From: Mark Leyse
Sent: Tuesday, April 19, 2011 10:42 PM
To: Boska, John
Cc: Phillip Musegaas; Deborah Brancato; Dave Lochbaum; Richard Webster; Raymond Shadis; Dudley, Richard; Diane Curran; Powers, Dana A; Ed Lyman; Anthony Z. Roisman; PDR Resource
Subject: Re: G20110218 2.206 Petition on Indian Point PCT
Attachments: Paper on Hydrogen Recombiners.pdf; Hydrogen Recombiners VI.pdf

Follow Up Flag: Follow up
Flag Status: Flagged

Dear Mr. Boska:

First, I want to clarify that in this e-mail I am speaking for myself and not representing Riverkeeper.

I have attached two papers on hydrogen recombiners. The first is the paper I mentioned in yesterday's PRB teleconference, "Studies on innovative hydrogen recombiners as safety devices in the containments of light water reactors." The second is a paper titled, "Containment Hydrogen Control and Filtered Venting Design and Implementation."

And below is a link to Matt Wald's article from the Blog about Energy and the Environment, "U.S. Dropped Nuclear Rule Meant to Avert Hydrogen Explosions," March 31, 2011, which mentions what James F. Steets of Entergy stated about Indian Point's hydrogen recombiners. (http://green.blogs.nytimes.com/2011/03/31/u-s-dropped-nuclear-rule-meant-to-avert-hydrogen-explosions/)

The article states: "James F. Steets, a spokesman for Indian Point, said that Units 2 and 3 there each had two recombiners and that one alone could eliminate all the hydrogen in a major accident."

As I pointed out in the meeting, what James F. Steets said about hydrogen recombiners is incorrect. What he claims demonstrates Entergy's lack of knowledge of the quantity of hydrogen that would be produced from Zircaloy oxidation and other sources in a major accident.

The last paragraph of "Studies on innovative hydrogen recombiners as safety devices in the containments of light water reactors" states:

"Even if recombiners could be made safe against unintended ignitions, these devices cannot solve the hydrogen problem for severe accidents. Conversion rates of present systems are not sufficient for massive hydrogen release and hydrogen transport to the recombiners cannot be assured in a sufficient way."

And the second paper, "Containment Hydrogen Control and Filtered Venting Design and Implementation" states:

"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 last page of the paper has a list of orders for hydrogen recombiners, eight plants outside of the US have ordered 50 or more.

Second, IP-2's system has two "redundant" passive autocatalytic recombiners; see page 2.3-61 of "Scoping and Screening Methodology for Identifying Structures and Components Subject to Aging Management Review and Implementation Results."

(http://www.nrc.gov/reactors/operating/licensing/renewal/applications/indian-point/ipec_lra_1_2.pdf)

"Scoping and Screening Methodology" states:

"The purpose of the hydrogen recombiners (HR system) is to reduce the hydrogen concentration in the containment volume following a design basis accident. The system includes two redundant passive autocatalytic recombiners that replaced earlier flame units. The recombiners are passive devices: they contain no moving parts and do not need electrical power or any other support system. Recombination is accomplished by the attraction of oxygen and hydrogen molecules to the surface of a palladium catalyst. The exothermic reaction of the combination produces heat, which results in a convective flow that draws more gases from the containment atmosphere into the unit. Based on a recent license amendment (Amendment No. 243), hydrogen recombination is no longer required as a safety function."

Third, IP-3 most likely still has electric hydrogen recombiners; see page 17413 of the Federal Register notice, "Entergy Nuclear Operations, Inc., Indian Point Nuclear Generating Unit No. 3; Exemption," dated April 9, 2003 (Entergy got an exemption for IP-3's post accident containment ventilation (PACV) system):

http://edocket.access.gpo.gov/2003/pdf/03-8628.pdf

Federal Register notice states:

"The primary system is the electric hydrogen recombiner system..."

Please place this e-mail in ADAMS public documents.

Sincerely,

Mark Leyse

On Tue, Apr 19, 2011 at 8:00 AM, Boska, John <John.Boska@nrc.gov> wrote:

Following the NRR Petition Review Board call with you yesterday, the PRB discussed your petition. The PRB reviewed your Request For Action (Section I of the petition) and decided that there was not sufficient cause to immediately require Indian Point 2 and 3 to reduce the licensing basis peak cladding temperature to 1600F. No other decisions were made by the PRB. I will inform you when the PRB reaches a decision for the Board's initial recommendation whether or not to accept your petition for further review.

John Boska

Indian Point Project Manager, NRR/DORL

U.S. Nuclear Regulatory Commission

301-415-2901

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Studies on innovative hydrogen recombiners as safety devices in the containments of light water reactors

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Abstract

In order to prevent the containment and other safety relevant components from incurring serious damage caused by a detonation of the hydrogen/air-mixture generated during a severe accident in light water reactors (LWR) passive autocatalytic recombiners (PAR) are used for hydrogen removal in an increasing number of European plants. These devices make use of the fact that hydrogen and oxygen react exothermally on catalytic surfaces generating steam and heat.

Experimental investigations at several research facilities indicate that existing PAR systems bear the risk of igniting the gaseous mixture due to an overheating of the catalyst elements caused by strong reaction heat generation. Innovative devices could overcome existing limitations making use of the knowledge deduced from experiments performed at the REKO facilities at Forschungszentrum Juelich (FZJ).

The paper analyses the mechanisms of the thermal behaviour of catalytic plate-type recombiners and presents experimental results on existing and innovative devices for hydrogen removal introducing the modular recombiner concept.

1. Introduction

For mitigation of hydrogen released during a severe accident in light water reactors (LWR), containments are retrofitted with passive autocatalytic recombiners (PAR) in Germany as well as in numerous European countries. These devices recombine hydrogen with oxygen on catalytic active surfaces producing steam and heat. For present PAR systems the exothermal reaction may lead to an overheating of the catalyst elements and consequently cause an unintended ignition of the hydrogen/air-mixture. During experimental investigations at several institutions, e.g., Battelle Model Containment (BMC, Kanzleiter, 1997), KALI facility (Braillard et al., 1997), and SURTSEY facility (Blanchat and Malliakos, 1997) ignitions were observed. Accordingly, the state-of-the-art report of the PARSOAR project (Bachellerie et al., 2003) within the scope of the 5th Euratom Framework Program considers the hydrogen ignition risk as most important open topic concerning PAR qualification. As a consequence, a careful review of existing devices is required and for the future optimised recombiner systems need to be designed.

The work program of the Institute of Safety Research and Reactor Technology (ISR) in the field of hydrogen management in LWR addresses open questions concerning PAR comprising basic research as well as development of new recombiner concepts.

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doi:10.1016/j.nucengdes.2003.10.009

Nomenclature

a	thermal diffusivity ($m^2\,s^{-1}$)
ΔC_{H_2}	hydrogen concentration difference in the boundary layer ($mol\,m^{-3}$)
c_p	specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
$D_{H_2,m}$	diffusion coefficient of hydrogen in the gas mixture ($m^2\,s^{-1}$)
d	geometry term (m)
ΔH_R	reaction enthalpy ($J\,mol^{-1}$)
Nu	Nusselt number
Pr	Pandtl number
$\dot{Q}_\alpha$	convective heat flow ($W\,m^{-2}$)
$\dot{Q}_\varepsilon$	radiative heat flow ($W\,m^{-2}$)
$\dot{Q}_\lambda$	conductive heat flow ($W\,m^{-2}$)
$\dot{r}$	reaction rate ($mol\,m^{-2}\,s^{-1}$)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (°C)
ΔT	temperature difference in the boundary layer (K)
v	flow velocity (m/s)
x	length (mm)
y_{H_2}	hydrogen concentration (vol.%)
Greek letters	
$\dot{\Phi}_R$	heat source ($W\,m^{-2}$)
λ	heat conductivity ($W\,m^{-1}\,K^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)

The scientific approach includes both experimental and theoretical investigations. The hydrogen laboratory provides three small-scale REKO test facilities and a galvanic catalyst coating station. Experimental basic research provides a deeper understanding of the physical and chemical processes in catalytic recombiners concerning reaction kinetics, conversion efficiency and thermal behaviour. These investigations generate a data base for numerical model validation. Based on a profound understanding of the relevant physical and chemical processes the work aims at the optimisation of today's safety concepts as well as at the development of new safety directed solutions for such applications where no suitable measures exist.

2. Basic research on catalytic recombiners

The basic research on catalytic recombiners performed at ISR serves to clarify the interactions of reaction kinetics, temperature distribution, heat and mass transfer as well as thermal hydraulic phenomena. The investigations concentrate on reaction kinetics on catalyst surfaces and the mechanisms generating and removing reaction heat. In this context the temperature distribution on the catalyst surface of a plate-type PAR has been measured and investigated during experiments at the REKO-3 test facility (Fig. 1).

The experimental set-up allows investigation of catalyst samples inside a vertical flow channel under well defined conditions comprising gas mixture, flow rate and inlet temperature. Gas mixture and flow rate are adjusted by means of mass flow controllers. The air preheater enables control of the inlet temperature. For the current experiments four sheets made of stainless steel and coated with washcoat/platinum catalyst material are arranged in parallel inside the flow channel (Fig. 2). Such a set-up represents a plate-type recombiner section, e.g., of Siemens design. The catalyst elements are exposed to a constant flow of a mixture of air, hydrogen and steam. Nitrogen may be added as diluent in case of emergency. The hydrogen conversion efficiency may be determined from gas analysis measurements. Two sampling points are foreseen in front of and behind the recombiner section.

The most important feature of the temperature measurement set-up is the determination of the catalyst temperatures. The catalyst sheets are equipped with thermocouples (TC) for measuring the distribution of the catalyst temperature. In order not to disturb neither the gas flow nor the catalyst coating by thermocouples attached on the catalyst surface, drillings were manufactured by means of spark erosion enabling thin thermocouples to be inserted at different locations inside the sample (Fig. 3). In such a way, the arrangement of a total of 10 thermocouples allows for determining the temperature distribution over the catalyst plate.

Experiments have been performed for different flow rates (0.25, 0.50, and 0.80 m/s) at two inlet temperatures (25 and 70 °C). Inlet hydrogen concentrations were varied between 0.5 and 4.0 vol.%. Fig. 4 displays an example for the transient of the catalyst temperature at a constant feed of 4 vol.% hydrogen in air at 25 °C and at a flow rate of 0.5 m/s.

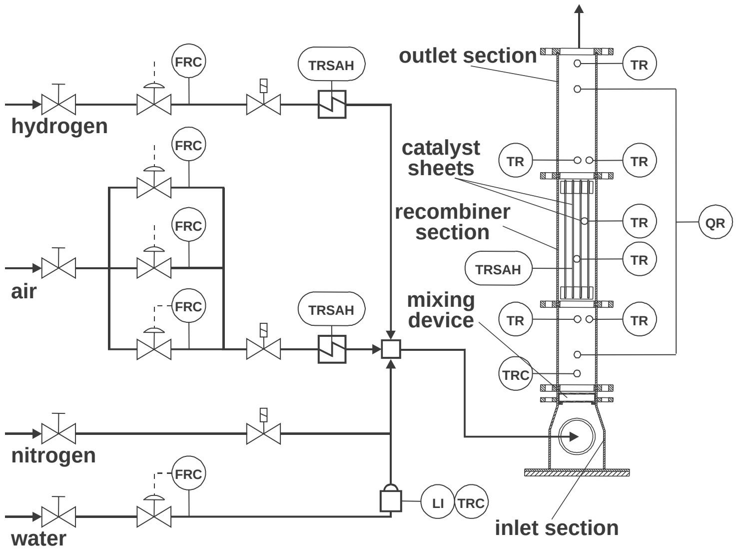

Fig. 1. Flow chart of REKO-3 test facility.

About two minutes after starting hydrogen feed the first significant heat development near the leading edge of the catalyst sheet can be observed. During the next six minutes temperatures rise in that region up to about 500 °C. Most noticeable is the distinct temperature gradient from the leading edge to the trailing edge of the catalyst sheet which conforms to the presumption that the exothermal hydrogen conversion takes place mostly in the very first surface section of the sheets. Conversion rates show that hydrogen removal is about complete, rate efficiencies above 90% were determined. About half an hour after starting the experiment steady-state conditions are reached. There is still a significant temperature difference across the plate of about 200 K. This effect has not been considered in numerical recombiner models so far developed for containment codes.

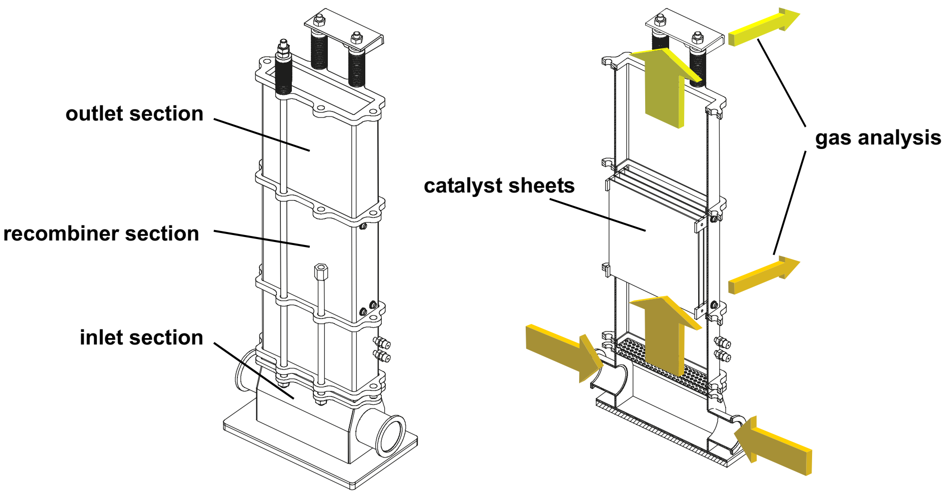

Fig. 2. Flow channel of REKO-3 test facility.

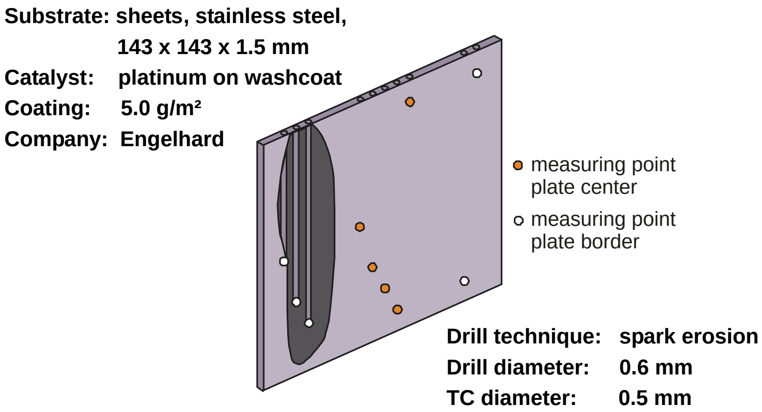

Fig. 3. Drilling holes for insertion of thermocouples.

The level of the temperature profile increases according to the inlet hydrogen concentration. Steady-state temperature profiles at different inlet hydrogen concentrations are shown in Fig. 5. In these experiments the inlet gas temperature was 70 °C, and the inlet velocity was 0.8 m/s which is typical for recombiners of that design (Kanzleiter and Seidler, 1995). At a hydrogen concentration of 4 vol.% maximum temperatures reach the ignition limit which is denoted in literature to be in the region of about 560 °C. Any further increase in the inlet hydrogen concentration would lead to catalyst temperatures above the ignition limit and hence increase the risk of an unintended ignition.

These results hint at the possibility of an ignition due to catalyst heating at hydrogen concentrations above 4 vol.%. This value is considerable lower than the findings from the above mentioned experiments

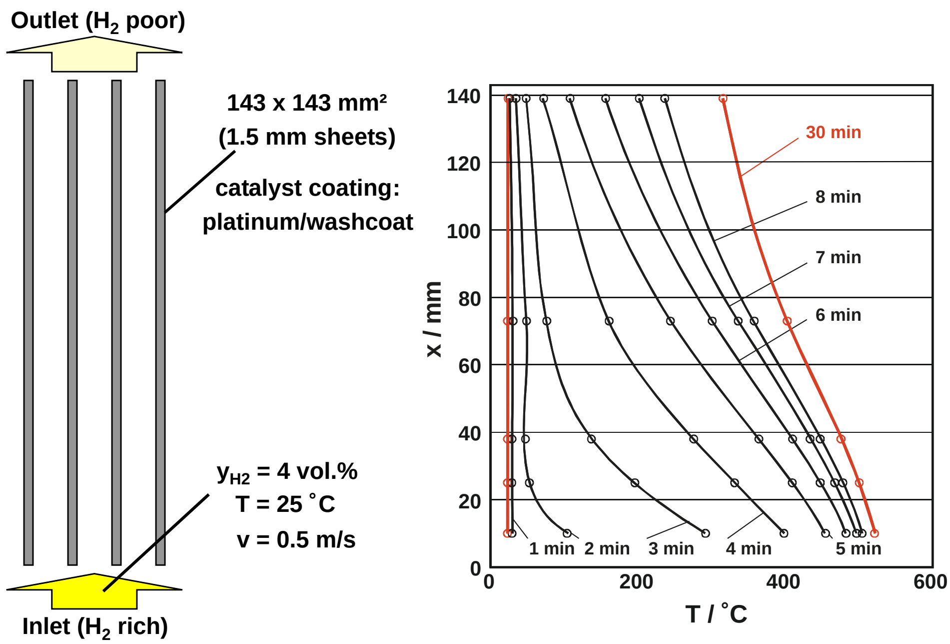

Fig. 4. Progression of catalyst temperatures at constant feed.

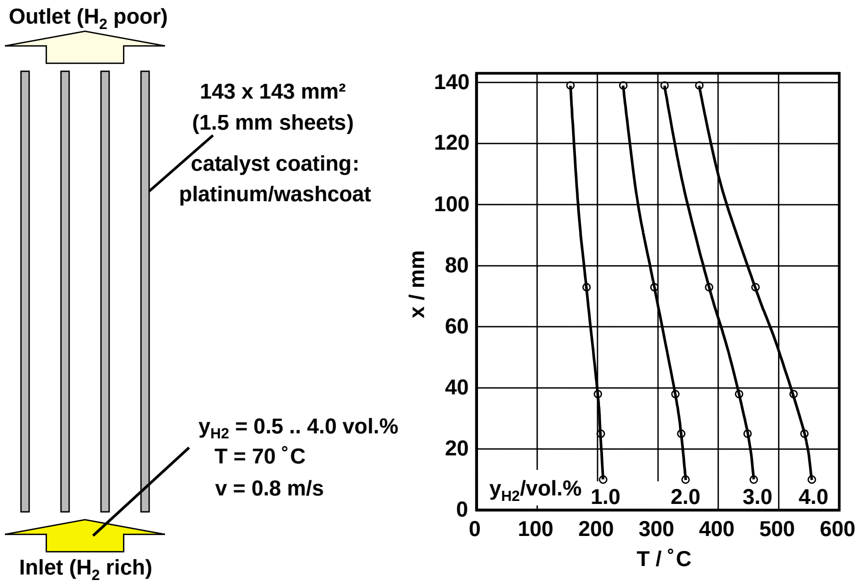

Fig. 5. Catalyst temperatures at different inlet hydrogen concentrations.

at BMC and KALI facilities where ignitions occurred at hydrogen concentrations of 7 vol.% and above. The reason for this deviation may be found in the fact that at active surfaces higher temperatures are needed for ignition due to the depletion of the combustible gas mixture at the hot surface. In addition, test conditions may have significant influence on the results. Nevertheless, ignition caused by non-catalyst parts heated up by direct contact with the catalyst sheets is already possible. The experimental results show clearly that present recombiner systems lack a mechanism that limits the system temperatures.

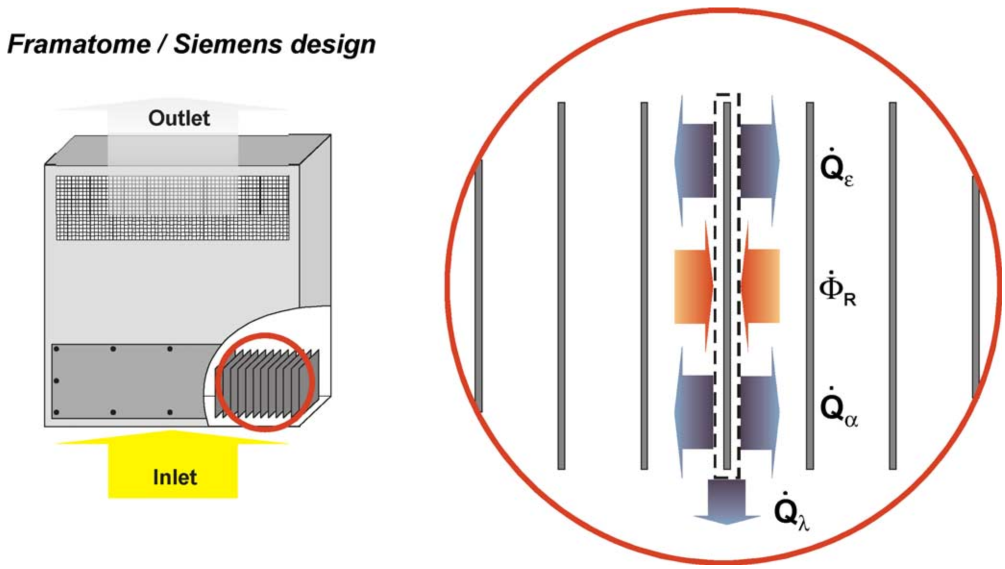

Fig. 6. Steady-state energy balance of a catalyst element inside a plate-type PAR.

A steady-state energy balance of a catalyst element (Fig. 6) clearly shows that the reaction heat generated on the surface due to the exothermal reaction is practically removed by convective heat transfer only. Such a simplification is justified by this particular PAR design. Heat conduction may be neglected due to the small contact area with colder structures as well as heat radiation as a result of the parallel arrangement of the catalyst sheets.

Consequently, for steady-state conditions the balance simplifies to

$$\dot{\Phi}_R = \dot{Q}_\alpha \tag{1}$$

where $\dot{\Phi}_R$ is the source term and $\dot{Q}_\alpha$ the convective heat flow. Experimental investigations of the reaction kinetics have indicated that recombination is controlled by mass transfer under typical conditions (Reinecke, 1999). As a consequence, the reaction rate can be formulated by means of a mass transfer law. Thus, the source term, the product of reaction rate $\dot{r}$ and reaction enthalpy ΔH_R can be written

$$\dot{\Phi}_R = \dot{r} \times \Delta H_R = Sh \frac{D_{H_2,m}}{d} \Delta C_{H_2} \times \Delta H_R \tag{2}$$

where Sh is the Sherwood number representing the dimensionless mass transfer coefficient, $D_{H_2,m}$ is the diffusion coefficient of hydrogen in the gas mixture, d is the geometry term, and ΔC_{H_2} is the hydrogen concentration difference in the boundary layer. The correspondent expression for the convective heat flow is

$$\dot{Q}_\alpha = Nu \frac{\lambda}{d} \Delta T \tag{3}$$

with the Nusselt number Nu, the heat conductivity λ, and the temperature difference in the boundary layer ΔT.

Assuming analogy of heat and mass transfer, as proposed by Avakian (2002), the equations for the Nusselt and the Sherwood number can be formulated similarly using in the case of heat transfer the Prandtl number

$$Pr = \frac{\nu}{a} \tag{4}$$

with the kinematic viscosity ν and the thermal diffusivity a and in the case of mass transfer the Schmidt number

$$Sc = \frac{\nu}{D_{H_2,m}} \tag{5}$$

Under these assumptions combining Eqs. (2) and (3) in Eq. (1) and using typical heat transfer laws we obtain e.g.,

$$\Delta T = \left[\rho \times c_p \left(\frac{\lambda}{D_{H_2,m}} \right)^2 \right]^{-1/3} \Delta H_R \times \Delta C_{H_2} \tag{6}$$

as an expression for the temperature difference that is necessary to remove the reaction heat released on the catalyst surface. In this relationship ρ is the density, and c_p is the specific heat capacity. It is easy to conclude that ΔT is almost proportional to the hydrogen concentration difference. As the hydrogen concentration at the catalyst surface is always close to zero due to the high activity of the catalyst material, the driving force for mass transfer is proportional to the inlet hydrogen concentration. From this simplified balance can be derived that increasing hydrogen concentrations must result in increasing catalyst temperatures and eventually lead to overheating and unintended ignitions.

3. Innovative recombiner concept

The experimental and theoretical findings presented above show that a strategy for reliably keeping system temperatures in recombiners below ignition limits demands a new recombiner design. Important requirements for new recombiner concepts are

- limiting the local heat production of the exothermal reaction; and
- enhancing the reaction heat removal from the system.

The latter aspect is not treated in this paper. In this context the combination of recombiners with additional safety devices, e.g., passive containment cooling devices, could be taken into account (Broeckerhoff et al., 2000).

A new concept may be realised applying a modular recombiner design (Fig. 7) where the single catalyst elements are limited in catalytic activity. For this purpose, alternative substrate materials and catalyst coatings are necessary, since washcoat coatings used in existing recombiners offer high specific surfaces which provide high local conversion rates.

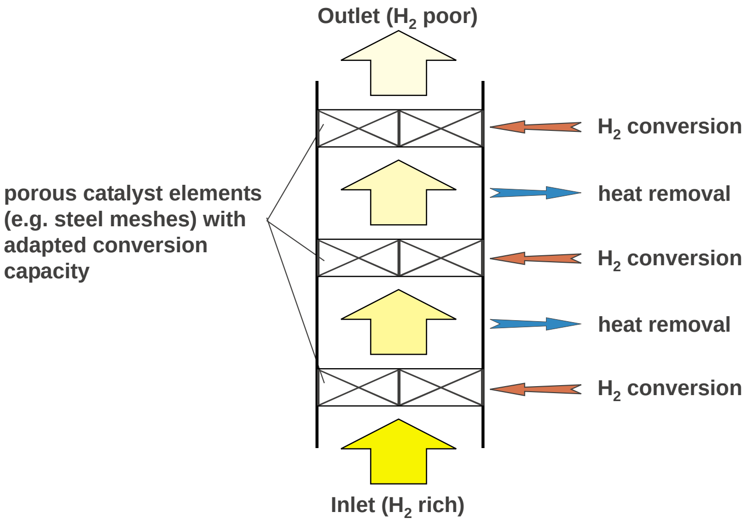

Fig. 7. Modular recombiner set-up.

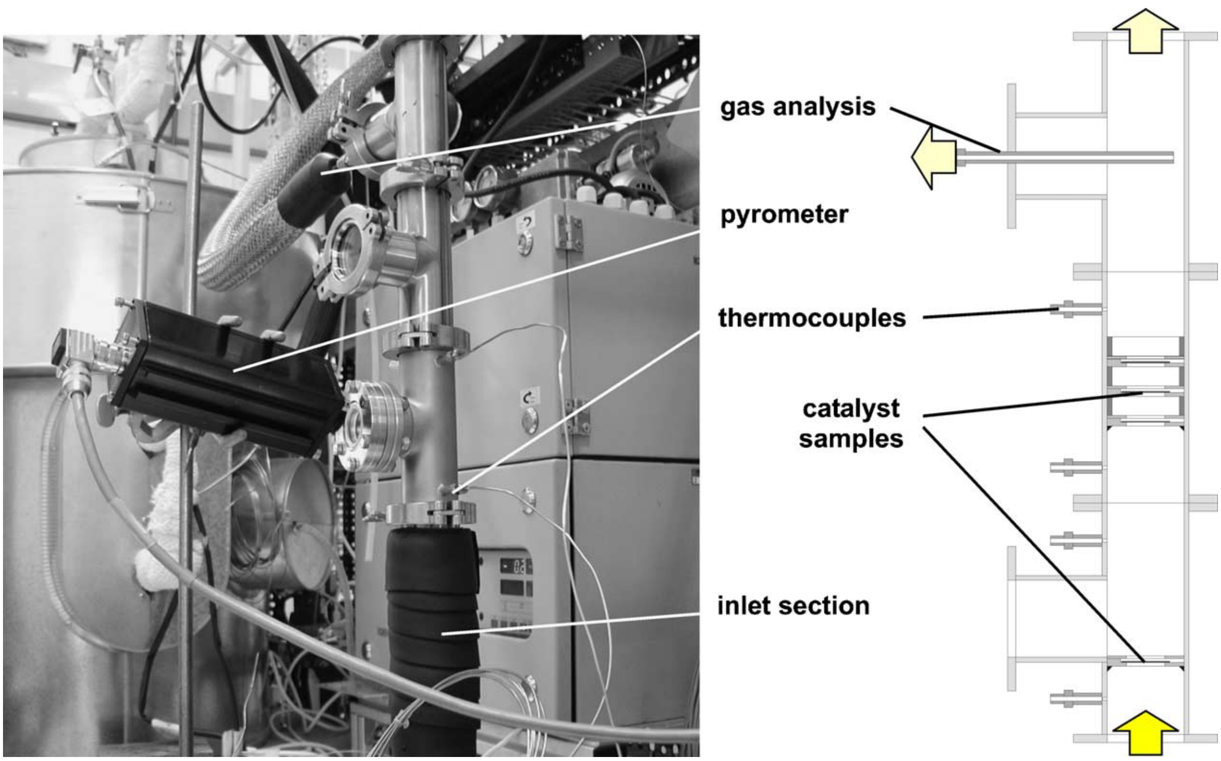

Fig. 8. REKO-1m test facility.

In order to demonstrate the feasibility of the modular concept, porous catalyst elements consisting of coated steel meshes are investigated in the REKO-1m test facility (Fig. 8) with respect to hydrogen conversion rates and thermal behaviour. Single catalyst samples or complete modules comprising of several elements are inserted inside a flow channel and exposed to a hydrogen/air flow of constant gas mixture, flow rate, and inlet temperature. The sample temperatures are measured by means of a pyrometer allowing contactless measurements. The reaction rates are determined by concentration measurements in the outlet section of the test facility.

In order to limit the heat release on the surface of the steel mesh the catalyst material has to be distributed in such a way that not all hydrogen and oxygen molecules diffusing on the surface find an active centre to react. A washcoat coating offers far too high specific surfaces for such a task. More reasonable is e.g., the deposition of catalyst material directly on the substrate surface by means of galvanic techniques, as it was presented by Reinecke et al. (2002). Fig. 9 shows the two different types of catalyst coatings. While on the left side the increase in active surface due to the washcoat technique is evident, the right side shows direct deposition of platinum on the substrate surface.

Samples with both types of coatings were tested in experiments at the REKO-1m test facility. The application of a catalyst with reduced active surface can significantly limit the reaction rates of the hydrogen recombination process, as shown in Fig. 10. While the reaction rates on washcoat coatings increase directly proportional to the inlet hydrogen concentration, new coatings with adapted conversion capacity show limited reaction rates in spite of increased hydrogen concentrations and thus avoid the risk of a local overheating. These experiments were conducted at a flow rate of 1.0 m/s. The inlet hydrogen concentration was varied between 2 and 24 vol.%. At higher inlet concentrations the reaction completely died down, likely due to depletion of oxygen.

In order to compensate the reduction in conversion efficiency of a single element these catalyst elements can easily be combined in a modular way as sketched in Fig. 7. With a set-up of three wire mesh elements e.g., conversion efficiencies around 70% have been reached at inlet hydrogen concentrations of up to 10 vol.% (Reinecke et al., 2002).

As expected, the catalyst temperatures measured (Fig. 11) show a very similar dependence from the hydrogen concentration. Obviously, a substantial limitation of the catalyst temperature has been achieved, although the temperature which is at about 600 °C is still close to the ignition temperature.

The conversion behaviour of the catalyst sample can be influenced by the characteristics of the

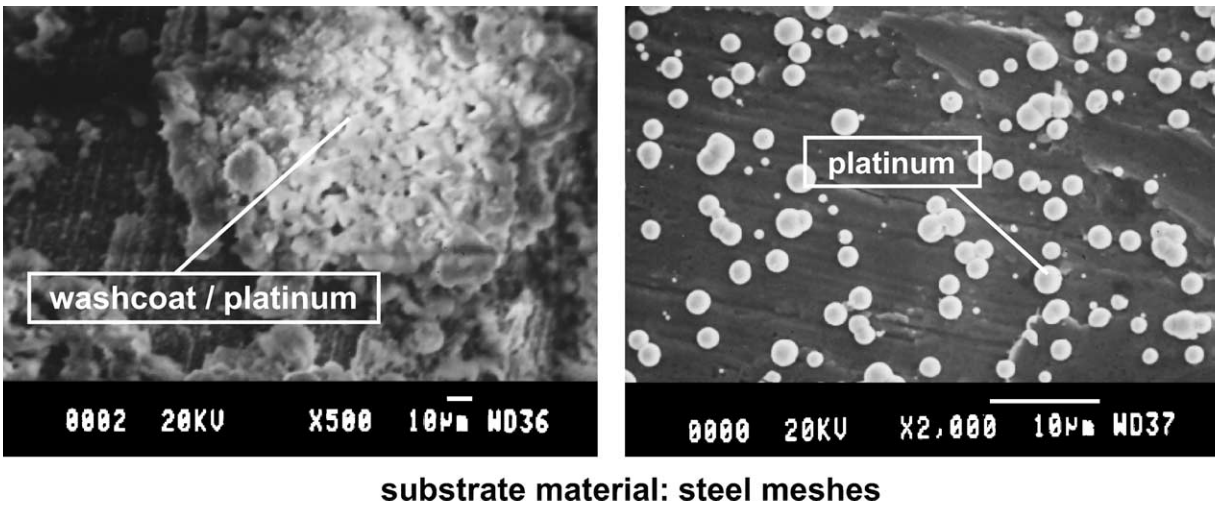

Fig. 9. Alternative catalyst coatings (SEM-micrographs).

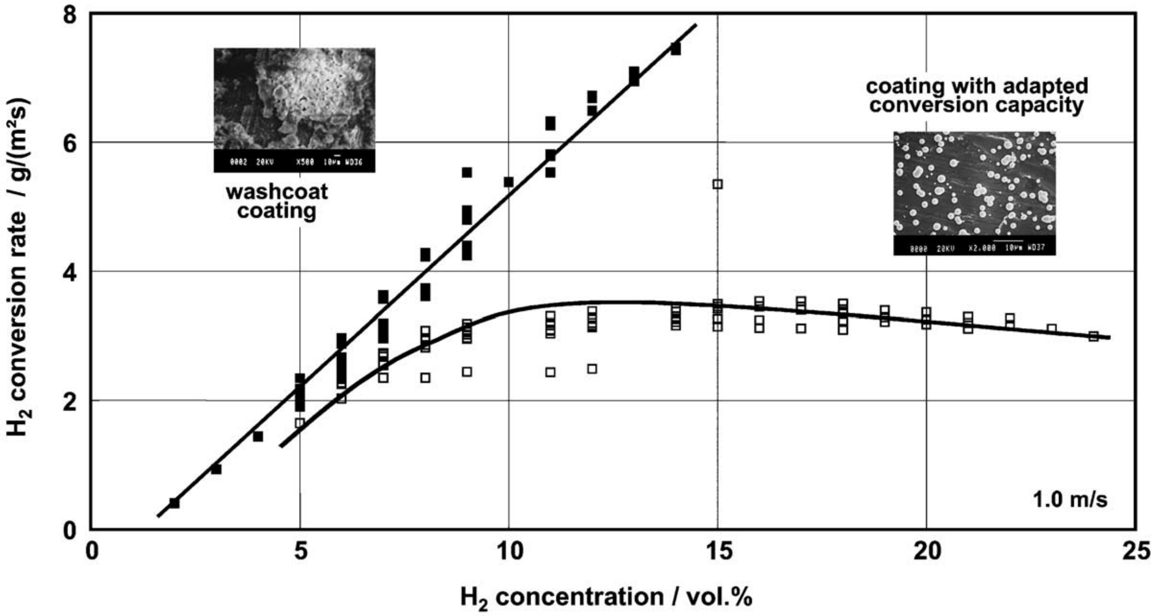

Fig. 10. Hydrogen conversion rates for porous substrates and alternative coatings.

catalyst deposition on the surface. As an example, Fig. 12 shows two different densities of platinum deposition on the surface of wire meshes made of stainless steel. Both coating densities lead to different conversion rates (Fig. 13). The correlation between the conversion behaviour and the coating characteristics is part of present investigations.

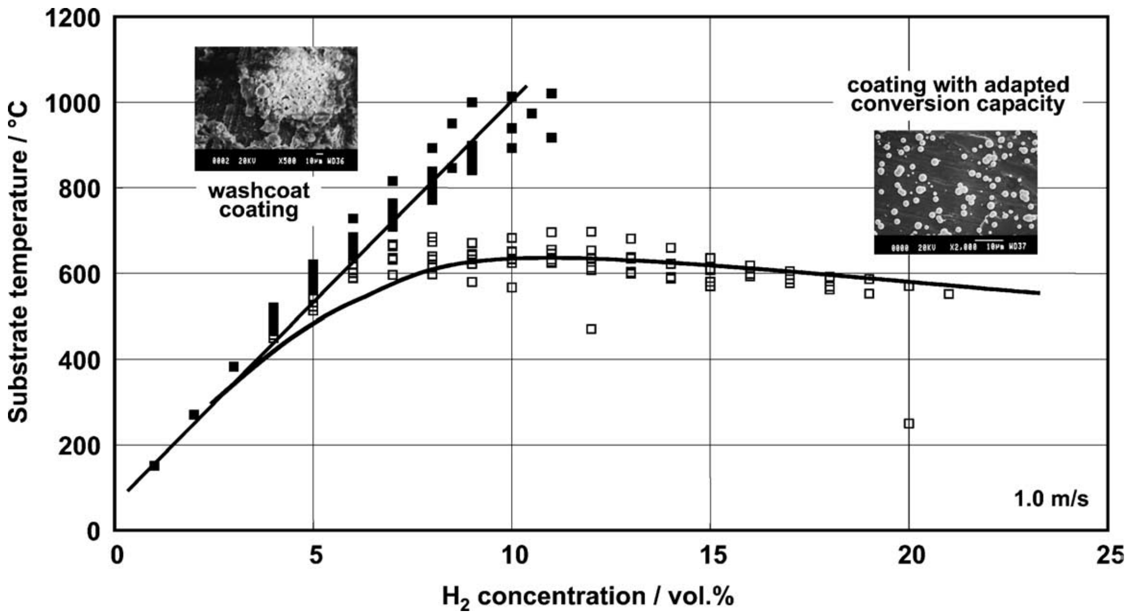

Fig. 11. Substrate temperatures for porous substrates and alternative coatings.

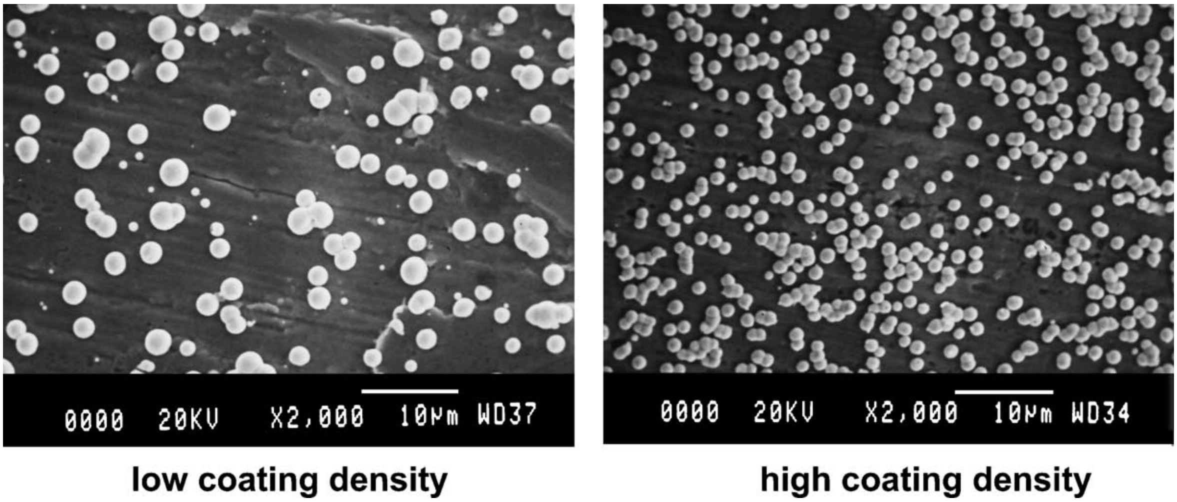

Fig. 12. Different catalyst coating densities.

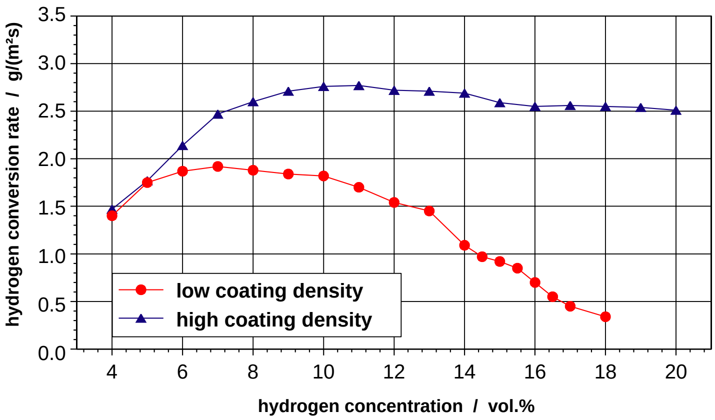

Fig. 13. Hydrogen conversion rates for porous substrates and different coating densities.

4. Conclusions

The experimental investigations presented clarify that existing plate-type PAR systems bear the risk of igniting the combustible containment atmosphere due to the local overheating of the catalyst elements caused by strong reaction heat generation. An analysis of the thermal behaviour of the catalyst elements shows that present recombiner systems lack a mechanism that limits the system temperatures. New devices ensuring system temperatures below the ignition limit can be realised in a modular set-up recombiner. In this concept the conversion rates of single catalyst elements are limited. For such a concept alternative catalyst coatings are required as coatings used in existing recombiners offer high specific surfaces which provide high local conversion rates.

The coating technique applied in the experiments presented in this paper has been used for demonstrating the feasibility of the concept. However, there are more important requirements on the catalyst elements that have to be taken into account. Further research work is focused on specific coatings for well defined conversion capacities and questions concerning start-up behaviour and material reliability.

Even if recombiners could be made safe against unintended ignitions, these devices cannot solve the hydrogen problem for severe accidents. Conversion rates of present systems are not sufficient for massive hydrogen release and hydrogen transport to the recombiners cannot be assured in a sufficient way. The combination of PAR with other existing concepts for hydrogen mitigation (Zhong, 2001), e.g., inerting or diluting, seems to be advisable even if these concepts also have limitations. An example is the reinforcement of PARs by means of catalytic coated thermal insulation elements as proposed in the THINCAT project within the 5th EURATOM Framework Programme (Fischer et al., 2003). The introduction of igniters as discussed in the past still seems to be very questionable as the prediction of hydrogen distribution and combustion in the containment is at present not reliable enough to ensure the safe application of this measure.

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Containment Hydrogen Control and Filtered Venting Design and Implementation

Bernd A. Eckardt, Michael Blase, Norbert Losch

Framatome ANP, Offenbach, Germany

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
H_2-control. Similar discussions starts for the WWERs.
For these tasks it has been necessary to develop means for containment atmosphere control which are capable of

- handling high H_2 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 H_2 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 H_2 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. H_2-Control

2.1 General Requirements

Plants to mitigate severe accidents.

In the event of a severe accident, large quantities of H_2 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 H_2 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 H_2 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 H_2 Reduction Technologies

Over the past two decades since TMI, several H_2 reduction technologies have been developed and tested to limit H_2 concentration in the containment atmosphere under LOCA conditions. Later, severe accident situations involving generation of large amount of hydrogen were investigated as well and H_2 reduction technologies to mitigate severe accidents were developed and tested.

2.3 H_2 Reduction Technologies for LOCA Control

In order to limit H_2 concentrations inside the containment in the event of a LOCA given an accident scenario involving comparably little H_2 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 m^3/h. Use of these units for H_2 reduction under postulated beyond-design-basis events – i.e. conditions exhibiting H_2 releases higher by several orders of magnitude – would therefore hardly prove effective.

3. H_2 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 H_2 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 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.

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 (I_2, CO, H_3B0_2 and CH_3I) / 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 $\geq$ 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.

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 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%.
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 $BaSO_4$ 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.

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 resupended 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.

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 TARCI 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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for LOCA

- Forced Flow Catalytic Recombiner
- Forced Flow Thermal Recombiner

for Severe Accidents

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

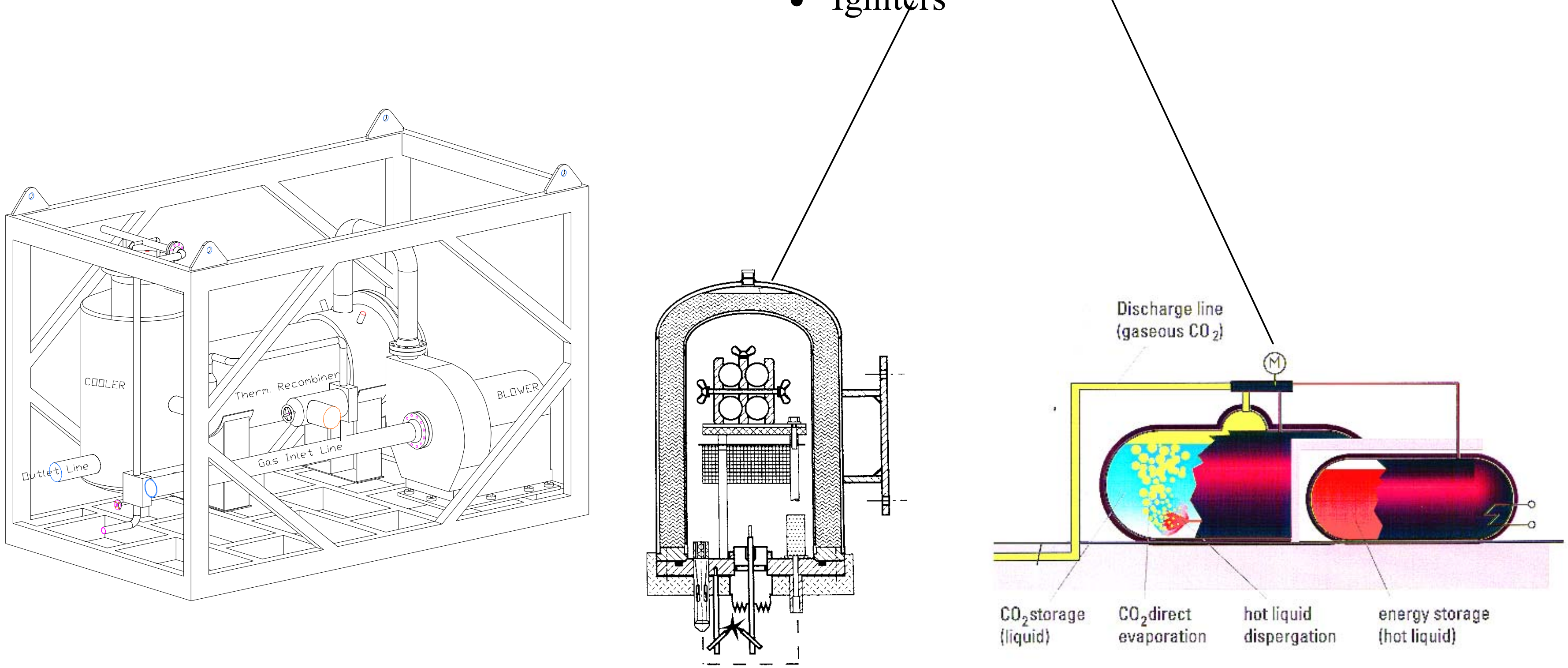
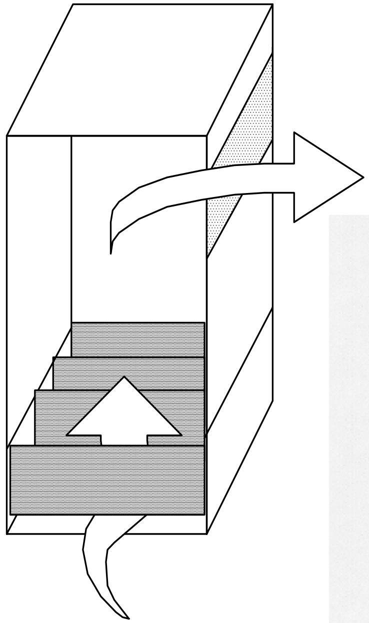


Figure 1 : Overview of Hydrogene Reduction Technologies

- **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

- **Function**



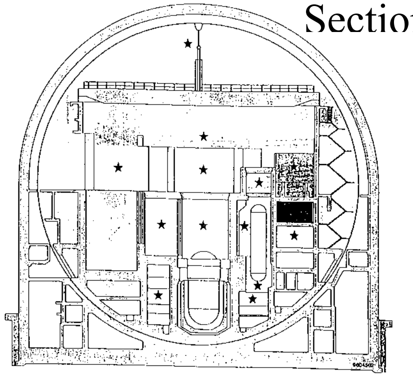
Removable Inspection Drawer
for easy access of catalytic plates

Inservice
Inspection
Equipment

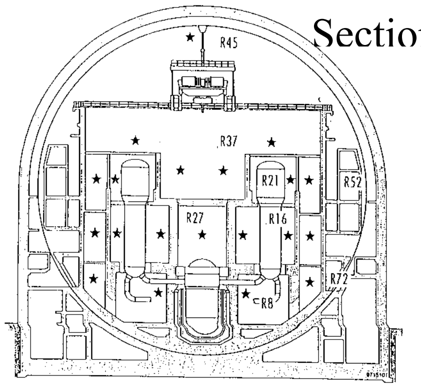
Figure 2 : PAR Function and Design

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

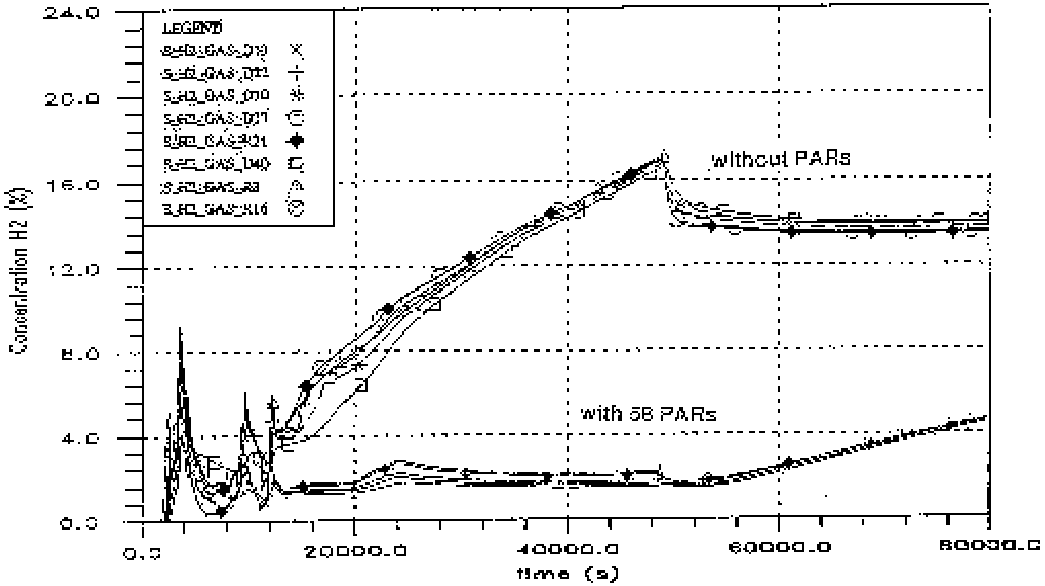
Sectional Drawing A-A



Sectional Drawing B-B



Positions of Recombiners are marked with *



Hydrogen concentrations inside the inner containment missile shield

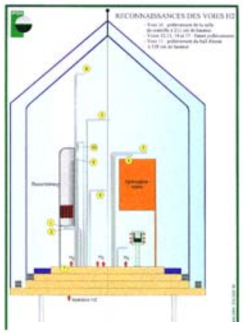
Finally the following Siemens PAR types and quantities were installed in GKN2:

29 x FR90/1-1500   3 x FR90/1-960
4 x FR90/1-750T   4 x FR90/1-320
18 x FR90/1-380T

Figure 3 : PAR System and Design

DEVELOPMENT OF
PASSIVE AUTOCATALYTIC
HYDROGEN RECOMBINER
SYSTEMS

GERMANY	Karlstein-Laboratories	Development and qualification since	1989
		Application for patents	since 1990
		Patents granted	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



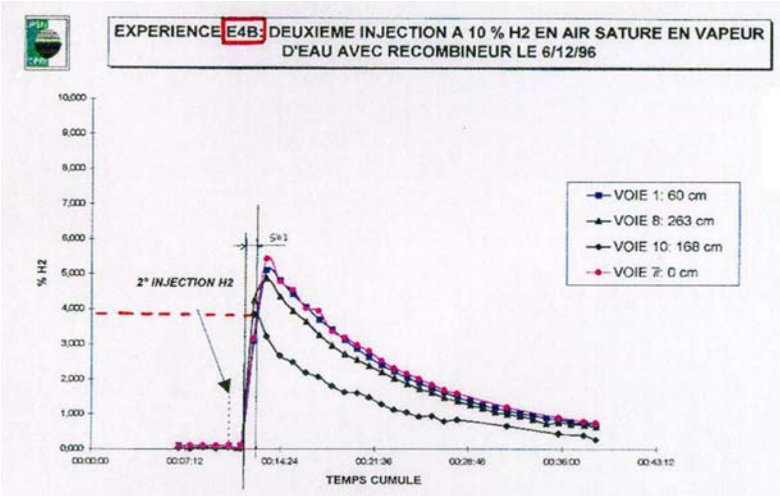
EDF / IPSN H2-PAR
Test Facility

Figure 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

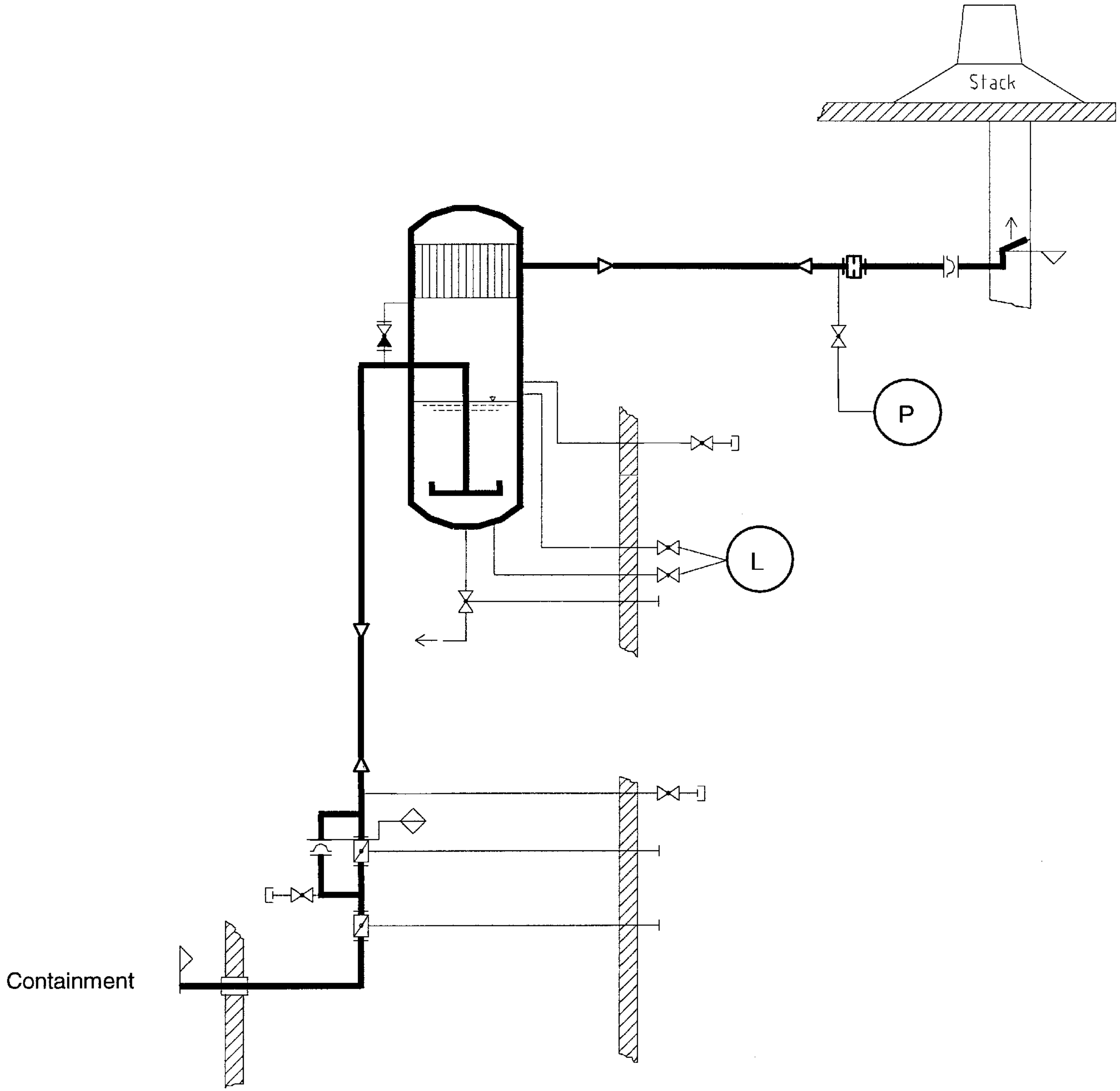
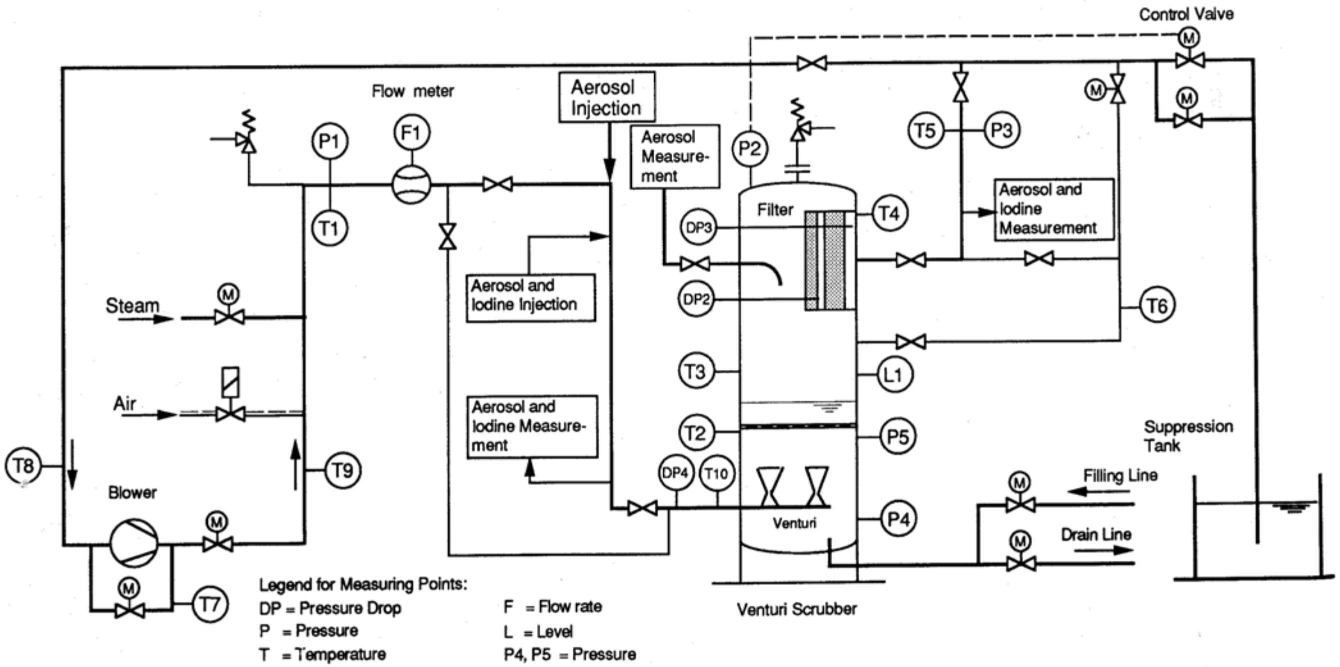


Figure 5 : Flow Diagram Sliding Pressure Venting



Containment Venting / JAVA Test Facility

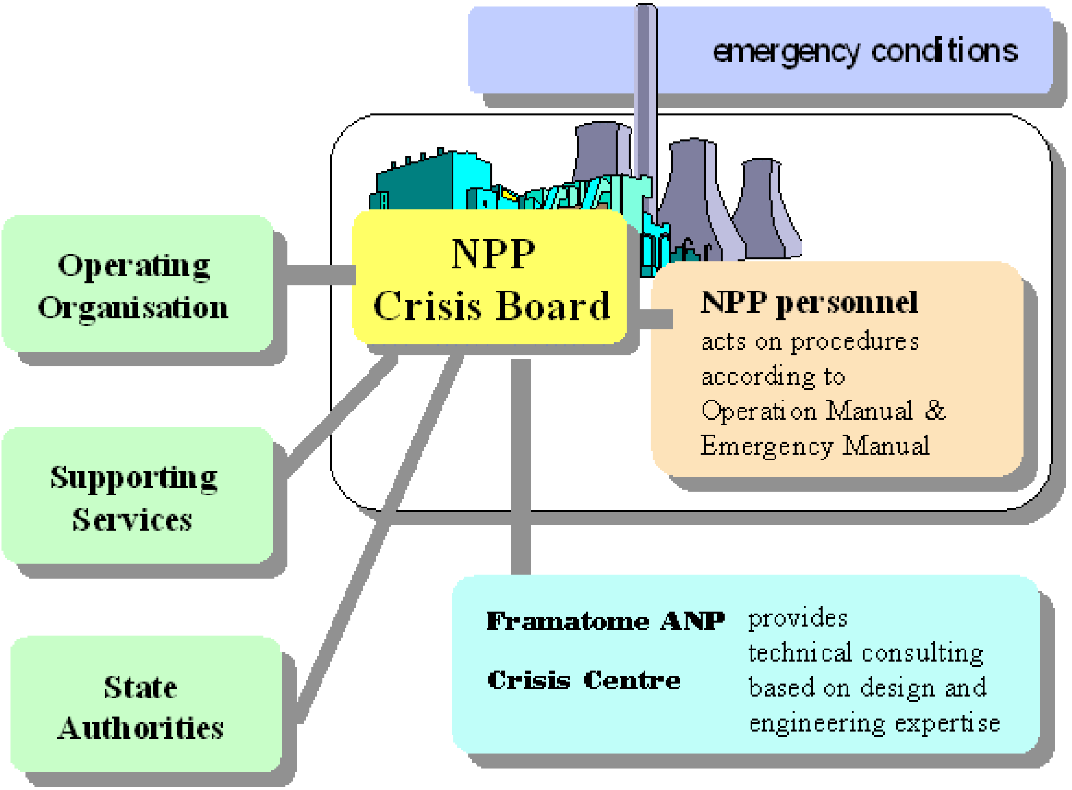
Test Parameters

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



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

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