), hydrazine, and boric acid solution.

4.1 Test Program

The test program consisted of three different phases. The first phase was the reference test where the PAR performance was measured under demineralized water spray and hydrogen injection. The second phase was the long-term spray test, including the sub phases of a pre- and post- test. The third phase was the final testing of PAR performance after the long spray test under containment spray solution.

4.2 Test Facility

For the PAR containment spray test, the test vessel VB 265 was used where a commercially available AREVA NP PAR [ ] was installed. The test vessel was equipped with a gas supply and a chemical feed system. To simulate the humid atmosphere, water was filled in the vessel and heated with two heating rods. The heating rods were controlled by two thermocouples. Two spray nozzles were installed inside the vessel and connected to the vessel sump. The spray nozzles were arranged directly behind the recombiner so that a significant quantity of spray droplet impacted the recombiner housing directly and created fine droplets. This arrangement stimulated more conservative conditions in comparison to design containment spray layouts where PAR spray nozzle distances are > 5 m.

The PAR was equipped with six standard catalytic plates instead of the fifteen possible plates to reduce the PAR capacity and allow for long term hydrogen depletion in the test vessel.

The following instrumentation was used to record the ambient conditions and PAR performance:

- Pressure VB 265 (P1).
- H_2-Concentration (Q3).
- Temperature VB 265 (T1).
- Temperature Catalytic Plate, Down (T2a).
- Temperature Catalytic Plates, Above (T2b).

See Figure 4-1and Figure 4-2 for the test setup.

4.3 Experimental Conditions

All tests were performed at a temperature of approximately [ ] and an absolute pressure of approximately [ ] inside the test vessel. The spray system was continuously running (just stopped for changing spray medium and during the night). The spray nozzles' inlet pressure was adjusted to approx. [ ]. Prior to each test the test vessel was flushed with air.

Table 4-1 lists the test matrix of the containment spray tests.

Table 4-1: Containment spray test matrix

[ ]

4.4 *Experimental Results*

4.4.1 Reference Test

Prior to the test, the vessel was purged with air. The spray system solution was demineralized water at a temperature of [ ] . The starting conditions were plotted at the beginning of the test. The air purging was stopped, and hydrogen was injected in the test vessel. The test began with the start of the hydrogen injection. The hydrogen sensor detected an increase of the hydrogen concentration in the test vessel. [ ] the start-up of the recombiner was indicated by an increase of temperature at the catalytic plates. The hydrogen was successfully depleted to an equilibrium level of [ ]

4.4.2 Pre Test (Long Term Test)

Prior to the test, the test vessel was purged with air. The spray system circulated the chemical solution at a temperature of [ ] All starting conditions were recorded at the beginning of the test. The air purging was stopped, and hydrogen was injected in the test vessel. The test started with the hydrogen injection. [ ] the start-up of the recombiner was indicated by an increase of temperature at the catalytic plates. The hydrogen was successfully depleted to an equilibrium level of [ ]

4.4.3 Long Term TSP Spray Test

Prior to the test, the test vessel was purged with air. The spray system circulated the chemical solution at a temperature of [ ] All starting conditions were plotted at the beginning of the test. The air purging was stopped, and the gas mixture of 3 percent by volume hydrogen in air was injected. The hydrogen level increased to 3 percent by volume within 12 min and reached the maximum H_2 concentration of 3.5 percent by volume after 20 minutes. [ ] after exceeding a H_2 concentration of 3 percent by volume, an increase of temperature at the catalytic plates was observed. The continuous H_2 injection and H_2 reduction by the PAR results in an equilibrium hydrogen concentration of [ ] in the test vessel. The test gas (3 percent by volume H_2 in air) continued to be injected. The injection was interrupted only to replace gas bottles. The hydrogen level decreased over the injection time. After eight hours of continuous injection, the long-term test was stopped. At this time, the hydrogen concentration was at [ ]

4.4.4 Post Test (Long Term Test)

Prior to the test, the test vessel was purged with air. The spray system circulated the chemical solution at a temperature of [ ] All starting conditions were recorded at the beginning of the test. The air purging was stopped, and hydrogen was injected in the test vessel. The test started with the hydrogen injection. [ ] the start-up of the recombiner was indicated by a temperature increase of the catalytic plates. The hydrogen was successfully depleted to an equilibrium level of [ ]

4.4.5 Third Phase Test

Prior to the test, the test vessel was purged with air. The spray system circulated the chemical solution at a temperature of [ ] All starting conditions were recorded at the beginning of the test. The air purging was stopped, and hydrogen was injected in the test vessel. The test started with the hydrogen injection. [ ] the start-up of the recombiner was indicated by an increase of temperature at the catalytic plates (See Figure 4-3). The hydrogen was successfully depleted to an equilibrium level of [ ]

4.4.6 Evaluation of the Test Results

The performed tests allowed for the evaluation of the chemicals in the containment spray water as well as the influence of the long-term spraying on PAR start-up and hydrogen depletion behavior. The test results are summarized in Table 4-2.

The Start-Up Behavior

The "reference test" (with demineralized water) and the "third phase test" (with chemical solution) show comparable start-up times of [ ] respectively. The "pre-test" (before long-term spraying) and the "post-test" (after long-term spraying) show comparable start-up times of [ ] respectively.

Conclusion:

The comparisons of PAR start-up behavior during the single tests and the depletion curves demonstrated that:

- PAR-efficiency is not significantly influenced by spraying of TSP, boric acid, and hydrazine (in comparison to demineralized water).
- Long-term spraying of the TSP, boric acid, and hydrazine solution had no detectible influence on the performance of the PAR.

Figure 4-1: Test Setup in Test Vessel

[ ]

Figure 4-2: Test Setup Diagram

[ ]

Figure 4-3: Plot of Third Phase Test

[ ]

Table 4-2: Test Results of Containment Spray Tests

5.0 CABLE BURN TESTS

Several test series were performed in the KALI test facility to study the effect of cable combustion fumes on PAR performance. Tests with representative U.S. plant-typical and French plant-typical cables were conducted.

5.1 U.S. Cable Burn Test

5.1.1 Test Program

For this test, U.S. plant-typical electrical cables containing chlorosulfonated polyethylene as cable jacket material was used. A baseline test, S6-022, was performed to measure the hydrogen depletion rate without PAR exposure.

5.1.2 Experimental Conditions

In Test S15, the recombiner catalyst was exposed for [ ] minutes to cable fire combustion products. After cooling, the tray containing the catalytic plates was packed in a leak-tight pouch, to conserve the combustion products from the cables, until its installation in the KALI test vessel for the hydrogen test. The test atmosphere contained [ ] by volume hydrogen, [ ] and no steam.

5.1.3 Experimental Results

Figure 5-1 compares the hydrogen depletion rate observed during the baseline test (S6) to that observed in Test S15. Both tests were conducted under identical conditions, except that, for Test S15 a PAR unit exposed to fumes from combustion of electrical cables was used. As shown in Figure 5-1, the effect of exposure to the combustion products from the cable fire was [ ]

5.2 French Cable Burn Test

5.2.1 Test Program

For this test, French plant-typical electrical cables of type NC (insulator and sheath PVC) and of Type ADR K1 (insulator EPR and sheath HYPALON) were used. Both types of cables are the most widespread products used in French nuclear power plants (NPP). To be representative of a site, 50 percent of PVC/PVC and 50 percent EPR/HYPALON were used for the cable fire experiment, which corresponds to the amount typical for French power plants. The PVC and CSPE (HYPALON) materials are halogenated agents and are identified recombiner poisons. The insulator material EPR does not contain halogen, and is, therefore, not an identified recombiner poison.

5.2.2 Experimental Conditions

[

] The tray was then installed above the burner and cables. The burner was started and burned the electrical cables. The recombiner catalyst was exposed for [ ] to cable fire to achieve the same level of cable degradation as the other test series. The reason was that the procedure for the U.S. Cable Burn Test Program used provided [ ] of fire exposure (burner). This duration proved to be insufficient to completely burn the French electric cable sheathing and insulation. With this same exposure, and using the same type of flame (burner), there was some sheathing and insulation that had little damage. The duration of exposure to fire was extended to attain a criterion that accounts for quantities to be burned and to achieve sheathing and insulation decomposition comparable to that of the U.S. cable. (See Table 5-1, Cadarache, Cable Burn Test Matrix). The burn durations were:

Test S15: 1 m U.S. cable – [ ]

Test No. 9/2: 2 m French cable (1 m of each cable type) – [ ]

After cooling, the tray containing the catalytic plates was packed in a leak-tight pouch, to retain the combustion products from the cables, until installation in the KALI containment for the hydrogen test. The performed hydrogen reduction test was carried out under the following conditions: [

]

5.2.3 Experimental Results

Despite these more severe environmental conditions, the recombiner operated efficiently, depleting the injected hydrogen (Figure 5-2). [

]

[

]

Table 5-1: Cadarache, Cable Burning Test Matrix

[ ]

Figure 5-1: H_2 Depletion Rate after U.S. Cable Fire

[ ]

Figure 5-2: Cadarache, H_2-Reduction during French Cable Burning Test

[ ]

Figure 5-3: Cadarache, Start-Up Delay during Cable Burning Test

Figure 5-4: Comparison H_2 Depletion Rate of plant-typical U.S versus French cable exposure

[ ]

6.0 HYDROGEN BURN TESTS

Two different hydrogen burn tests were conducted to study the effect on the catalyst exposed to a hydrogen deflagration. One test was at the Cadarache Nuclear Centre. The other test was conducted at the AREVA NP Laboratories at Karlstein (Germany).

6.1 H_2-PAR tests at the Cadarache Nuclear Centre

6.1.1 Test Program

Hydrogen burn tests were conducted as part of the H_2-PAR tests at the Cadarache Nuclear Centre. The general description of the test facility is provided in Section 2.0.

Tests E12, E12Bis, and E13 were performed to investigate deflagrations under dry atmosphere conditions and potential impact on the PAR performance.

6.1.2 Experimental Conditions

The tests were performed in the H_2-PAR test facility under dry steam condition to allow for a deflagration. To produce a deflagration in tests E12 and E12Bis, 23 moles of hydrogen were injected within [ ] in an ambient dry atmosphere of [ ] This results in a theoretical equivalent of hydrogen + air ratio of 9.9 percent (without recombiner). The hydrogen concentration was measured and documented by four different methods (i.e., chromatographic, spectrographic, capacities, comex) during the E12 test. Figure 6-1 depicts the hydrogen concentration over time.

The following tests were performed after the hydrogen burns in saturated steam condition. The following test parameters were achieved: [

]

6.1.3 Experimental Results

The dry air of tests E12 and E12Bis allowed for an ignition and deflagration load on the PAR unit (see Figure 6-1). The deflagration burned the available hydrogen which resulted in an end of test. Test (E13) was benchmarked against the reference test E2Bis, [

]

6.2 Hydrogen Burn Tests at the AREVA NP Laboratories

To verify function after a hydrogen deflagration, several tests were performed together with the German authorized inspection agency (TÜV) under the AREVA NP test program.

6.2.1 Experimental Conditions

For the Karlstein laboratory test, a small size PAR segment model was used, since the test facility VB12000 could not accommodate a full size recombiner. The detailed test setup and description of the test facility is provided in Section 8.2.2. The test conditions were as follows:

- Temperature [ ]
- Steam/ Humidity Inert Gas: [ ]
- H_2-Concentration: [ ]
- Pressure: [ ]

To produce a hydrogen deflagration and to investigate potential effects on the installed PAR, an igniter was used.

6.2.2 Experimental Results

[

]

Figure 6-1: Hydrogen Concentration during E12 Test

[ ]

Figure 6-2: Comparison of Ambient H_2 Concentrations for Experiments E2Bis and E13

[ ]

7.0 TEST PROGRAM FOR BWR AND PWR CONDITIONS

The program was performed by CEA (French Energy Atomic Commission) using the KALI H_2 facility located at the Cadarache Research Centre.

7.1 Objective of the Test Program

This experimental program was designed to study the performance and behavior of the PARs to control combustible gases during and after a postulated accident (design basis and severe) in boiling water reactors (BWR) and pressurized water reactors (PWR).

7.2 Experimental Conditions

7.2.1 Test Facility

The program was performed in the KALI H_2 facility, the same as used for the spray tests described in Section 3.0 (see also Figure 3-1). The PAR model was tested in the 15.6 m^3 steel vertical axis cylindrical vessel with a design pressure of 12 bar. The facility was instrumented to measure hydrogen, oxygen, and carbon monoxide concentrations; pressure; and gas temperatures at two locations: the PAR inlet and the upper part of the test vessel.

Vessel average concentrations of various gaseous constituents were measured at intervals during each test. Before measuring average concentration, the atmosphere was homogenized by intermittent operation of a fan. Temperature was measured and documented at three different locations within the PAR model. The facility had the capability to inject heated air, water spray, steam, hydrogen, carbon monoxide, and nitrogen.

7.2.2 PAR Unit Tested

The tests were performed with the smallest commercial available recombiner of PAR.

7.2.3 Test Matrix and Conditions

Tests conditions were generally selected to represent DBAs and severe accidents in both non-inerted PWRs and inerted BWRs.

The general effects of the following parameters on PAR recombination capacity were studied:

- Effect of hydrogen concentration (2 to 10 percent volume in dry air).
- Effect of ambient gas temperature and pressure.
- Effect of steam and low oxygen concentrations.
- Effect of potential poisons such as carbon monoxide and cable burn products. Note: The effect of U.S. plant-typical cable fire identified in this test series is discussed in Section 5.1.
- Effects of wetness on PAR start up delay.

Figure 7-1 presents the complete test matrix. Figure 7-2 is a benchmark between the Cadarache facility and the Karlstein laboratory.

7.3 Generic Experimental Results

The following sections describe the achieved results during the extensive test series.

7.3.1 Startup Performance—Effect of Hydrogen Concentration (Low Hydrogen, Excess Oxygen Conditions)

[

]

7.3.2 Startup Performance—Effect of Oxygen Concentration (Low Oxygen, Nearly Stoichiometric Conditions)

Because inert BWR containments operate with ≤4 percent oxygen, this test condition represents the lowest initial oxygen concentration (under which startup must occur), as expected in a nitrogen inert BWR containment. Test S4 [

]

7.3.3 Startup Performance—Effect of Wetness

All tests conducted in the presence of steam resulted in initial PAR startup within [ ] of introduction of hydrogen. These tests were conducted at initially saturated conditions at temperatures ranging from [ ]

[

]

Cold wet testing under low oxygen, nearly stoichiometric conditions [ ] (Test S3/2). Under steam condensing, elevated temperature [ ] hydrogen with excess oxygen conditions and [ ] oxygen with nearly stoichiometric conditions (Tests S5, S9, S10, S11).

7.3.4 *Effect of Ambient Gas Temperature*

Figure 7-3 compares the observed hydrogen depletion rate of the baseline case (Test S6, [ ]) to that observed when all conditions are maintained except that the gas temperature is increased to [ ] (Test S7, [ ]). The depletion rate at [ ] is observed to be [ ] of that observed at [ ]

7.3.5 *Effect of Pressure*

Figure 7-4 compares the observed hydrogen depletion rate of the baseline case (Test S6, [ ]) to that observed when all conditions are maintained except that gas pressure is increased by a factor of [ ] (Test S8, [ ]).

Based on the increase in mass density of hydrogen [ ], an increase in hydrogen depletion rate by a factor of [ ] would be expected at a given hydrogen concentration. The observed increase was [ ]

7.3.6 *Effect of Steam*

Figure 7-5 compares the two tests conducted with [ ] percent by volume hydrogen at [ ] one with no steam and one with [ ] percent by volume steam. Test S8 was conducted at [ ] Test S9 was conducted at [ ] Between these tests, two parameters were changed—temperature and the replacement of some of the air with steam. Based on the observed effect of temperature discussed previously, [ ]

[ ]

7.3.7 *Effect of Carbon Monoxide*

Because carbon monoxide (CO) gas is only produced by core-concrete interaction, which may occur late in a severe accident scenario, it would be expected that a significant amount of hydrogen gas would already have been released into the containment (pre-heating the PAR catalyst material due to recombination) prior to the production of CO gas. Accordingly, the testing to assess the effect of CO was conducted by first injecting H_2 to [ ] vol percent, allowing recombination until the vessel average hydrogen concentration had been reduced to [ ] vol percent, and then injecting CO gas to a concentration of [ ] percent by volume.

Figure 7-6 compares the observed hydrogen depletion rate from the baseline test (S6 at [ ]) to that observed when CO was injected to [ ] percent by volume with an existing H_2 concentration of [ ] percent by volume (Test S12, [ ]).

[ ]

7.4 *Summary of Test Program*

Under dry conditions, initial PAR startup is immediate even at low hydrogen concentrations ([ ] percent by volume hydrogen). The time required for full heat-up was [ ] minutes. [ ]

Several tests were conducted with varying degrees of wetting by steam condensation, previous cold water spray from the vessel dome, or previous spray directly into the top of the PAR unit. The performed tests identified, that under realistic accident conditions, which are tests at a temperature of more than [ ] and hydrogen concentrations of more than [ ] percent by volume, [

]

Under excess oxygen conditions, after the PAR unit reached a quasi-steady thermal condition, the hydrogen depletion rate varied from [ ] of inlet flow area at [

]

[

]

The hydrogen depletion performance of the PAR model tested in the KALI vessel was nearly identical to that observed during previous testing by AREVA NP. The low hydrogen concentration tests were conducted under excess oxygen conditions (typical of a non-inert containment). Several low oxygen concentration tests were conducted at nearly stoichiometric conditions representative of an inert containment. [

]

[

]

[

] Figure 7-7 presents the test parameters and results in tabular form.

Figure 7-1: EPRI / EDF Test Matrix

Figure 7-2: EPRI / EDF Test, Summarizing of Qualification Tests

[ ]

Figure 7-3: Effect of Ambient Gas Temperature

Figure 7-4: Effect of Pressure

Figure 7-5: Effect of Steam

Figure 7-6: Effect of Exposure to Carbon Monoxide

Figure 7-7: EPRI / EDF Test, Summarizing of Qualification (5 Sheets)

8.0 DEVELOPMENT AND QUALIFICATION TESTS AT THE AREVA NP KARLSTEIN LABORATORIES

For the application of the PARs in German PWRs, the hydrogen recombiners were subjected to a Type Test by the authorized inspection agency TÜV Bayern. This test program was performed at the AREVA test facility in Karlstein (Germany) using the VB12000 test vessel.

Two types of recombiners were tested. The only difference between these two types is that one has a modified housing design, the catalyst is the same in both recombiners.

8.1 Theoretical Test Program

8.1.1 Objective of the Test

The objective of the test was to compare an already type tested and qualified component, which is the AREVA NP [ ] against the catalyst of the PAR. [ ]

Within the scope of the PAR type test, the documentation was reviewed and checked for completeness and consistency (e.g., equipment description; assembly drawings; parts lists; written manufacturing and test procedures for manufacture; loading specification and analyses; stipulated practical tests; and the test equipment used). The theoretical test also included checking manufacturer verification of the capability to resist thermal and radiological loading, chemical impurities in the containment atmosphere, and integrity during operational vibration including loads occurring during earthquakes. Dimensional drawings were available for the almost full-size test specimens.

The type tests on the [ ] included a series of verification tests on functional capability under loads which may occur in the event of their use (e.g., pressure, temperature, mechanical vibrations, and atmospheric impurities).

[

]

8.1.2 *Experimental Conditions*

The following experimental tests were performed with the [

]

- Tests with elemental iodine, carbon monoxide and boron.
- Submergence test.
- Tests with methyl iodide.
- Tests with welding and solvent vapors.

8.1.3 *Experimental Results*

[

] On the basis of the manufacturing and test documentation, it was verified that the [

]

In both components, the catalytic plates are contained in an open housing and convection flow establishes along their length. This means that the results of tests using atmospheric impurities performed on the [ ] are likewise applicable to the catalytic recombiner.

[

]

The theoretical tests showed that the loads to be expected during severe accidents had been taken into consideration.

8.2 Practical Test Program

8.2.1 Objective of the Test

The objective of the TÜV type test recombiner tests was to obtain measured values of the hydrogen depletion rates under different ambient conditions.

The following test phases were conducted:

- Preliminary test.
- Recombination test under differing thermohydraulic conditions (Test Step No. 2.1-2.3.b).
- Functional test after prior loading through hydrogen deflagration (Test Step No. 3.1-3.5).
- Long-term recombination test (Test Step No. 4.3-4.4).
- Recombination test after exposure to oil and cable fire.

The practical tests and the prevailing conditions are given in the test and examination sequence plan (see Figure 8-1).

8.2.2 Experimental Conditions

8.2.2.1 PAR Unit Tested

Because the test facility could not accommodate a full size PAR, for test purposes the tests on hydrogen reduction capability were performed using three full-size test specimens [ ] The recombination capability of the catalytic recombiner is proportional to [

]

8.2.2.2 Test Facility VB12000

The tests were performed in AREVA's test facility VB12000 in Karlstein, Germany. The dimensions and design data for the test vessel are given in Figure 8-2. For tests in a humid atmosphere, the test vessel was connected to a heating system. The water inventory in the test vessel (1.6 m^3) was pumped continuously through a flow heater by a recirculation pump. A fan was installed to provide a homogeneous atmosphere in the test vessel during hydrogen injection.

In recombination tests, the initial conditions for steam and hydrogen were set in accordance to the test program. In the presence of air and steam, hydrogen was injected into the vessel until a previously calculated pressure was achieved. The set values were checked using the indication from the hydrogen analyzer.

In addition to the equipment required in the test set-up for the recombination tests, a hydrogen igniter with an external power source was installed in the test vessel for functional tests after pre-loading through hydrogen deflagration.

8.2.2.3 Test Conditions

The tests performed at the test facility in Karlstein and the prevailing conditions are listed in the test and examination sequence plan (see Figure 8-1). The recombination tests were performed in dry and humid atmospheres with steam contents of up to [ ] percent by volume.

For PWR accident conditions, the containment pressure and temperature depend essentially on steam content. Therefore, the tests at higher pressures were performed with steam content at saturated conditions.

For recombination tests after exposure to oil and cable fire, the catalyst insert that holds the plates was initially exposed to the smoke from burning oil. A [ ] quantity of oil was burned in [ ] minutes. During this time, the flames occasionally reached the catalyst. The catalytic active areas were subsequently covered in a thick layer of soot. The insert was then placed in the recombiner and subjected to a hydrogen/air mixture in test vessel VB12000. The same catalyst insert was then exposed to the smoke from a cable fire. The cable sections used had differing insulating materials such as those used in power plants. The fire lasted [ ] minutes. The catalytic active areas were covered in a uniform, thick layer of soot. The catalytically coated insert was again placed in the recombiner and subjected to a hydrogen/air mixture in the test vessel VB12000.

Recombination tests were also performed using the largest recombiner type in the containment mockup at the Battelle Institute in Frankfurt, Germany. The Battelle containment mockup was divided into five compartments, at an overall volume of ≈209 m^3. The tests were carried out at [ ] in a steam / air mixture containing [ ] vol percent steam. Hydrogen was injected continuously at [ ] during the tests. The test program was composed of:

- Determination of the start of recombination for the catalyst (lower hydrogen

level).

- Determination of hydrogen reduction to the smallest possible hydrogen concentration.
- Determination of the recombination capacity of the recombiner.

8.2.3 Test Results

The measured PAR performance of the practical tests were used to develop an empirical equation for the hydrogen depletion rate in dependence of total pressure, hydrogen concentration, ratio of hydrogen concentration related to oxygen concentrations, and recombiner type. Figure 8-3 provides the normalized hydrogen depletion rate, applicable for the PAR in the U.S. EPR design.

Functional tests after pre-loading of hydrogen burn observed that [

]

For long-term recombination tests, the hydrogen depletion behavior was determined over a period of [ ] hours. The hydrogen and oxygen concentrations were held nearly constant during the test. Afterwards, the hydrogen depletion performance was checked against the previously determined performance. [

]

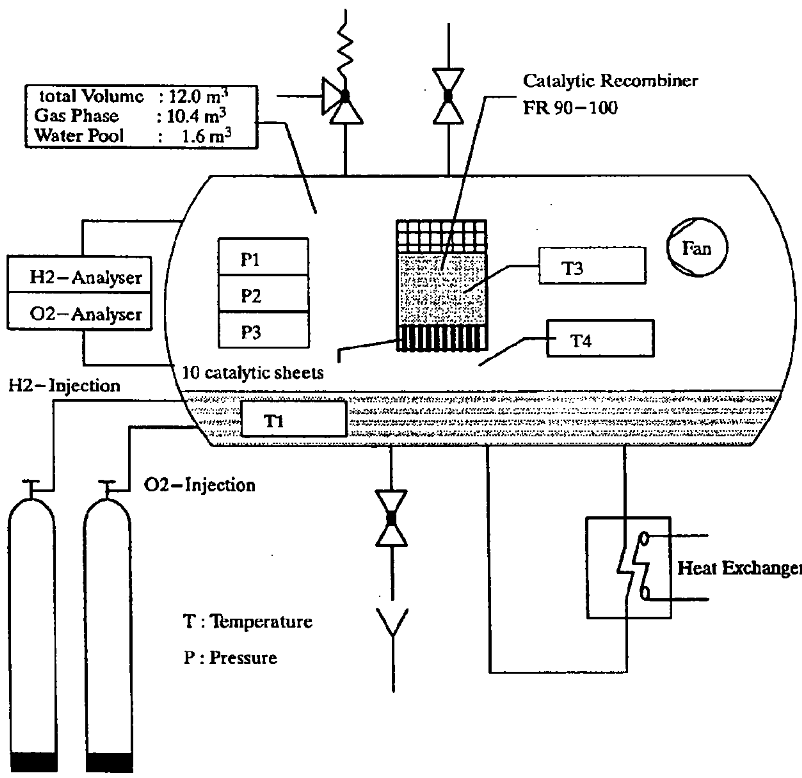
[

] The recombination test result and test protocol after the exposure to the oil fire are shown in Figure 8-4 and Figure 8-5.

Figure 8-1: AREVA NP Test and Examination Sequence Plan

[ ]

Figure 8-2: AREVA NP Test, Test Vessel



Test Vessel VB12000

TÜV Type Test

- Resistance to thermal aging and radiation
- Resistance to chemical impurities in the reactor containment atmosphere
- Recombination rates under various ambient conditions
- Endurance and vibration test
- Resistance to fire from cable or oil and fumes from solvents or welding

The legibility issues on this page are not pertinent or essential to this report.

Figure 8-3: Normalized Hydrogen Depletion Rate

Figure 8-4: Recombination Test after Exposure to Oil Fire

Figure 8-5: Test Protocol - Recombination Test after Exposure to Oil Fire

9.0 CAE IPSN PHEBUS 02 CATALYTIC COUPON TEST

The Phebus 02 tests at Cadarache, France, were performed with catalytic coupons from different PAR vendors. These coupons represent a small catalytic surface area. Atmospheric test conditions were the following: [

]

A low hydrogen concentration at the outlet indicates that the catalyst has recombined a large amount of injected hydrogen. Figure 9-1 shows the AREVA NP catalyst high hydrogen reduction efficiency. The temperature of catalyst indicates its start-up behavior and also its efficiency. Figure 9-2 shows that the AREVA NP catalyst provided high temperature levels and, therefore, high performance concerning start-up behavior and hydrogen reduction rate

Figure 9-1: IPSN PHEB.02 Catalytic Coupon Test

Figure 9-2: IPSN PHEB.02 Catalytic Coupon Test

10.0 PAR LOAD ANALYSIS

U.S. EPR site-specific load calculations and structural analyses will be performed to verify the mechanical strength of the PAR. This section describes the general approach of a stability analysis by an example for a European EPR reactor.

The mechanical strength of the PAR was verified by the equivalent static load method (ESLM) considering acceleration values of DBE and airplane crash (APC) derived from the seismic response spectra curves of the Reactor Containment Building.

This calculation was done for two PAR types. The following load cases were considered:

- NOL: Normal Operating Condition (Dead Weight).
- LOCA: Loss of Coolant Accident.
- DBE: Design Basic Earthquake.
- APC: Airplane Crash.
- SA: Severe Accident.

10.1 Mathematical Verification

To verify the resistance of the PAR-Housing, the following steps were taken:

- Generation of a mathematical model.
- Frequency analysis to get the dynamic behavior.
- Analysis Performance (ESLM).

The analysis was performed as a finite element analysis applying the program code ANSYS.

10.1.1 Mathematical Model

The PAR is a welded design, the frames are welded to the casing. To represent the PAR, a mathematical model was created (Figure 10-2) consisting of:

- The drawer composed of sheets, inserts and spacers for catalytic plates.
- The housing (containing the drawer) basically composed of the housing sheets, the upper/lower mounting point reinforcement profiles (U50/U60) and three frames to brace the housing sheets.

10.1.2 Load Cases and their Combinations

The seismic analysis for the PAR-housing structure takes place by covering the acceleration, load control and superposition control as shown in Figure 10-1.

Figure 10-1: Load Cases and their Combinations

10.2 Results

The stability of the PAR-Housing structure including the catalytic plates was not affected by the above mentioned load cases. The allowable stresses were not exceeded for the entire PAR structure. The detailed results are listed in Table 10-1. The graphical result of the mathematical analysis for the normal operating load ± design basic earthquake is shown in Figure 10-3, and the severe accident load case is shown in Figure 10-4.

Figure 10-2: Overview of Mathematical Model

[ ]

Figure 10-3: Result Illustration for the NOL ± DBE Load

Figure 10-4: Result Illustration for the Severe Accident Load Case

[ ]

Table 10-1: Analysis Stress Results

[ ]

11.0 OPERATIONAL EXPERIENCE

PAR-based hydrogen mitigation systems have been installed in many types of nuclear power plants to reduce the risk associated with the formation of hydrogen in DBAs or SAs.

The PARs are installed in more than 100 NPP in several countries around the world. This is over 3000 PARs with an experience of more than 200 annual in-service inspections (ISI).

The already performed >200 annual tests (ISI) criteria were met, with positive results confirming PAR system operability, except for those exposed to the following:

[ ]

Even though exposed to the above adverse conditions, the plates continued to exhibit catalytic functions.

Some of the affected catalysts were regenerated or replaced by spare parts to reduce the catalyst contamination effects, minimize the start-up times, and restore the PAR to original performance conditions.

[ ]

In conclusion, operating experience has shown that:

- The specific multiple precious metal thin plate catalyst technology shows acceptable functional behavior after more than 10 years operation.

- For highly contaminated catalyst (e.g., CO-compounds, oil, boric acid) catalytic function could be demonstrated during the ISI.

- [

  ]

APPENDIX A
SUMMARY OF QUALIFICATION TESTS AND RESULTS

This appendix provides a summary of the qualification tests, results, and locations of the test.

Table A-1: History of Development of Passive Autocatalytic Hydrogen Recombiner Systems

GERMANY	Karlstein-Laboratories (Section 5.0/ 7.0/9.0)	Development and Qualification Application for Patents Patents granted Containment Spray Test (TSP)	Since 1989 Since 1990 Since 1991 2006
FRANCE	Cadarache (Section 4.0)	EDF KALI H_2-Tests Qualification for 900 MW PWR French accident scenario (Spray incl. NaOH, H_2BO_3)	1995
USA/FRANCE	Cadarache (Section 6.0/8.0)	EPRI/EDF KALI H_2-Tests Qualification for US-ALWR	1995/96
FRANCE	Cadarache (Section 3.0/10.0)	IPSN/EDF H_2 PAR-Tests Aerosol Tests etc. (Te, Se, J, Cs, etc.) Pretest: Phebus Catalytic Coupons EDF/CEA KALI H_2-Tests Deflagration/ Degradation	1996-1998 1998 1998

Table A-2: Test Conditions and Results of the IPSN/EDF Test Program (Section 2.0)

[ ]

Table A-3: Test Conditions and Results of the CAE/EDF – KALI Test Program (Section 3.0)

[ ]

Table A-4: Test Conditions and Results of the Containment Spray Test (TSP) (Section 4.0)

[ ]

Table A-5: Test Conditions and Results of the CEA/EDF - KALI Cable Burn Test Program (Section 5.0)

Table A-6: Test Conditions and Results of the CEA/EDF - KALI Hydrogen Burn Test Program (Section 6.0)

[ ]

Table A-7: Test Conditions and Results of the EPRI/EDF - KALI Test Program for PWR/BWR Conditions (Section 7.0)

Table A-8: Test Conditions and Results of the AREVA NP Test Program (Section 8.0)