International Atom Forum
"THE NUCLEAR ENERGY IN EAST EUROPE: OPTIONS, CHALANGES AND FUTURE“
organized by BULATOM and Bulgarian Nuclear Society,
with the co-operation of FORATOM and IAEA;
June 28-30, 2002, International House of Scientists “F. J. Curie”
“St Constantin” Resort, Varna, Bulgaria

Paper Title:

Containment hydrogen and atmosphere activity control to mitigate severe accidents in VVERs and western PWRs.
- Design and status of implementation -

Keywords: Hydrogen Reduction, Hydrogen Measurement, Confinement Venting,

Author: Robert Feuerbach
Phone: +49/69807-93686
FAX: +49/69807-94567
E-Mail: Robert.Feuerbach@framatome-anp.de

Company: Framatome Advanced Nuclear Power
Department: NGES5
Berliner Strasse 295
D- 63067 Offenbach
Germany

Abstract

In the hypothetical event of a core meltdown accidents significant pressure build-up and release of hydrogen and radioactive material in the confinement can occur.
In order to prevent loss of containment integrity with significant radioactive releases to the environment as a result of overpressurization of the containment, decisions have been taken by the authority and plant staff for accident management.

For accident management nuclear power plants in Europe have been or will be backfitted with supplementary systems for monitoring the containment hydrogen concentration, for the early removal and reduction of hydrogen and filtered venting system to retain radioactive aerosols and iodine.

Hydrogen Monitoring System

The hydrogen monitoring system provides the information of local H_2 -concentration in the containment during DBA and severe accident situations. The first generation of hydrogen monitoring technique based on sampling systems. With this system technique containment atmosphere samples from different locations are transported outside the containment to be analyzed. No continuous measurement of the hydrogen concentration is possible. The measured H_2-concentration must be corrected by the condensed volumetric part of steam. The new Hydrogen Monitoring System avoids these disadvantages. It consists of several H_2- Sensors installed inside confinement, cable penetrations and electronic arranged outside the confinement. It displays and records continuously information of the local and temporal distribution of hydrogen.

For severe accident management, the on-site Emergency Response Team will supplied continuously with information of the local hydrogen concentration in the containment from the new Hydrogen Monitoring System. No additional decisions or Start-Up measures are required. The function of the hydrogen countermeasures can be checked.

The status of implantation of hydrogen monitoring equipment (Sampling - System) in NPPs in the European Community and EU-candidate-countries (Bulgaria, Czech Republic, Hungary and Slovakia) shows nearly 100%.

The Framatome ANP H_2-Sensor - System for continuous monitoring the hydrogen concentration is already installed in 36 NPPs (>400 measuring circuits).

Kozloduy 5&6 will be backfitted with a H_2 - Sensor System until 2003.

Hydrogen Reduction System

If large quantities of hydrogen released into the containment atmosphere ignition of these mixtures can lead to uncontrolled turbulence-combustion process, which could jeopardize the integrity of the containment.

The Hydrogen Reduction System consists of several Passive Autocatalytic Recombiners (PAR) located in several compartments of the confinement. The number of PARs to be installed depends on the Type of NPP, structure of containment and the investigated accident scenario (e.g. DBA conditions approx. 6 to 20 PARs; severe accident conditions approx. 20 to 60 PARs).

For severe accident management with PAR technology is no need of any operator actions. The PARs are absolutely passive components. If H_2 is released in the containment, the hydrogen reduction of the PARs is self-starting.

The status of implantation of PARs in the European Community and EU-candidate-countries will be, including the already with utilities or authorities agreed installations for the next years, approx. 70% to 80% of NPPs. Up to now more than 1000 PARs are already installed in NPPs.

The PAR design for NPPs of the EU-Candidate-Countries covers DBA situations. Kozloduy 5&6 will be backfitted with PARs until 2003.

Filtered Venting System

In order to maintain containment integrity in the event of a severe accident with core damage a depressurization system is necessary. Depressurization is a measure for severe accident management, that is intended to limit and reduce the pressure inside the containment by a controlled discharge of the gas mixture from the containment to the environment and thereby to prevent its failure at elevated pressures. For this purpose, the containment atmosphere is conducted to the vent stack through a Filtered Venting System to retain radioactive aerosols and iodine.

Especially for VVER 440-230 application, the Filtered Venting System shall serve for a long term a soft subatmospheric pressure in the confinement. The Filtered Venting System proposed for this application is based on the assumption that an additional accident location system to control the confinement pressure is available (e.g. Russian vortex condenser for the first blow down). The Filtered Venting System reduces significantly the radioactivity (>99.9%) before release. It avoids uncontrolled releases and serves for a long term of a soft subatmospheric pressure in the confinement.

For severe accident management, the on-site Emergency Response Team has to take the necessary strategic decisions for containment depressurization via the Filtered Venting System if it is obvious that the containment pressure can not be limited below the design pressure.

The status of implantation of Filtered Venting System in NPPs in the European Community and EU-candidate-countries (Bulgaria, Czech Republic, Hungary and Slovakia) is, that up to now, approx. 80% of NPPs already backfitted with a Filtered Venting System or a backfitting is agreed with the authorities and will be performed in the next few years.

Kozloduy 5&6 will be backfitted with Filtered Venting System until 2004.

1 Introduction

During severe accident scenarios large quantities of hydrogen are released into the containment atmosphere within a short period of time. Ignition of these mixtures can lead to an uncontrolled combustion process, which could jeopardize the integrity of the containment. The released Steam, generated hydrogen and heating up of the containment air will cause a build-up of pressure inside containment. During severe accident scenarios the overpressure design values of the containment can be exceeded.
The German Reactor Safety Commission (RSK) has demanded investigations and developments for the early removal and reduction of hydrogen.
In order to maintain containment integrity even in the event of a severe accident with core damage, the RSK recommended the installation of a filtered venting system to retain radioactive aerosols and iodine and specified the requirements for the design and mode of operation.

General overview about emergency management in case of severe accidents in German NPPs
After onset of an accident an on-site Emergency Response Team (ERT) is activated (Figure 1) / 1/.
The decision to activate the ERT at an early stage of the accident is made by the plant management. Latest 1 hour after the alarm is actuated, the ERT must be fully operational. After becoming operational the emergency response team staff assumes responsibility for the accident management direction within the plant.
The emergency response staff and the plant management take the decision to activate external experts and support organizations such as the manufacturer's emergency response staff and the nuclear technical task force (a crisis management company formed by the German NPP operators).

Beyond – design – basis operating of the NPP
If the design- basis event symptom oriented measures are insufficient to guarantee that the critical safety functions are fulfilled, beyond-design-basis accident management measures will be initiated (Figure 2) / 1/.

2 Monitoring of H_2- Concentration in the Containment

Monitoring of the Hydrogen concentration in the containment is a necessary part of the incident instrumentation of a NPP.

The first generation of hydrogen monitoring technique based on sampling systems. With this system technique containment atmosphere samples from different locations are transported outside the containment to be analyzed. No continuous measurement of the hydrogen concentration is possible. The measured volumetric values of Hydrogen must be corrected by the volumetric part of steam.

To avoid these disadvantages, hydrogen sensors were developed which are able to measure the hydrogen concentration during the accident directly in the containment.

Such a H_2 - Monitoring System (Figure 3) consists of several Hydrogen Sensors (measuring range 0 – 10 Vol.%) located inside the containment, telemetric cables and a signal processing unit located outside the containment.

In the signal processing unit the sensor signals are processed and the actual H_2 concentrations can be displayed and logged on a multichannel recorder or the Plant Computer in the main control room. If the hydrogen concentrations reaches a certain level in the containment, alarms are generated (UKTS).

The Framatome ANP Hydrogen Monitoring System provides the following features:

- immediately available after an accident,
- no additional decisions or Start-Up measures required in extreme situations,
- measurement values are obtained directly from accident proof H_2-sensors installed inside the containment,
- simultaneous and continuos recording of all measured values of the system,
- no radioactive samples outside the containment and radiation exposure of the operating personal,
- measuring of the real H_2-concentration inside containment without correction of humidity and steam,
- optional accident proof temperature measurement of the hermetic zone atmosphere with integrated resistance thermometer inside H_2-Sensor.

2.1 Severe Accident Management at elevated hydrogen concentration

For severe accident management, the on-site Emergency Response Team will supplied continuously with information of the local hydrogen concentration in the containment. No additional decisions or Start-Up measures required. The function of the hydrogen build-up countermeasures can be checked.

2.2 Status of implantation

The status of implantation of hydrogen monitoring equipment (Sampling - System) in NPPs in the European Community and EU-Candidate-Countries (Bulgaria, Czech Republic, Hungary and Slovakia) shows nearly 100%.

The Framatome ANP H2-Sensor - System for continuous monitoring the hydrogen concentration is already installed in 36 NPPs (>400 measuring circuits). Kozloduy 5&6 will be backfitted with an H2-Sensor System until 2003.

3 Hydrogen Build-up Countermeasures

3.1 General requirements for hydrogen reduction during severe accident

Regarding the demand from German Reactor Safety Commission (RSK) investigations and developments for the early removal and reduction of hydrogen were performed.

These systems must meet requirements by featuring the following characteristics:

- highly efficient, exhibiting H_2 reduction rates, for example, of greater than 50 kg/h
- high functional reliability, such as resistance to poisoning by Te, Se, Iodine or CO, etc.

- simple design
- integrated passive equipment
- cost-effective
- easy to integrate into existing plants.

3.2 Reviewing of existing technologies for H_2 - reduction for DBA

Over the past two decades since TMI accident, several H_2 reduction technologies have been developed and tested to limit H_2 concentration in the containment atmosphere under DBA conditions. Requirements governing associated analyses were stipulated in the related guidelines e.g. in Germany, issued by the German Reactor Safety Commission (RSK).

Corresponding H_2 reduction technologies (Figure 4) such as

- thermal recombiners,
- forced-flow heated recombiners
- catalytic recombiners, etc.,

were qualified in extensive experimental test series under DBA conditions and subsequently installed in nuclear power plants.

Investigation about the use of these technologies for severe accident conditions shows, that the throughput rate of thermal and catalytic recombiners designed for use under DBA conditions is limited to several hundred m^3/h. The use of these units for H_2 reduction under postulated severe accident conditions – e.g. conditions with H_2 releases higher by several orders of magnitude – would therefore ineffective.

3.3 Development of H_2 reduction technologies for severe accidents

To reduce the large amount of hydrogen generated during severe accidents, new H_2 reduction technologies were developed and tested.

The advantages and drawbacks of new the H_2 reduction technologies were investigated e.g. of:

- Igniters,
- post-inertisation system techniques
- Passive Autocatalytic Recombiners (PARs)

3.3.1 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 (Figure 4) 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 behavior. 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 behavior.

Ultimately, on basis of these facts, the regulatory authorities did not recommend the installation of igniters.

3.3.2 Pre- and Post-Inertisation

Inertisation 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 (Figure 4).

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.

3.3.3 Passive Autocatalytic Recombiners (PAR)

Passive Autocatalytic Recombiners (PARs) (Figure 5) use catalytic coatings to transform molecular hydrogen and oxygen into water vapor. They are passive, 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.

Passive Autocatalytic 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.

Ultimately the Passive Autocatalytic Recombiners system was selected as H_2 mitigation measure to be implemented in German NPPs.

3.4 Hydrogen Reduction System with PARs

3.4.1 Function of PAR

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 (Figure 5). 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 behavior 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 containment, the recombiner is available in various sizes.
Since PARs have no moving parts and requires 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.

3.4.2 Composition of a Hydrogen Reduction System using PARs

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

The number of PARs to be installed depends on the Type of NPP, structure of containment and the investigated accident scenario (e.g. DBA conditions approx. 6 to 20 PARs; severe accident conditions approx. 20 to 60 PARs).

The arrangement of the individual PARs inside the containment is determined by the projected H_2 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 H_2 reduction capacity and the effects of the recombiner system on gas distribution.

The effectiveness of such PAR systems has been demonstrated 2 / by comparing analysis results from a representative severe accident sequence with and without PARs postulated to occur in a FRAMATOME ANP Convoy-series plant (Figure 6).

These analysis results showed that only in few local areas in the containment did combustible gas mixtures form for a limited time span, and H_2 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.

Design-Basis-accident analysis were performed for the VVER 1000 – 230 NPP, Kozloduy Units 5&6. Figure 7 shows the effectiveness of hydrogen reduction with 8 PARs Type FR90/1-380T.

3.4.3 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 (Figure 8). Some tests were conducted in the Battelle multi-compartment facility. Independent organizations have participated in / or performed qualification testing of the FRAMATOME ANP design, such as TÜV, CEA, IPSN, EPRI and EDF, etc.

Qualification and Functional Tests

The following test 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 (I_2, CO, H_3B0_2 and CH_3I) / 3 /
- 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) / 4 /
- Wet condition during startup with direct water spray on the catalyst / low oxygen content, etc.

Ultimately, a new test facility (Figure 8) for simulating aerosol exposure with a molten core substitute and poisons like tellurium and selenium, etc., was constructed in Cadarache, France to demonstrate the behavior of the PAR under severe accident conditions.
Because of the importance of these tests, Figure 8 shows the depletion curve of the recombiner after the comprehensive poisoning element mixture test.

PAR Operation under elevated H_2-Concentrations

The chemical reaction at the catalyst of hydrogen / oxygen being exothermal and will lead to increased PAR temperatures, if elevated H_2 concentrations will occur. These basic PAR phenomena and the possibility to ignite H_2 mixtures have been discussed frequently. Because this behavior is in certain limits PAR-type specific additional tests have been performed.

To study the behavior 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 H_2 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.

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.

3.5 Severe Accident Management at elevated hydrogen concentration

For severe accident management in Germany, an on-site Emergency Response Team (ERT) is activated. Decisions to manage the accident must be taken (Figures 1 and 2).

If the hydrogen control in the containment is based on the Passive Autocatalytic Recombiner (PAR) technology, there is no need of any operator actions. The PARs are absolutely passive components. If H_2 is released in the containment, the hydrogen reduction of the PARs is self-starting.

In spite of this, for additional information for the Emergency Response Team (ERT), the hydrogen concentration values of the containment atmosphere are available using the measuring results of the hydrogen monitoring system and Post Accident Sampling System (PASS).

3.6 Status of implementation and operation of PAR Systems

Implementation Experience

The first PAR systems to be installed in actual nuclear power plants were in Belgium in 1995 /5 /.
Installation of a complete PAR system comprising for example 20 to 60 individual PAR units was usually performed over a period of two weeks during the plant refueling 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 with approx. > 1000 PARs have been ordered or backfitted to

- Western PWR nuclear power plants to mitigate severe accident situations

and to

- VVER plants to cope with DBA conditions (exception: severe accident design for NPPs Kalinin 1 and Rovno 1+2)

Operating Experience

One of the questions to be answered with respect to operating experience with recombiners was whether any relevant ageing could 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 (Figure 5). Each individual catalytic sheet is exposed to a pre-mixed test gas, containing hydrogen in order to measure its catalytic efficiency.

Since 1995 more than 1000 PARs are installed in NPPs and 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 Containment Venting

In the hypothetical event of a core meltdown accidents significant pressure build-up and release of hydrogen and radioactive material in the containment can occur.

Depressurization is a means that is intended to limit and reduce the pressure inside the containment by a controlled discharge of the gas mixture created during a core meltdown accident from the containment to the environment and thereby to prevent its failure at elevated pressures. For this purpose, the containment atmosphere is conducted to the vent stack through a pipe and a filter equipment.

4.1 General Requirements

As a result of the investigations about design parameters for containment venting, risk studies have been performed. Furthermore experiments based on aerosol release were executed. Based on these cognition, the Reactor Safety Commissions established requirements.
Under consideration of the requirements of the various countries enveloping requirements for filtration systems could be formulated. The Commissions paid close attention in particular 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.

Furthermore it was necessary to verify elemental iodine and aerosol resuspension in the scrubber unit during continuous operation over $\geq$ 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 $\eta_{Aerosol}$>99,99%
- Retention rate of molecular iodide η_{I2}>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.

4.2 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 Figure 9. The venturi scrubber unit is operated at pressures close to the prevailing confinement pressure / 6 /.
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. 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.

Conditioning the water with caustic soda and other additives attains optimum retention of iodine in the pool of water inside the scrubber.

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 retention efficiency for aerosols of 99.99 % and more. This retention capability also applies to micro-aerosols of less then 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%.

In case of venting the released activity will be measured by an emission monitoring system to serve as a basis for implementing emergency response actions and as accurate accident documentation. / 7/

Especially for VVER 440-230 application, the Filtered Venting System shall serve for a long term a soft subatmospheric pressure in the confinement. The Filtered Venting System proposed for this application (Figure 10) / 8/ is based on the assumption that an additional accident location system to control the confinement pressure is available (e.g. Russian vortex condenser for the first blow down). 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 a molecular sieve unit is used in addition. The Filtered Venting System reduces significantly the radioactivity (> 99.9%) before release. It avoids uncontrolled releases and serves for a long term of a soft subatmospheric pressure in the confinement.

4.3 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.

4.3.1 JAVA Test Facility

Figure 11 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 11.

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.

4.3.1.1 Aerosol Retention

Medium-energy venturi operation tests were performed using soluble uranine and nonsoluble $BaSO_4$ aerosols having mass mean diameters in the region of 1 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.

4.3.1.2 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 unfavorable effect on gas sorption such as the following:

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

Iodine revolatization tests yielded revolatization 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%.

4.3.2 ACE Tests (Filter Testing)

The performed filter tests were divided into aerosol tests (Aerosol and DOP-test) and resuspension tests.

<u>Aerosol Tests</u>

The atmospheric tests carried out at Battelle Northwest as part of the international filter comparative tests were performed under standardized 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

<u>DOP Tests</u>

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 resu-pended aerosol mass but also the hard-to-retain micro-aerosols having a diameter of d_{50} = 0.15 µm to 0.5 µm 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.

4.4 Severe Accident Management by Filtered Venting

For operator aids in the course of accident operating procedures and regulations have been implemented in German NPPs.
For severe accident management the on-site Emergency Response Team (ERT) for German nuclear power plants is activated by immediate set up of the accident. This ERT has to take quickly the necessary strategic decisions, to receive and to distribute information and to co-ordinate the emergency measures (Figures 1 and 2).

The design of the venting system is such that

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

4.4.1 Procedure to vent in German NPPs

Preparation (Figure 2) to activate the venting system shall be performed when,

- it is obvious that the containment pressure can not be limited below the design pressure following order from the on-site Emergency Response Team (ERT) and consultation of External Experts (Figure 1).

Activation of venting shall be performed:

- After information and permission of the External Experts following the advice from the on-site Emergency Response Team (ERT).
- Before containment pressure has reached the test pressure of the containment (e.g. 6bar for convoy plant).

4.5 Implementation status 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 small NPP buildings like in the BWR plants in Finland (Teollisuuden 1, 2), Netherlands (Borssele) or Switzerland (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 VVERs application, e. g. for Kosloduy 5 / 6 and in TACIS 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.

References

/ 1 / J. Ungethuem, M.D. Stokes (Framatome ANP),
Overview of beyond-design basis accident management with particular reference to severe accident scenarios in German Pressurized Water Reactors,
OECD Workshop, Vilingen-PSI, Switzerland, 10 – 13 September 2001

/ 2 / J. Rohde, B. Hüttermann, B. Schwinges (GRS),
The Use of Catalytic Recombiners: An Effective Mitigation Measure;
EUROSAFE, Paris 1999

/ 3 / P. Rongier, E. Studer (IPSN),
H2PAR Facility;
OECD/NEA/CSNI Workshop, Winnipeg, 1996 May 13-15

/ 4 / G. Avakian, L.Averlant, O. Braillard (CEA),
Hydrogen Mitigation by a SIEMENS Recombiner in KALI Facilities;
ENS, Brussels, 1996

/ 5 / J. Snoeck, C. Solaro (Tractebel), P. Moeyaert (Electrabel)
First Experience with the Installation of Passive Autocatalytic Recombiners;
OECD/NEA/CSNI Workshop, Winnipeg, 1996 May 13-15

/ 6 / B. Eckardt, (Framatome ANP)
Sliding Pressure Venting Process for PWR and BWR Plants Process Design and Test Results,
21st DOE/NRC NUCLEAR AIR CLEANING CONFERENCE Containment Venting

/ 7 / B.A. Eckardt, R. Betz, G. Roebig, (Framatome ANP),
Containment In-Situ PASS and Emission Monitoring system Design and Implementation,
OECD Workshop, Vilingen-PSI, Switzerland, 10 – 13 September 2001

/ 8 / R. Feuerbach, (Framatome ANP)
Hydrogen countermeasures and activity retention by filtered venting for VVER440 / V230 NPP Confinement,
International Meeting June 6-8, 2001, Varna, Bulgaria Nuclear Power in Eastern Europe,

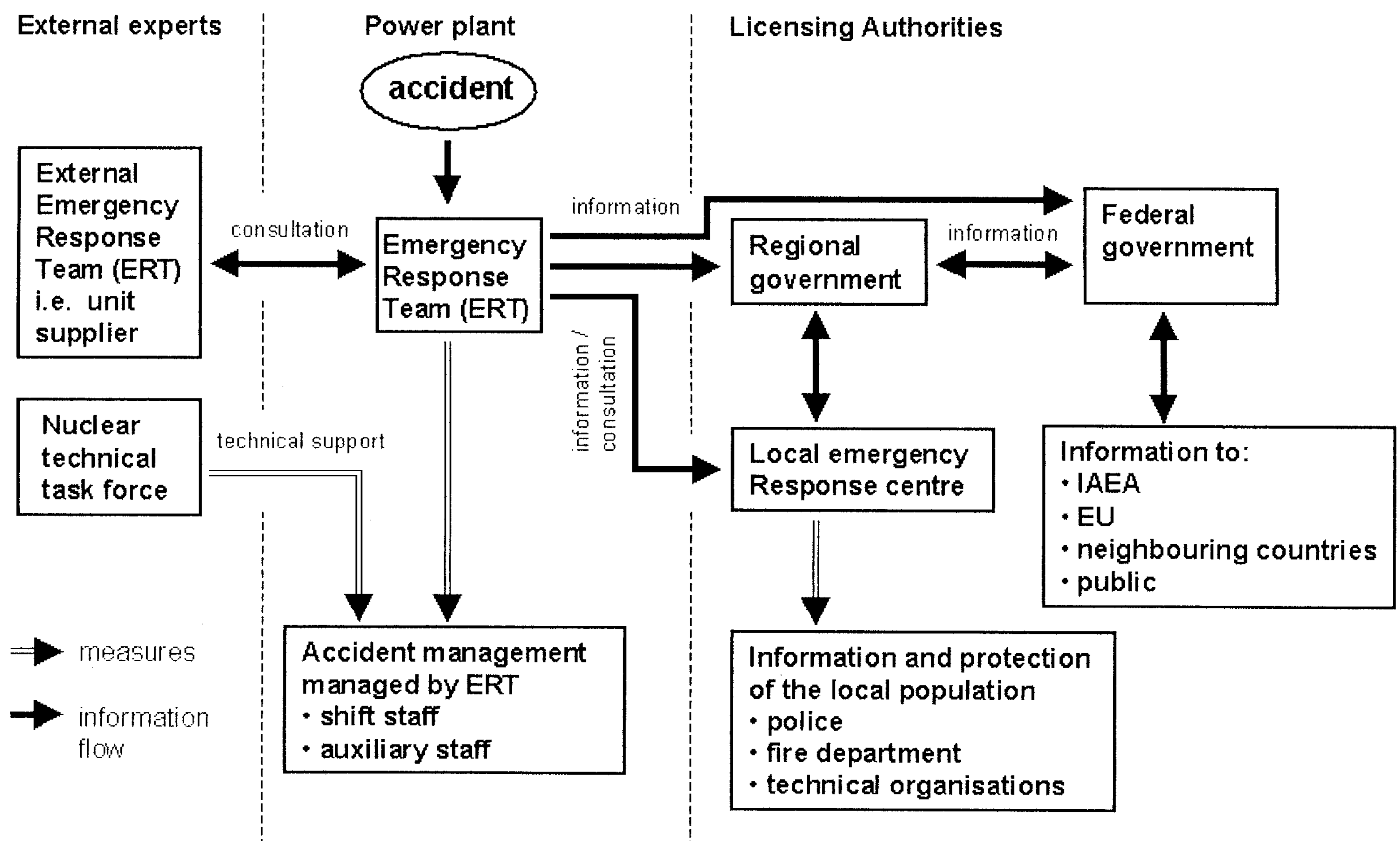


Figure 1: Management of Severe Accidents in German Nuclear Power Plants

Decisions		Accident Management Beyond-Design-Basis			
Emergency Procedures	**Initiation Criteria**	**Core temp. < 800°C**	**Core oxidised**	**Core badly damaged**	**Core ex vessel**
Secondary bleed and feed	Coolant temp- >300°C or other criteria		Implementation		
Secondary side controlled depressurisation	Secondary side heat sink not available		Implementation		
Primary side bleed and feed	RPV level < min or coolant temp. >400°C		Implementation		
Alternative primary side coolant injection	Coolant injection not available or not sufficient		Implementation		
Injection of coolant into the containment sump	Containment sump level too low or during containment venting		Implementation		
Cooling of the con-tainment from inside and outside	Δp cont./atm. >1 bar and no heat sink available			Implementation	
Containment sampling	When core damage occurs			Implementation	
Application of hydrogen recombiners	Passive system, self initiating			Implementation	
Filtered containment venting	Δp cont./atm. 6 bar (design pressure)		Preparation Period		Implementation
Emission Monitoring	Start with preparation of venting			Implementation	
Filtering of control room air	Before containment venting is initiated		Preparation Period		Implementation

Figure 2: Applicability of Emergency Procedures for Severe Accidents in German NPPs

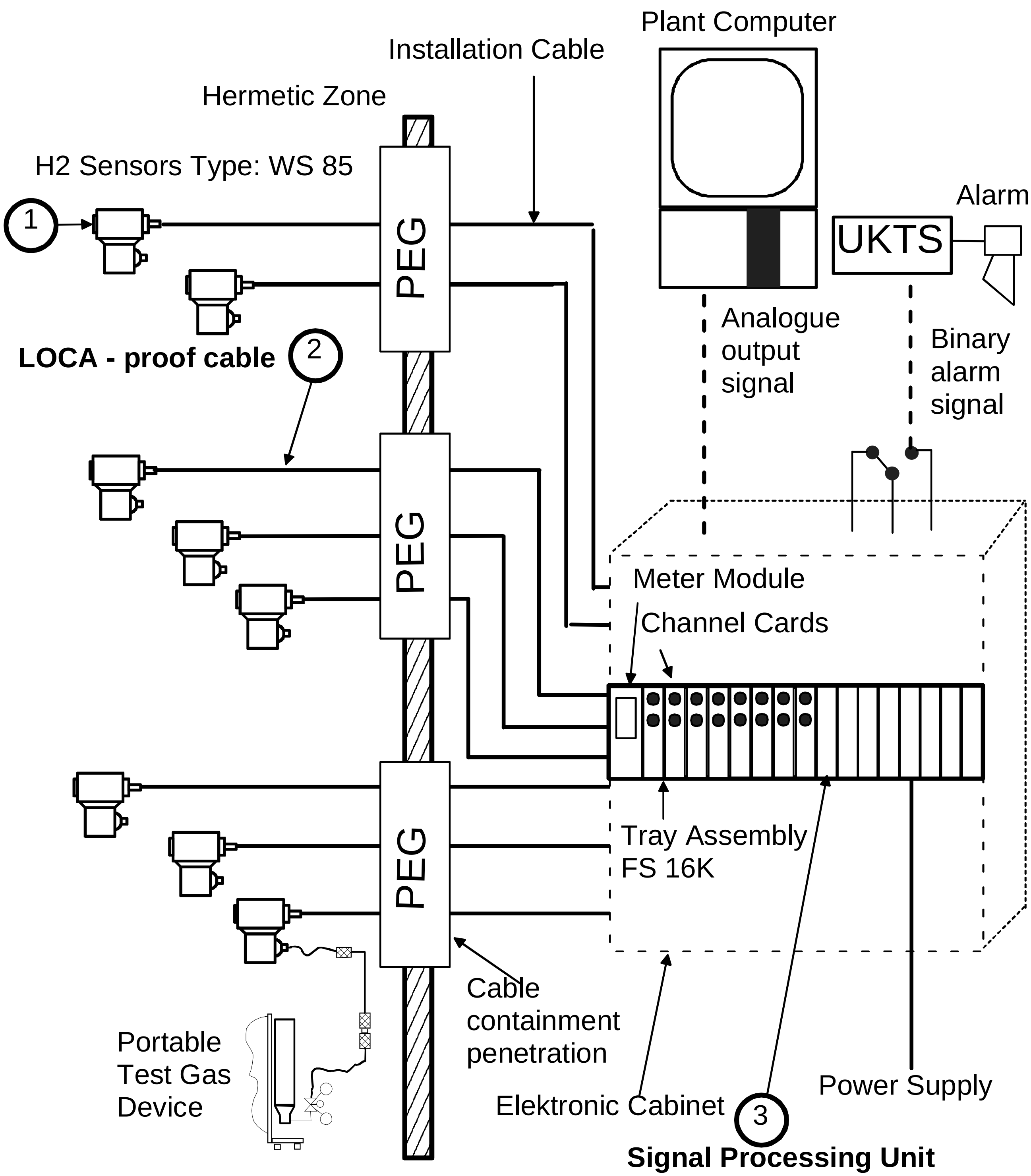


Figure 3: Hydrogen Monitoring System

for Design Basis Accident

- Forced Flow Catalytic Recombiner
- Forced Flow Thermal Recombiner

for Severe Accidents

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

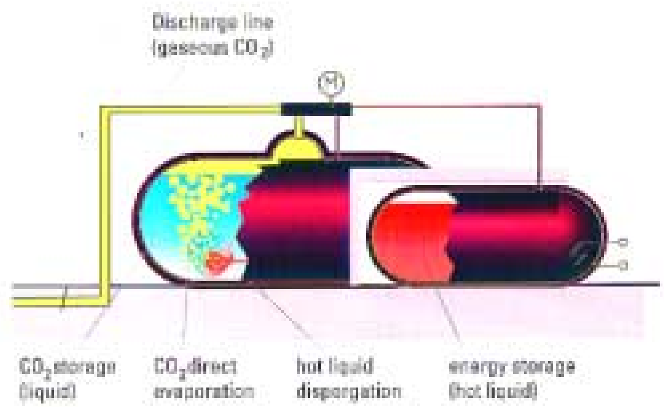
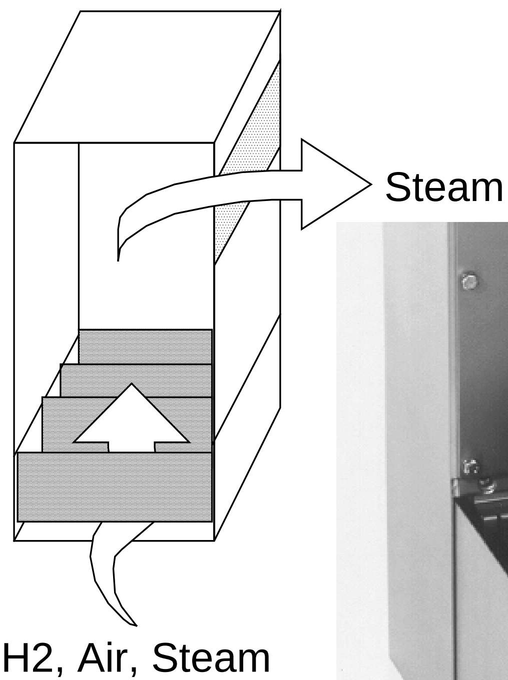
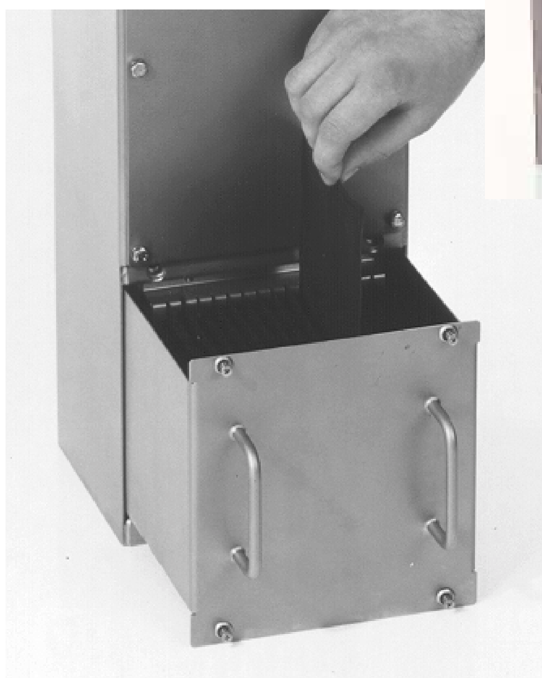


Figure 4: Overview of Hydrogene Reduction Technologies

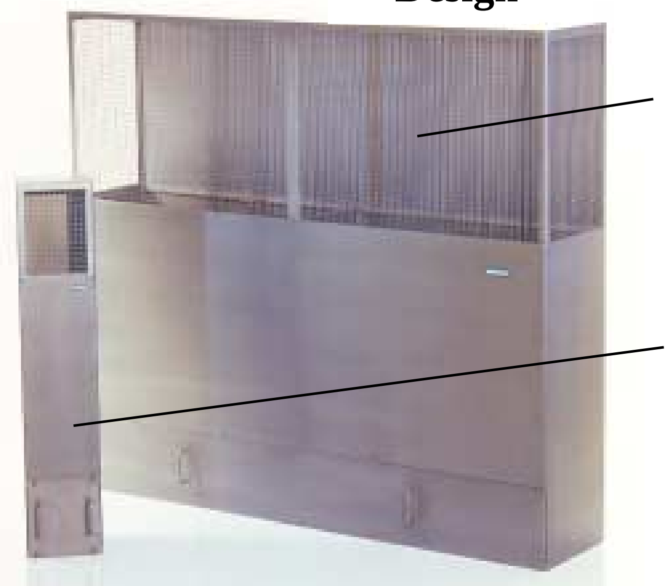
- **Function**





Removable Inspection Drawer
for easy access of catalytic plates

- **Design**



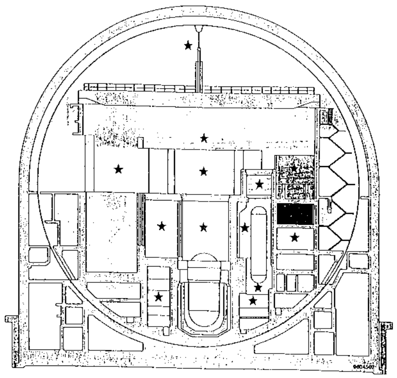
The following PAR-types are available:

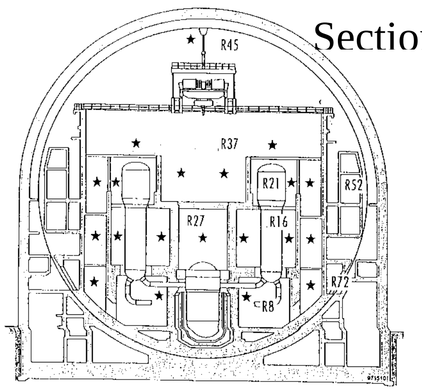
- FR90/1-1500
- FR90/1-750T
- FR90/1-380T
- FR90/1-960

Inservice
Inspection
Equipment

Figure 5: PAR Function and Design

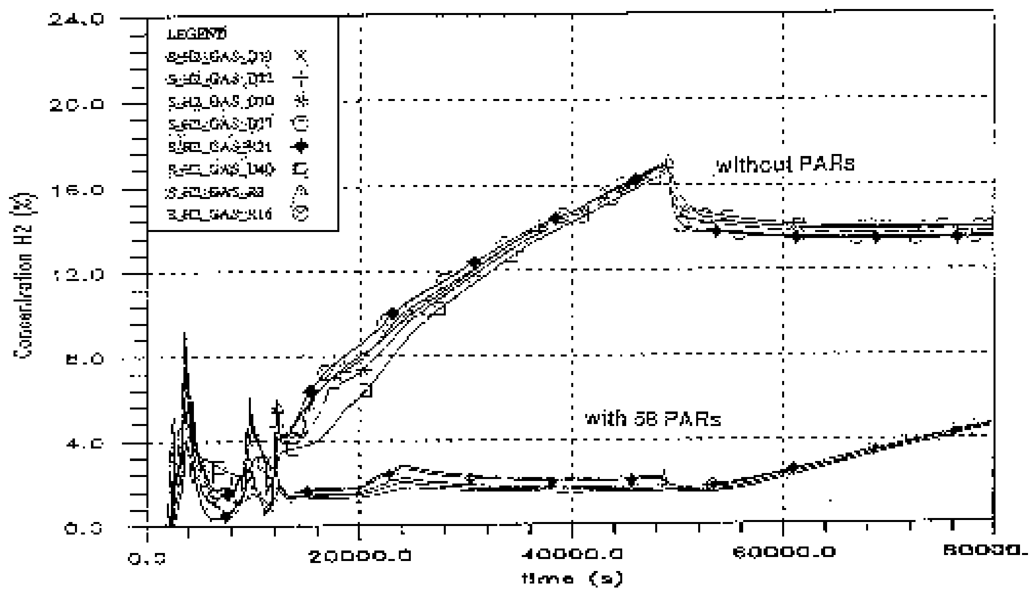
For the German PWR Reference Plant GKN2 Hydrogen Distribution and Reduction Analyses were performed by GRS with RALOC





Sectional Drawing B-B

Positions of Recombiners are marked with *



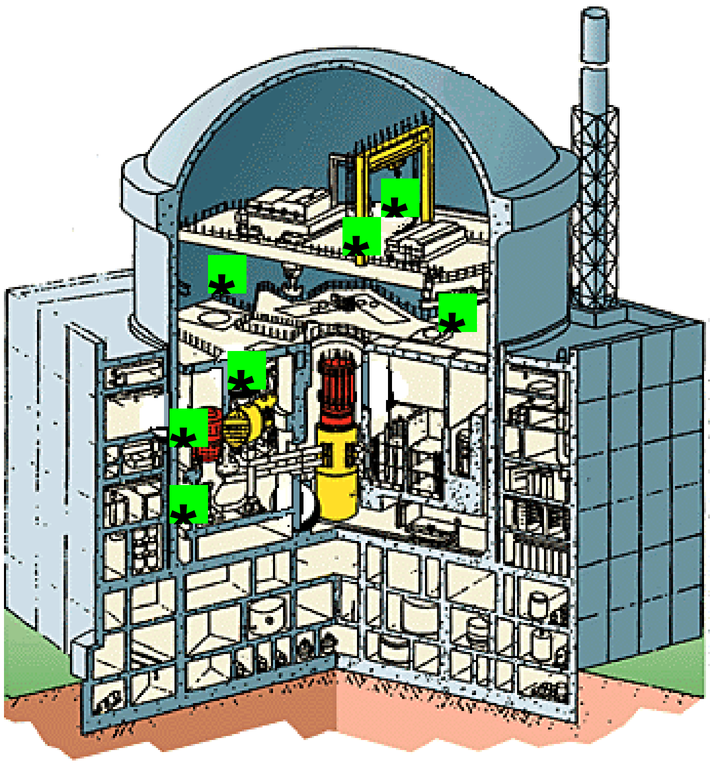
Hydrogen concentrations inside the inner containment missile shield

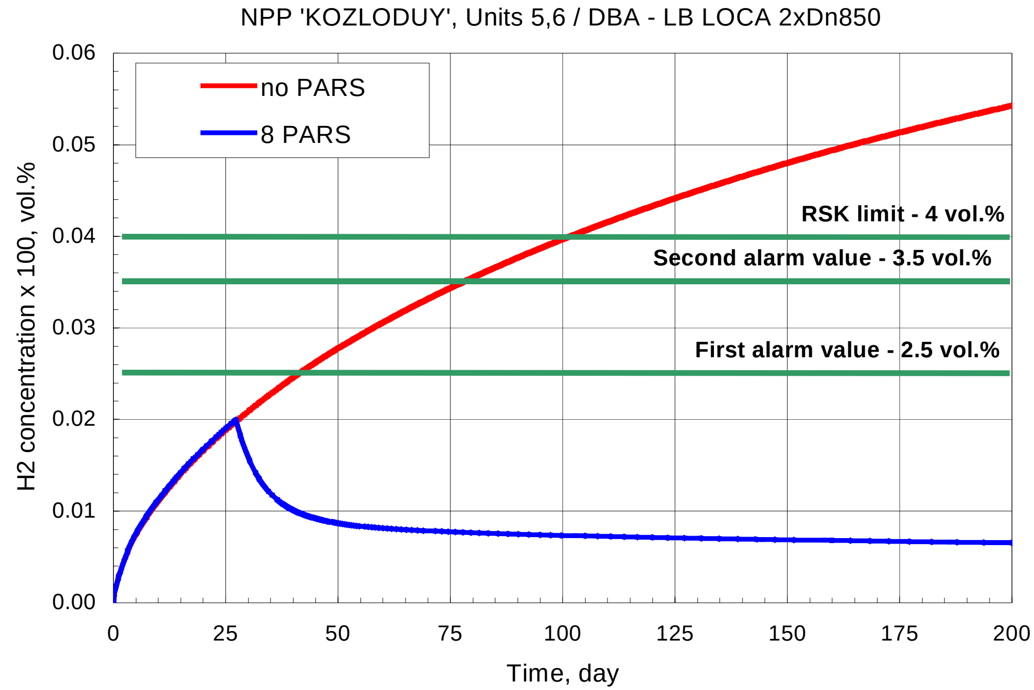
Finally the following Framatome ANP PAR types and quantities were installed in GKN2:

29 x FR90/1-1500   3 x FR90/1-960

4 x FR90/1-750T   4 x FR90/1-320

Figure 6: Passive Autocatalytic Recombiner (PAR) System for severe accident





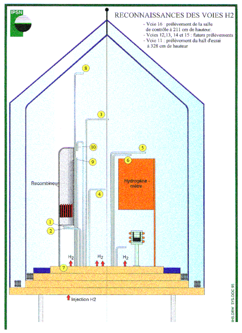
Post-LOCA Hydrogen volumetric concentration inside the containment without and with installed 8 PARs of Framatome ANP Type: FR90/1-380T

Analyses were performed by ENPRO with MELCOR

Figure 7: PAR System for Design Basis Accident (Kozloduy 5&6)

DEVELOPMENT OF
PASSIVE AUTOCATALYTIC
HYDROGEN RECOMBINER
SYSTEMS

GERMANY	Karlstein-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_3BO_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	Karlstein-Laboratories	Deflagration tests	2000



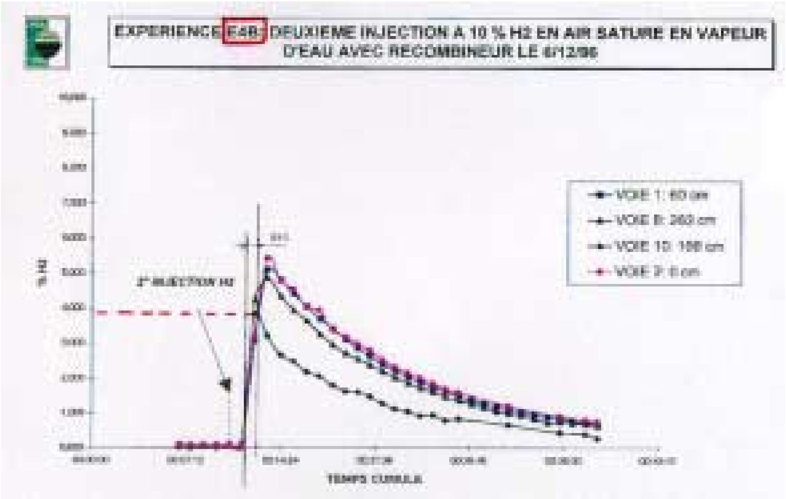
EDF / IPSN H2-PAR Test Facility

Figure 8: 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)



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

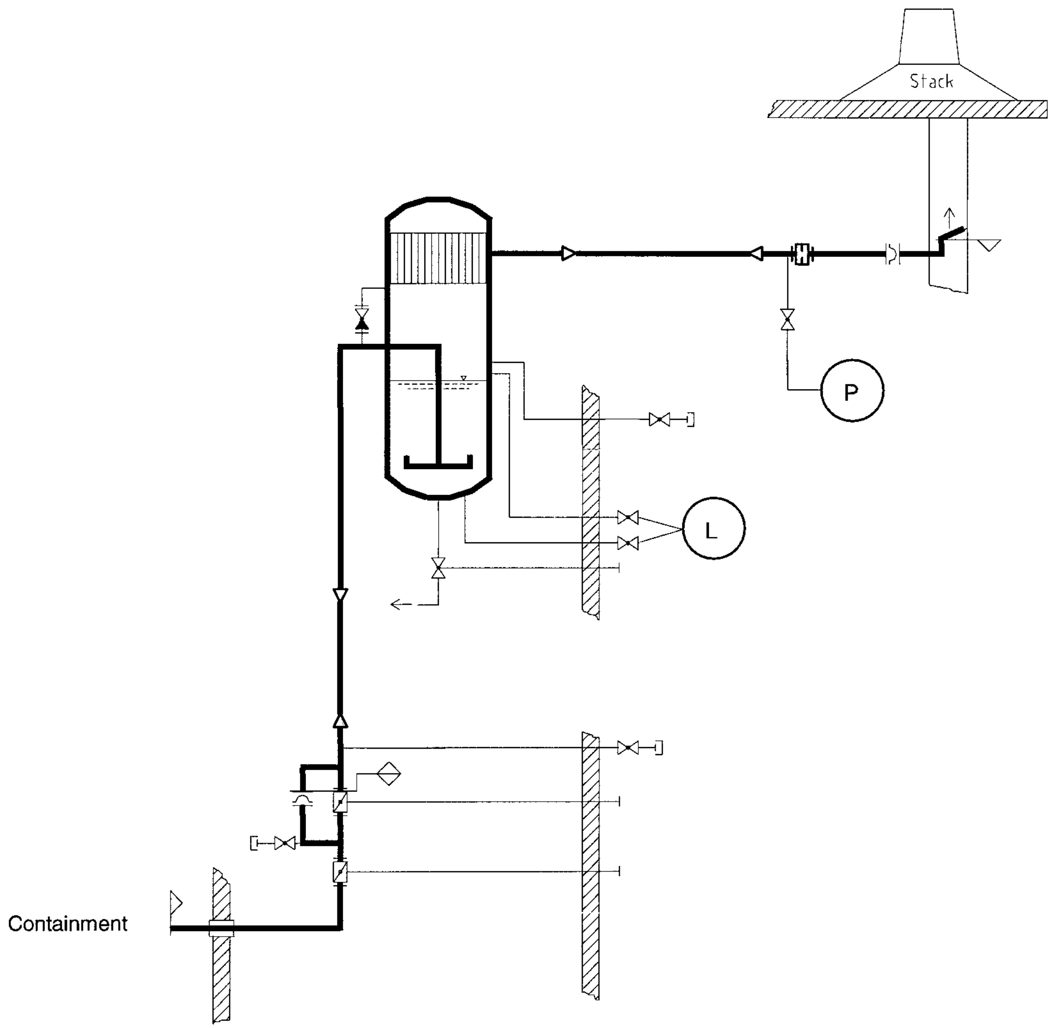


Figure 9: Simplified Flow Diagram for Filtered Venting (Kozloduy 5 & 6)

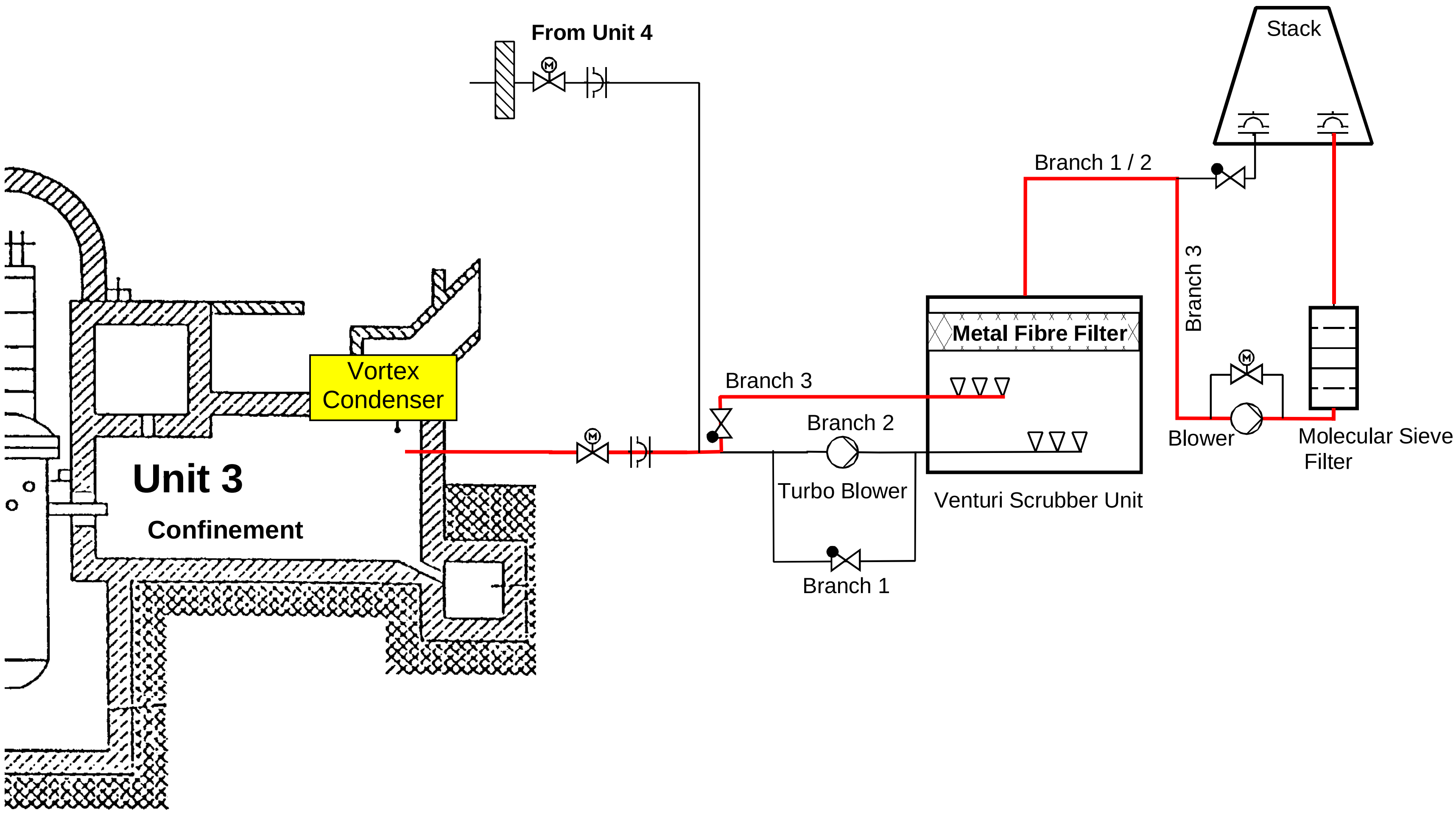
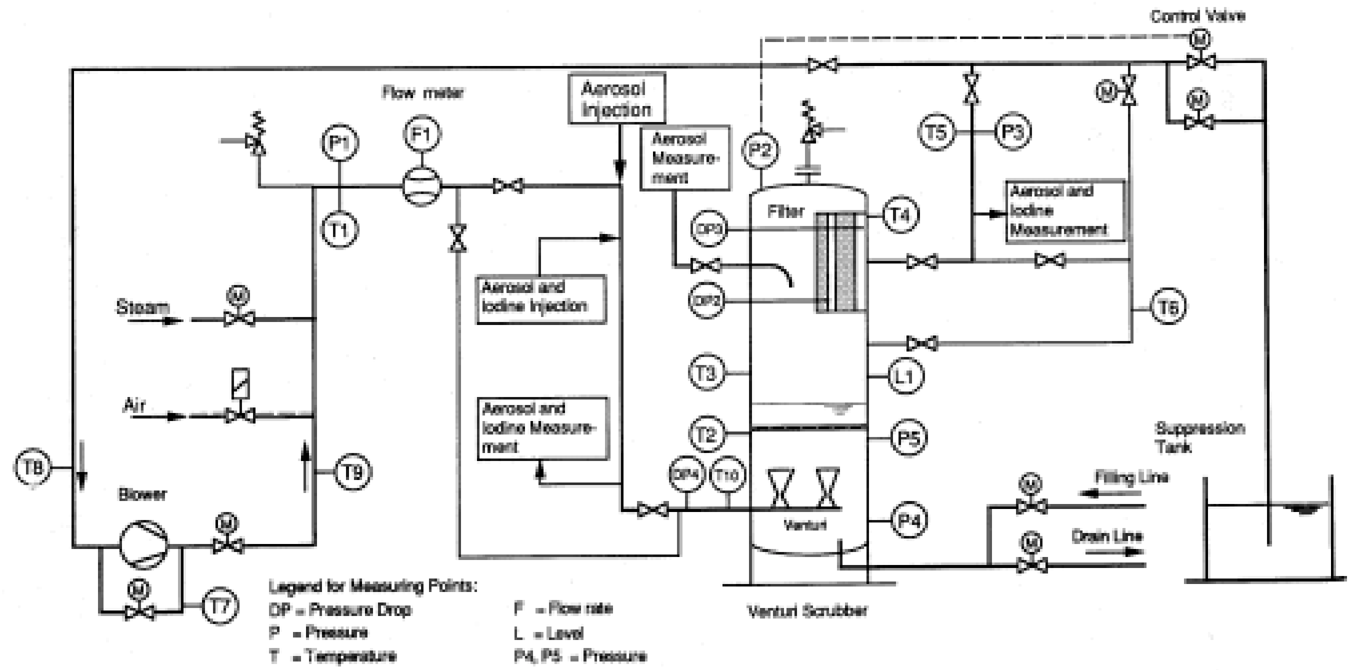


Figure 10: Proposal of a Filtered Venting System (Kozloduy 3 & 4)



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 11: JAVA Test Facility and Test Parameters for Filtered Venting