

Containment Hydrogen Control and Filtered Venting Design and Implementation

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Abstract

Research into the hypothetical event of core melt accidents has continued and new accident mitigation technologies have been developed. Decisions have been taken to implement these new mitigation measures in operating nuclear power plants to mitigate severe accidents. In order to prevent loss of containment integrity as a result of overpressurization, nuclear power plants in the Federal Republic of Germany as well as in most other European countries have been or will be backfitted with systems for filtering the containment atmosphere and systems for

H₂-control. Similar discussions start for the WWERs.

For these tasks it has been necessary to develop means for containment atmosphere control which are capable of

- handling high H₂ production rates as well as
- cleaning and measuring high contaminated atmosphere.

In addition, the systems should feature a simple design, incorporate passive equipment to as large an extent as possible, be cost-effective and be easy to integrate into various types of plants.

The advantages and drawbacks of various hydrogen countermeasures to mitigate severe accidents, for example of igniters, passive autocatalytic recombiners (PARs), post inertization, etc. have been investigated and ultimately the PAR system selected as the H₂ mitigation technique to be implemented or already have been backfitted to Western PWR plants and Soviet-designed VVER nuclear power plants.

A PAR system consists of a large number of passive individual autocatalytic recombiners - for example anywhere from 30 to 60 individual PARs - distributed inside the containment to accommodate a wide range of release scenarios.

The effectiveness of such a PAR system has been demonstrated by analysis comparing a representative severe accident sequence with and without the presence of PARs.

Initial Framatome-ANP PAR system installations were carried out in Belgian nuclear power plants in 1995. To date more than 25 PAR systems have been installed in nuclear power plants. In total more than 1000 PAR units have been ordered or backfitted to Western PWR plants and Soviet-designed VVER nuclear power plants.

The hydrogen control system is based on the Passive Autocatalytic Recombiner (PAR) technology. There is no need of any operator actions because of the self-starting feature of the catalyst if H₂ is released.

In addition the hydrogen concentration values of the containment atmosphere will be available for the plant operators in most PAR applications, using the measuring results of the hydrogen sensor system or PASS systems.

During venting system process design particular importance is attached to the requirements regarding, for example, high aerosol loading capacity, provisions for decay heat removal from the scrubber unit, the aerosol spectrum to be retrained and entirely passive function of the re-

tention unit. To meet above - mentioned requirement, a combined venturi scrubber unit was developed which comprises a venturi section and metal fibre section and could be operated in the sliding pressure mode and the atmospheric pressure mode.

This scrubber systems was tested using a full-scale model and has now been installed in 16 PWR and BWR plants in Europe.

Detail design work of venting systems for WWERs application, e. g. for Kosloduy 5 / 6 and in TARCIS project No. R2.08/95, for the reference NPP Balakovo, have been completed.

The activation of the venting system shall be performed to avoid overpressurization of the containment and will be decided from the on-site crisis board and needs:

- the permission of the local state government
 - and will be initiated in close contact with Emergency Technical Support Centre of the plant.
- Additional information before and during operation of the venting system will be received from the In-Situ PASS and Emission Control System.

1. Introduction

In order to reduce the residual risk associated with hypothetical severe nuclear accidents, systems and components for filtered containment venting and H₂ reduction had to be developed. During severe accident scenarios large quantities of hydrogen may be released into the containment atmosphere within a short period of time, ignition of these mixtures can lead to uncontrolled turbulence-combustion process which could jeopardise the integrity of the containment and exceed overpressure design values of the containment.

Systems are intended to protect the containment, the last barrier for the confinement of radioactivity, against loss of integrity in the event of internal overpressurization due to hypothetical severe accident sequences and thereby to minimize to as great an extent as possible any unavoidable releases of activity to the environment.

For operator aids in the course of accident operating procedures and regulations have been implemented.

For severe accident management the overall crisis organisation for the German nuclear power plants is activated by immediate set up of the on-site accident management organisation. This on-site accident management organisation is lead by a crisis board to take quickly the necessary strategic decisions, to receive and to distribute information and to co-ordinate the emergency measures

This paper describes the new technologies including their verification which result in a reduction in risk in the event of severe accident scenarios, the implementation status and procedures and the regulation for operation of these systems.

2. H₂-Control

2.1 General Requirements

Plants to mitigate severe accidents.

In the event of a severe accident, large quantities of H₂ could be produced causing an additional build-up of pressure inside containment.

In the meantime, the advantages and drawbacks of various hydrogen formation countermeasures to mitigate severe accidents, e.g. of igniters, passive autocatalytic recombiners (PARs) and post-

inertization, etc., have been investigated, and ultimately the PAR system selected as H₂ mitigation measure to be implemented.

These systems must meet requirements by featuring the following characteristics:

- high functional reliability, such as resistance to poisoning by Te, Se, iodine or CO, etc.
- highly efficient, exhibiting H₂ reduction rates, for example, of greater than 50 kg/h
- simple design
- integrated passive equipment
- cost-effective
- easy to integrate into existing plants.

2.2 H₂ Reduction Technologies

Over the past two decades since TMI, several H₂ reduction technologies have been developed and tested to limit H₂ concentration in the containment atmosphere under LOCA conditions. Later, severe accident situations involving generation of large amount of hydrogen were investigated as well and H₂ reduction technologies to mitigate severe accidents were developed and tested.

2.3 H₂ Reduction Technologies for LOCA Control

In order to limit H₂ concentrations inside the containment in the event of a LOCA given an accident scenario involving comparably little H₂ release, requirements governing associated analyses and countermeasures were stipulated in the related guidelines issued by the German Reactor Safety Commission.

Corresponding countermeasures such as thermal recombiners (see *Fig. 1*), forced-flow heated catalytic recombiners, etc., were qualified in extensive experimental test series under LOCA conditions and subsequently installed in nuclear power plants in operation.

2.4 Conclusions

The throughput rate of thermal and catalytic recombiners designed for use under LOCA conditions is limited to a several hundred m³/h. Use of these units for H₂ reduction under postulated beyond-design-basis events – i.e. conditions exhibiting H₂ releases higher by several orders of magnitude – would therefore hardly prove effective.

3. H₂ Reduction Under Severe Accident Conditions

During a severe accident, large amounts of hydrogen can be released inside the reactor containment and increase hydrogen concentrations significantly.

The following hydrogen control systems were considered in a system comparison and analysis.

3.1. Igniters

Igniters have already been installed in some nuclear power plants and were also subject to intensive deliberation for severe accident applications in European countries. Various igniter systems have been developed and tested such as glow plugs, autonomous spark igniters (*Fig. 1*) and high-frequency spark igniters.

Engineering studies for implementation of igniter systems have been performed to determine for example the required quantity and location of igniters, combined with analysis of gas distribution and

studies of combustion behaviour. In addition, detailed lumped parameter analyses as well as 3D-code analyses to investigate gas distribution and combustion have been conducted. Uncertainties were identified with respect to, among other aspects, hydrogen distribution and combustion behaviour. Ultimately, on basis of these facts, the installation of igniters was not recommended by the regulatory authorities.

3.2 Pre- and Post-Inertization

Inertization is an established technique for preventing any fire loads from occurring inside the containment.

Pre-inerting systems using N_2 have therefore already been implemented in many BWR plants. For applications in PWR plants, investigation has concentrated on CO_2 as inerting agent because smaller quantities are needed. To avoid the disadvantages posed by liquid CO_2 injection, a semi-passive post-dilution system which injects gaseous CO_2 only was developed and related prototype tests successfully conducted (*Fig. 1*).

However, owing to the additional burden placed on plant operating personnel and the complexity of the system, etc., this CO_2 post-dilution system was also not recommended by the regulatory authorities.

A different situation is given in the case of a multiple-unit WWER, because in this case a central CO_2 post-dilution system could be considered also as an economical interesting solution.

3.3 Passive Autocatalytic Recombiners (PAR)

3.3.1 Function

Passive autocatalytic recombiners (PARs) use catalytic coatings to transform molecular hydrogen and oxygen into water vapour. They are self-starting and self-feeding, even under cold and wet conditions. The buoyancy of the hot gases expelled at the top of PAR vertical flow channels sets up natural convective flow currents that promote mixing of combustible gases in the containment.

Recombination of these gases commences as soon as hydrogen is released into containment as a result of a design-basis or severe accident.

Catalytic recombiners with a far greater capacity than those installed for a design-basis event considerably limit the rise in the hydrogen concentration even under steam-inerted atmospheric conditions.

3.3.2 PAR Design

The catalytic recombiner comprises a metal housing designed to promote natural flow, with the gas inlet arranged at the bottom and gas outlet at the top (*Fig. 2*). Numerous parallel plates with a catalytically active coating are arranged vertically in the bottom of the housing.

The cover of the housing at the top of the recombiner protects the catalyst against direct spraying of water and aerosol deposition, thus allowing recombiner operation under spray conditions.

Easy access of the catalytic plates is provided by way of a removable inspection drawer. The catalyst consists of a thin stainless steel plate coated with a special multi-precious-metal catalyst. The catalyst allows low starting temperatures. Hydrophobic behaviour of the catalyst is ensured without additional layers. The units are therefore extremely temperature- and radiation-resistant.

Development tests were conducted to optimize the configuration so that a maximum rate of recombination is achieved in a housing of minimum size. To allow flexibility in the arrangement of these devices in the various compartment areas of a containment, the recombiner is available in various sizes.

Since PARs have no moving parts and require no external energy source, no operational procedures

are required and the units are designed to provide ease of maintenance. It is projected that this will lead to greater life-cycle cost-effectiveness.

3.3.3 PAR System Design

A PAR system consists of many single PARs distributed inside the containment to accommodate a wide range of hydrogen release scenarios.

The arrangement of the individual PARs inside the containment is determined by the projected H₂ release rate, location and distribution, the containment geometry and operational constraints on maintenance areas, accessibility, etc.

These analyses have investigated PAR positioning, determination of local and global H₂ reduction capacity and the effects of the recombiner system on gas distribution.

The effectiveness of such PAR systems has been demonstrated / 1 / by comparing analysis results from a representative severe accident sequence with and without PARs postulated to occur in a FRAMATOME ANP Convoy-series plant (see *Fig 3*).

These analysis results showed that only in few local areas in the containment did combustible gas mixtures form for a limited time span, and H₂ concentration is reduced significantly.

The containment atmosphere becomes inert at the end of the first day after the onset of accident conditions such that catalytic reaction is limited due to oxygen depletion.

3.3.4 National and International Qualification Tests

In addition to development tests on model and full-size FRAMATOME ANP devices, an extensive test qualification program was conducted to measure depletion rates under a range of hydrogen concentrations, steam/pressure conditions and various potential adverse poisoning conditions (*Fig. 4*). Some tests were conducted in the Battelle multi-compartment facility. Independent organisations have participated in and/or performed qualification testing of the FRAMATOME ANP design, such as TÜV, CEA, IPSN, EPRI and EDF, etc.

3.3.4.1 Qualification and Functional Tests

The following tests series, for example, were conducted for the FRAMATOME ANP PAR:

- tests at various pressures, temperatures and steam and hydrogen concentrations
- tests under exposure to catalytic poisons (I₂, CO, H₃BO₂ and CH₃I) / 2 /
- tests following hydrogen combustion, submergence in water, and oil and cable fires (including US and French cable)
 - within spray water system (French PWR plant conditions) / 3 /
 - wetted condition during startup with direct water spray on the catalyst / low oxygen content, etc.

Ultimately, a new test facility (*Fig 4*) for simulating aerosol exposure with a molten core substitute and poisons like tellurium and selenium, etc., was constructed in Cadarache, France to demonstrate the behaviour of the PAR under severe accident conditions.

Because of the importance of these tests, *Fig. 4* shows depletion curve of the recombiner after the comprehensive poisoning element mixture test.

3.3.4.2 PAR Operation under Elevated H₂-Concentrations

The chemical reaction at the catalyst of hydrogen/oxygen being exothermal and will lead to increased PAR temperatures, if elevated H₂ concentrations will occur. These basic PAR phenomena and the

possibility to ignite H₂ mixtures have been discussed frequently. Because this behaviour is in certain limits PAR-type specific additional tests have been performed.

To study the behaviour of the FRAMATOME ANP PAR under this condition various deflagration tests have been executed.

On basis of these tests it could be concluded, that under H₂ concentrations up to 8 or 10 Vol. %,

- Ignition caused by this PAR type seems to be very unlikely, taking into account realistic ambient conditions including some steam content.

During these test series it also could not be observed any significant PAR spelling effect nor ignition caused by such airborne catalytic material.

3.3.4.2 Test Results

On basis of these new test results it was concluded that poisoning resistance of the FRAMATOME ANP PAR has now also been demonstrated under realistic severe accident conditions. Testing covered the potential catalyst inhibitors or poisons like fumes from welding and solvents, water, steam, elementary iodine, carbon monoxide, boric acid and methyl iodine as well as oil or cable fire.

4 Implementation and Operation of PAR Systems

4.1 Implementation Experience

The first PAR systems to be installed in actual nuclear power plants was in Belgium in 1995 / 4 /.

Installation of a complete PAR system comprising for example 40 to 60 individual PAR units was usually performed over a period of two weeks during the plant refuelling outage. The total project time required for a PAR implementation project, including engineering, manufacture and installation in the containment was approximately 1 year.

To date 37 PAR systems have been ordered or backfitted to

- Western PWR nuclear power plants to mitigate BDBA situations and to
- Soviet-designed VVER plants to cope with DBA conditions (exception: BDBA design for Kalinin 1)

Detailed information regarding the PAR implementation status and installed pieces are given in Fig. 7.

4.2 Operating Experience

One of the questions to be answered with respect to operating experience with recombiners was whether any relevant ageing can be expected to occur under operational conditions.

FRAMATOME ANP catalytic recombiners are constructed of metals and other materials whose physical properties do not change significantly under long-term exposure to operating temperature and radiation environments in the containment. This fact was confirmed by the poisoning tests.

In order to prove functional capability, a preventive maintenance program was implemented to ensure that the PAR devices remain capable of performing the required safety function over their entire service life.

This program consists of inservice visual inspections and testing of the installed PAR catalyst.

In these inservice inspections and tests some representative catalyst sheets are removed from the PARs. The removed specimens are placed in a standard inservice test apparatus. Each individual cata-

lytic sheet is exposed to a pre-mixed test gas containing hydrogen in order to measure its catalytic efficiency.

Since 1995 more than 50 annual inservice inspections have been carried out, all of them with positive test results. Because FRAMATOME ANP PARs have no significant ageing mechanism that cannot be tracked by inservice inspection, these components are expected to retain a qualified service life equal to that of the overall plant.

4.3 Severe Accident Management

General:

For Severe Accident Management a special organisation providing support needed and taking decisions is agreed.

The principal organisation of such plant crises team is given in Fig. 7.

The hydrogen control system is based on the Passive Autocatalytic Recombiner (PAR) technology.

In terms H₂ control there is no need of any operator actions, because of the self-starting feature of the catalyst if H₂ is released.

In spite of this for additional information of the crises team the hydrogen concentration values of the containment atmosphere will be available in most PAR applications, using the measuring results of the hydrogen sensor system or PASS system.

5. Containment Venting

5.1 General Requirements

As a result of these investigations of design parameters for containment venting risk studies have been performed as well as additional experiments based on aerosol release, the Reactor Safety Commissions established requirements. Under consideration of the requirements of the various countries enveloping requirements for filtration systems could be formulated.

In particular, close attention was paid by the Commissions to the question of the aerosol particle sizes that should be retained.

– Particle size distribution

Because of its considerable influence on the retention capability of the system, the aerosol distribution was calculated in the course of parametric studies based on experiments. Analysis of these parameters revealed that aerosol mass mean diameters of less than 1 µm could be expected, primarily on account of the long-term effects of concrete-melt interaction.

It was further necessary to verify elemental iodine and aerosol resuspension in the scrubber unit during continuous operation over ≥ 24 or 48 h and to take this into account when verifying the removal efficiencies.

Additional requirements included:

- Passive removal of decay heat from the filter > 7 kW to 400 kW
- Retention rate of aerosols $\eta_{\text{Aerosol}} > 99,99\%$
- Retention rate of molecular iodide $\eta_{\text{I}_2} > 99\%$

For WWER 440 application additional requirements, as

- Maintaining a subatmospheric pressure in the confinement during long term post accident phase and
- post accident treatment of confinement leakage's have to be fulfilled.

5.2 Venting process

The Framatome-ANP venting system employs a venturi scrubber followed by a combined droplet separator and metal-fibre filter. A principle flow diagram of the Sliding Pressure Venting is given in Fig. 5. The venturi scrubber unit is operated at pressures close to the prevailing confinement pressure / 5 /. The venting flow entering the scrubber is injected into a pool of water via a small number of submerged, short venturi nozzles. The ratio of the diameter of the aerosols and the venturi throat precludes any clogging.

As the vent gas passes through the throat of the venturi nozzle, the incoming gas flow develops a suction which causes scrubbing water to be entrained with it and, on account of the large difference between the velocity of the scrubbing water particles and that of the incoming vent flow, a large proportion of the aerosols are removed.

At the same time, the particles of the entrained scrubbing water provide large mass transfer surfaces inside the throat of the nozzle, which permit effective sorption of iodine.

Optimum retention of iodine in the pool of water inside the scrubber is attained by conditioning the water with caustic soda and other additives.

In view of the mechanism occurring inside the venturi, most of the iodine and aerosol particles are in fact separated inside the throats of these nozzles.

The pool of water surrounding the nozzles acts as the primary droplet separation section and also serves as a secondary stage for retention of aerosols and iodine.

The gas exiting from the pool of water still contains small amounts of hard-to-retain aerosols as well as scrubbing water droplets. In order to ensure high retention efficiencies even over a long period of time - for example, 24 or 48 hours - a high-efficiency droplet separator and micro-aerosol filter is provided as a second retention stage. Even under extremely low flow conditions the reduced venturi retention efficiency is fully compensated by the filter demister.

Both venturi scrubber sections provide a retention efficiency for aerosols of 99.99 % and more. This retention capability also applies to micro-aerosols of less than 0.5 μm so that, for example, variations in the particle size distribution of the aerosols cannot diminish the removal efficiency. The retention efficiency for elemental iodine under all operating conditions including overpressure conditions is above 99%. The retention efficiency for organic iodine was found to be better than 85% to 95%.

If the system will be operated in the Long term post accident phase for confinement leakage treatment the formation of further portions of organic iodide could be postulated.

To increase the retention efficiency also for organic iodide to values of > 99% a molecular sieve unit is used in addition.

5.3 Performed Qualification for Venturi scrubber unit

Pre-tests performed for the purpose of process selection of a Venturi scrubber unit were conducted under atmospheric pressure and room temperature conditions on individual sections of the process such as the venturi and the metal-fibre filter.

After final selection of the process design, it was necessary to perform functional tests under representative conditions.

These tests covered aerosol removal efficiency tests as well as tests for iodine retention on a full-scale test facility, especially at pressures above atmospheric.

A full-scale test facility (JAVA Test Facility) was erected specifically for the purpose of conducting the tests of this verification program.

5.3.1 JAVA Test Facility

Figure 5 shows the flow diagram and the test parameters of the JAVA test facility.

The facility can be operated as a closed loop or as an open circuit connected to a steam boiler (22 MW) and suppression tank.

A summary of the main test parameters and the test results are given in *Figure 6*.

Equipment for aerosol and iodine injection as well as measurement was installed upstream and/or downstream of the scrubber and filter section.

Each test was monitored from a central control desk. This desk was equipped with recorders for continuous documentation of all physical data.

Aerosol Retention

Medium-energy venturi operation tests were performed using soluble uranine and nonsoluble BaSO₄ aerosols having mass mean diameters in the region of 1 μ m.

Even under low flow conditions, almost all of the aerosols (between 97% and 99%) were retained in the venturi section.

As a result of the combination of venturis with a metal-fibre filter demister, even at system pressures of 0.1 to 1 MPa retention efficiencies of > 99.99% were verified under full-flow conditions and also at reduced gas flows - due to the greater efficiency of the second section.

Due to this mode of operation, again almost all of the aerosols (95% to 99 %) were removed in the venturi section.

Furthermore, for the entire unit, retention efficiencies > 99.99% were obtained.

Iodine Retention

The total iodine removal efficiency of the entire venturi unit was determined in short-term and long-term tests.

The elemental iodine removal efficiencies provided by this two stage filtration equipment were consistently > 99.5%. These results have been obtained even under operating conditions that have an unfavourable effect on gas sorption such as the following:

- elevated system operating pressure, and
- reduced venturi velocities under atmospheric conditions.

Iodine revitalisation tests yielded revitalisation rates of < 0.1% over an operating period of 24 hours and using an air content in the vent flow of 10% by volume.

Furthermore, as a result of the capability of the measuring techniques to discriminate between elemental iodine and organic iodide, it was possible to verify an average organic iodine removal efficiency of 85% to 95%.

5.3.2 ACE Tests (Filter Testing)

The performed filter tests were divided into aerosol tests and resuspension tests.

Aerosol Tests

The atmospheric tests carried out at Battelle Northwest as part of the international filter comparative tests were performed under standardised test conditions using the following aerosols and included resuspension measurements.

A plasma-torch-generated mixed aerosol (Cs, Mn, I) and a micro-aerosol (DOP) served as the principal test aerosols.

The removal efficiencies (DFs) of the Framatome-ANP (Siemens) Combined Venturi Scrubber (SCVS) which were determined by the mixed aerosol test are shown below:

Aerosol	DF
CS	1.400.000
Mn	> 1.000.000
I	300.000

DOP Tests

The removal efficiency measurements carried out with the DOP micro-aerosol having an AMMD < 0.7 µm showed a significant reduction in the decontamination factors to:

$$DF_{DOP} = 4.500 - 20.000$$

The selected two-stage filter process thus allowed adequate decontamination factors to be achieved despite the substantial reduction in the decontamination factors when using the smaller test aerosol DOP.

Resuspension Tests

Because resuspension has a significant effect on iodine and aerosol removal efficiencies during continuous operation and because of requirements imposed by the authorities in this respect, the subject of resuspension is discussed below on the basis of real measured values.

Resuspension is primarily caused by the gas mixture rising in the pool and the formation of small bubbles in the boiling scrubbing water.

The effect of a boiling pool has been examined in detail in which determined not only the resuspended aerosol mass but also the hard-to-retain micro-aerosols having a diameter of $d_{50} = 0.15 \mu\text{m}$ to $0.5 \mu\text{m}$ generated by film droplets.

The following table shows the resuspension values determined during the ACE resuspension test on the FRAMATOME ANP (Siemens) Combined Venturi Scrubber (SCVS).

Test	Concentration mg/std m ³ NCG		
	Cs	Mn	I
AA17R	8	< 4	< 0,1
AA18R	8	< 4	0,4

The high efficiency of the integrated filter demister in the SCVS on the pool resuspension retention becomes evident.

6. Implementation of Venting Systems

The specific design of the system for sliding pressure operation has resulted in compact overall dimensions which means that, despite the high mass flows of up to 14 kg/s, the system is capable of being backfitted in existing buildings like in the BWR plants in Finland, Borssele, or Gösgen.

Up to now the Sliding Venturi Scrubber system is installed in 18 plants of BWR and PWR type in Europe.

Detail design work of venting systems for WWERs application, e. g. for Kosloduy 5 / 6 and in TARCHI project No. R2.08/95, for the reference NPP Balakovo, have been completed.

For WWER 440 application the additional requirements for post accident treatment of confinement leakage's the two stages venturi scrubber unit has to be equipped with an additional organic iodine filter stage on molecular sieve basis. The basic design for such system has been finished, e. g. for Bohunice.

7 Severe Accident Management

For operator aids in the course of accident operating procedures and regulations have been implemented in German NPP's.

For severe accident management the overall crisis organisation for the German nuclear power plants is activated by immediate set up of the on-site accident management organisation. This on-site accident management organisation is lead by a crisis board to take quickly the necessary strategic decisions, to receive and to distribute information and to co-ordinate the emergency measures (Fig. 7).

The design of the venting system is such that

- the pressure can be limited to the test pressure
- the pressure will be reduced by a factor of two (which means, depending on plant type and the NPP power 3.5 to 12 kg/s steam air mixture at 4 to 6 bar).

Releasing containment atmosphere via a combined venturi scrubber two safety related targets are met:

- keep the integrity of the containment
- Retention of activity to avoid long term land contamination.

Relevant additional information of the containment atmosphere before and during venting will be delivered by the In-situ PASS, the emission control system and the hydrogen monitoring system.

7.1 Procedure to vent

Preparation to activate the venting system shall be performed when,

- it is obvious that the containment pressure can not be limited below 5.3 bar (e. g. the design pressure for a convoy plant) following order from the crisis board and support of emergency technical support centre of the plant.

Activation of venting shall be performed:

- After information and permission of the state government following the advice from the on-site crisis board.
- Before containment pressure has reached 6 bar (test pressure, e. g. for convoy plant).

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Test Results"

for LOCA

- Forced Flow Catalytic Recombiner
- Forced Flow Thermal Recombiner

for Severe Accidents

- Passive Autocatalytic Recombiners (PARs)
- Pre-/Post-Inertisation
- Igniters

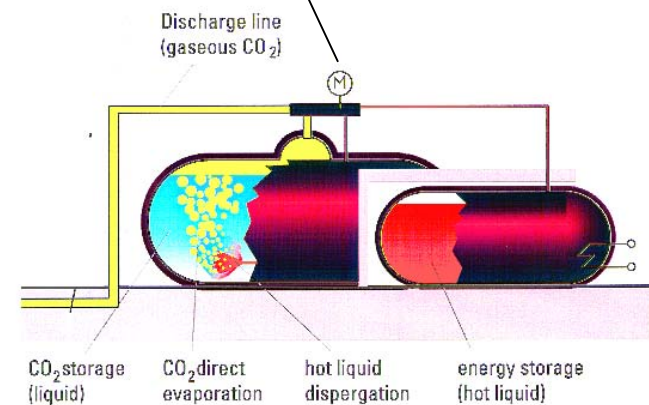
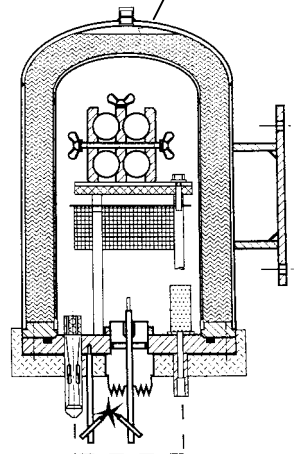
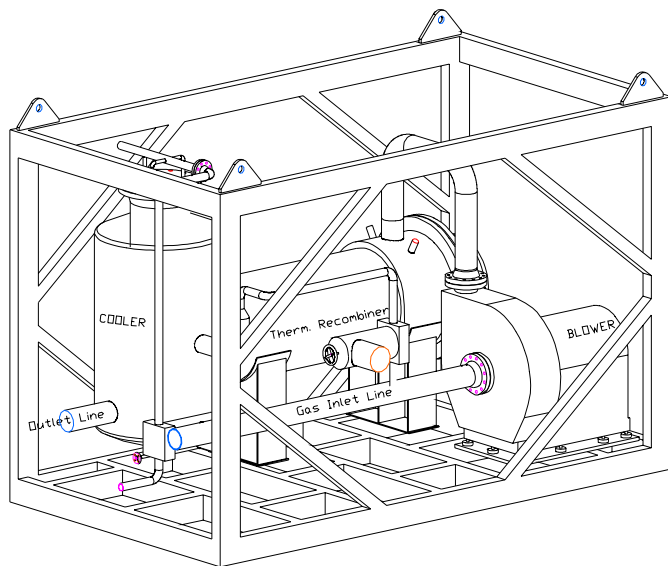
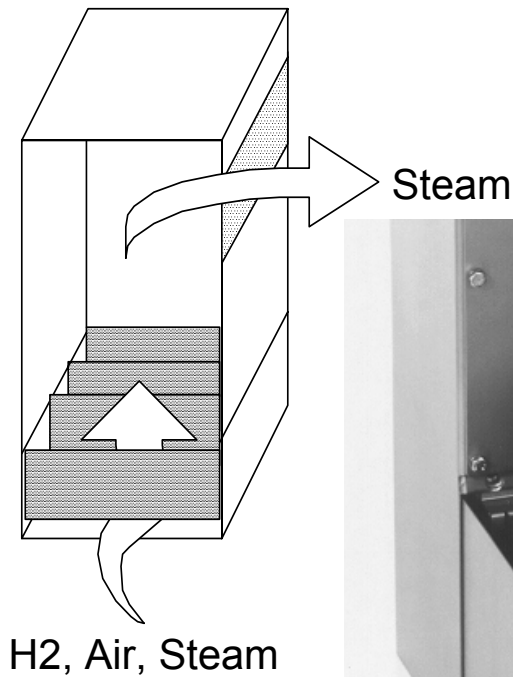


Figure 1 : Overview of Hydrogene Reduction Technologies

- **Function**



Removable Inspection Drawer
for easy access of catalytic plates

Figure 2 : PAR Function and Design

- **Design**



The following
PAR-types are
available:

- FR90/1-1500
- FR90/1-750T
- FR90/1-380T
- FR90/1-960
- FR90/1-320
- FR90/1-150

Inservice
Inspection
Equipment



Sectional Drawing A-A

Sectional Drawing B-B

LEGEND

REF-GAS-019	x
REF-GAS-021	+
REF-GAS-070	*
REF-GAS-071	o
REF-GAS-021	♦
REF-GAS-140	□
REF-GAS-03	△
REF-GAS-016	○

Graph Data:

Time (s)	Concentration H ₂ (%) without PARs	Concentration H ₂ (%) with 58 PARs
0.0	0.0	0.0
10000.0	10.0	2.0
20000.0	14.0	2.5
30000.0	16.0	2.5
40000.0	16.0	2.5
50000.0	14.0	2.5
60000.0	14.0	2.5
70000.0	14.0	2.5
80000.0	14.0	2.5

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DEVELOPMENT OF PASSIVE AUTOCATALYTIC HYDROGEN RECOMBINER SYSTEMS

GERMANY	Karlsruhe-Laboratories	Development and qualification since	1989
		Application for patents Patents granted	since 1990 since 1995
	Model containment	Performance test in a multi-compartment geometry	1991
BELGIUM		Qualification, development of calculation method, partition considerations	1993
FRANCE	Cadarache	EDF-KALI-Tests; qualification for 900 MW PWR French accident scenario (Spray incl. NaOH, H ₃ BO ₃)	1995
USA/FRANCE	Cadarache	EPRI-KALI-Tests; qualification for US-ALWR	1995/1996
FRANCE	Cadarache	IPSN-PAR H ₂ -Tests Aerosol-Tests (Te, Se, J, Cs, etc.)	1996-1999
FRANCE	Cadarache	EDF/CEA PAR H ₂ -Tests Elevated H ₂ -concentrations	1998
Germany	Karlsruhe-Laboratories	Deflagration tests	2000



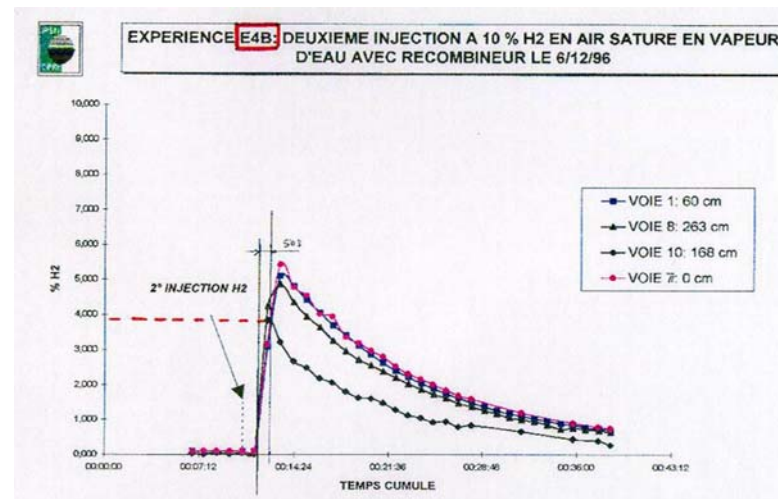
EDF / IPSN H₂-PAR
Test Facility

Figure 4 : PAR Qualification

Aerosol tests with a molten core substitute

The tests were conducted under severe accident conditions in terms of:

- Composition of aerosols (e.g. Se, Te, ...)
- Concentration of aerosols (approx. 200 mg/m³)
- Sequence of H₂ and aerosol release



Result: The Efficiency of the Recombiner was not influenced by exposure to a realistic aerosol spectrum

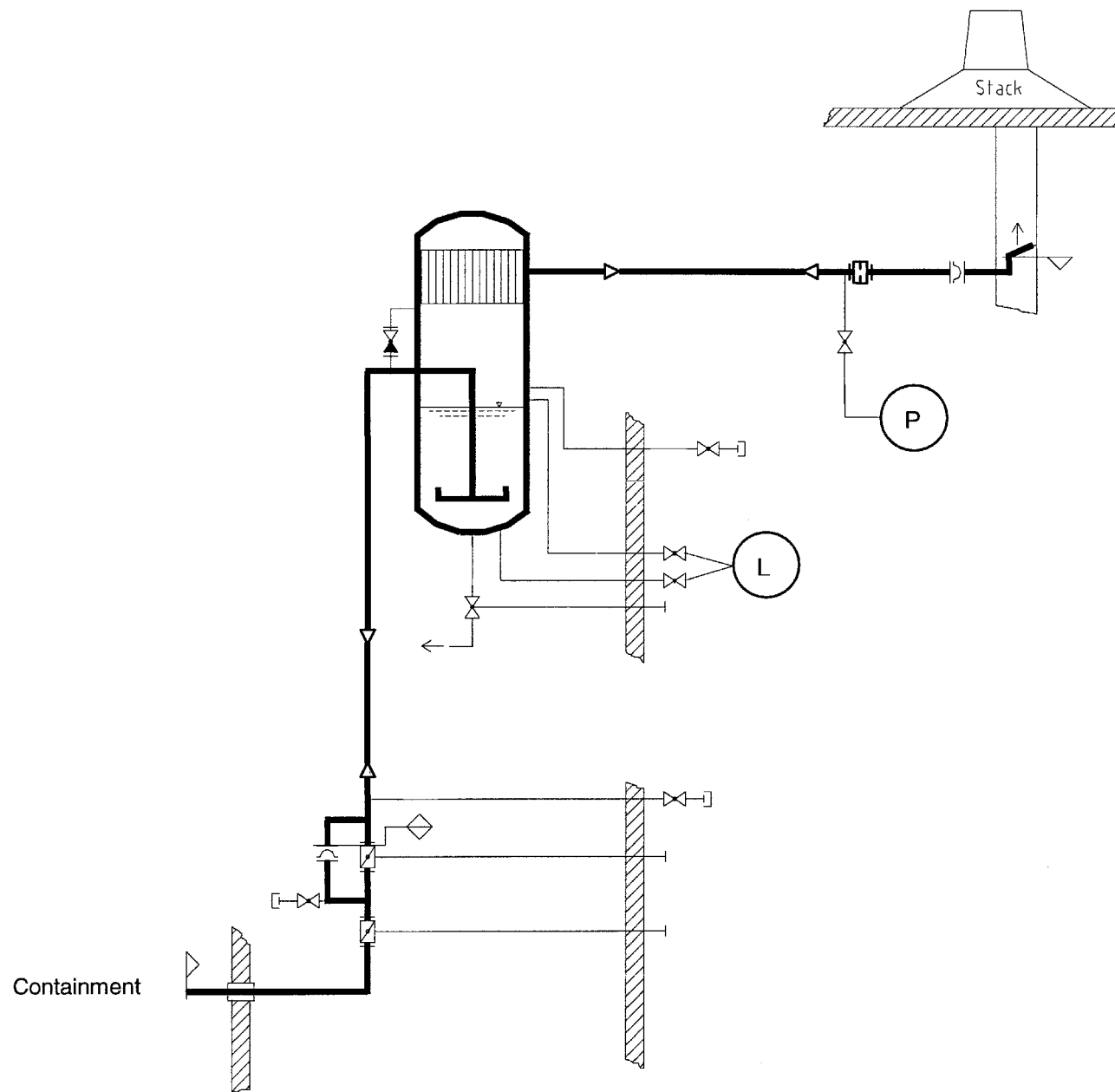
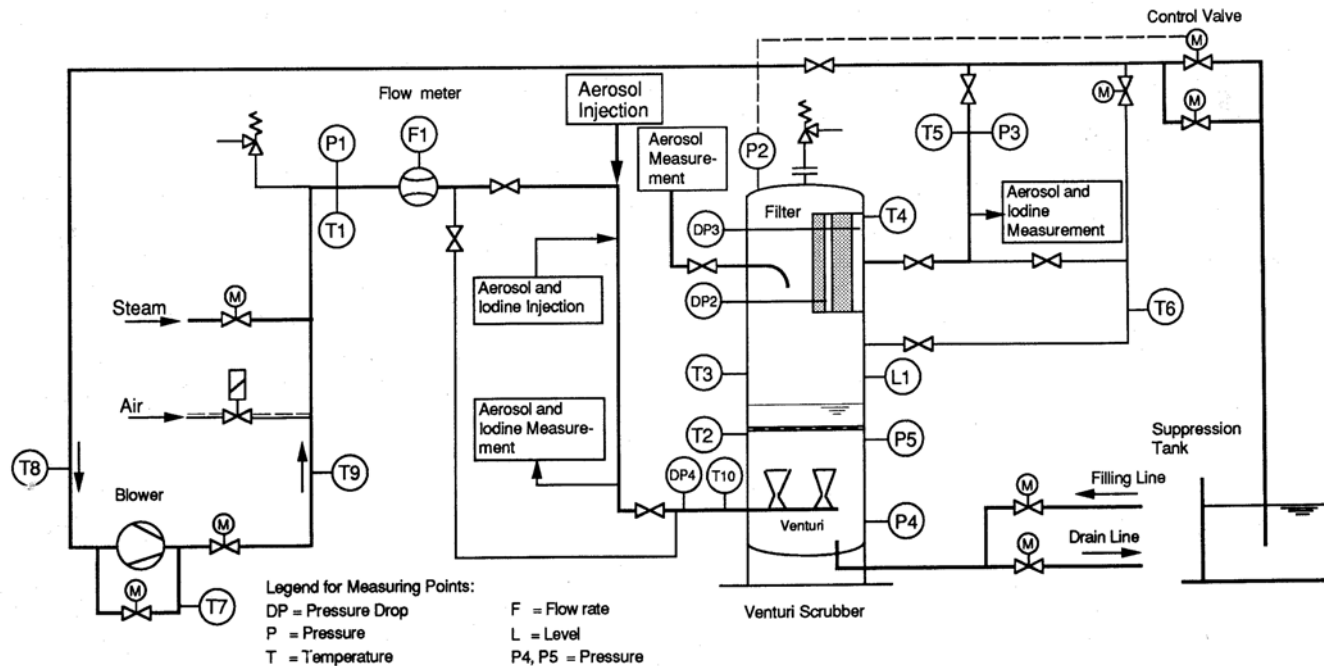


Figure 5 : Flow Diagram Sliding Pressure Venting



Containment Venting / JAVA Test Facility

Test Parameters

Pressure	1 – 10 bar
Temperature	50 – 200°C
Flowrate	300 – 3.000 m ³ / h
Mass flow	0.05 – 4.0 kg/s
Carrier gas	Air / steam
Aerosol concentration	SnO ₂ 0.1 – 0.6 g / m ³ BaSO ₄ 0.1 – 0.6 g / m ³
Uranine	≤ 0.001 g / m ³
Iodine	Elemental Iodine (I-123 tracer)

Operating Modes

Steady-state recirculation operation
 Steady-state once-through operation
 Transient once-through operation
 (start-up simulation)

Figure 6 : JAVA Test Facility and Test Parameters

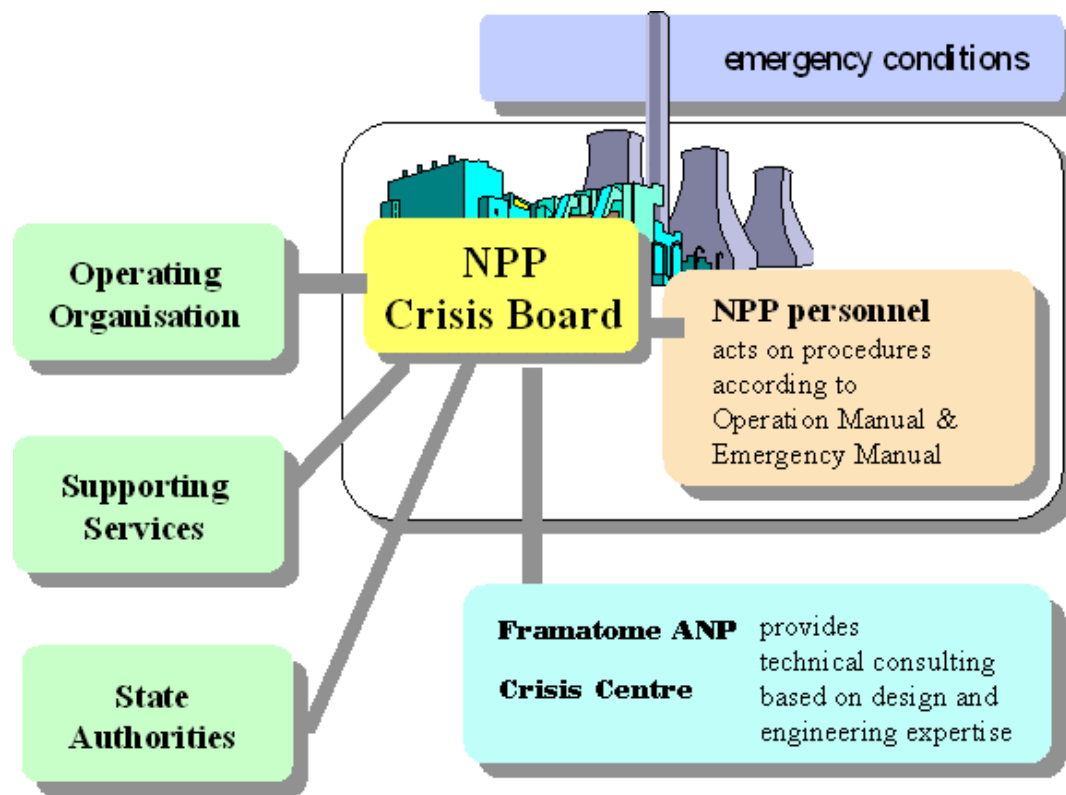


Figure 7 : On-Site Accident Management Organisation and References of Hydrogen Recombiner Systems

ORDERS FOR PASSIVE AUTOCATALYTIC HYDROGEN RECOMBINER SYSTEMS

		Pieces supplied	
BELGIUM	Doel 1	24	operable
	Doel 2	26	operable
	Doel 3	40	operable
	Doel 4	37	operable
	Tihange 1	37	operable
	Tihange 2	38	operable
	Tihange 3	42	operable
CZECH REPUBLIC	Dukovany 1	16	operable
	Dukovany 2	16	operable
	Dukovany 3	16	operable
	Dukovany 4	16	operable
	Temelin 1	22	operable
	Temelin 2	22	operable
HUNGARY	Paks 1	16	operable
	Paks 2	16	operable
	Paks 3	16	operable
	Paks 4	16	operable
NETHERLANDS	Borssele	20	operable
SLOVAKIA	Mochovce 1	16	operable
	Mochovce 2	16	operable
RUSSIA	Kalinin 3	50	under construction
	Kalinin 1	40	under construction
GERMANY	Neckar 1	37	operable
	Neckar 2	58	operable
	Grafenrheinfeld	60	operable
	Isar 2	58	operable
	Emsland	58	operable
	Grohnde	58	operable
	Brockdorf	59	under construction
	Unterweser	52	operable
BULGARIA	Kozloduy 5	8	under construction
	Kozloduy 6	8	under construction
CHINA	Tianwan 1	44	under construction
	Tianwan 2	44	under construction
SPAIN	Trillo	32	under construction
UKRAINE	Rovno 1	9	under construction
	Rovno 2	9	under construction