PARs Governing Parameters and Criteria for Unified Protocol of Performance Rating and Safety Margins Assessment

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1 Introduction

A use of PARs (Passive Autocatalytic Recombiners) as key element of hydrogen safety providing is generally foreseen in the advanced reactors under construction as well as for safety upgrade of the NPPs under operation [1–3]. PARs convert hydrogen into water vapor by means of passive mechanisms and have been qualified for operation under the conditions of nuclear power plant accidents. These devices are aimed on the one hand to provide both high instantaneous and integral removal rate and on the other hand to limit build-up of flammable clouds by means of depletion and PAR induced mixing processes [3–7]. As shown in [1–3], after the Fukushima Dai-ichi accident, it was underlined the need to investigate the effectiveness of mitigation with PARs under the specific conditions of the late phase of a severe accident. In a severe accident NPP atmosphere with a degraded core should be confirmed PARs resistance to [2–9]:

- radiation (operational radiation, radiation following a core melt accident);
- different pressures, temperatures, steam and hydrogen concentrations;
- exposure to catalytic poisons (I_2, CO, H_3BO_3, CH_3I), chemicals caused by thermal cable degradation, and aerosols from a molten core substitute;
- consequences of hydrogen combustion, submergence in water, oil fire, cable fire;
- consequences of interaction with spray water systems and seismic vibrations;
- wetting during start-up, exposition to direct water spray on the catalyst;
- consequences of low-oxygen conditions;
- consequences of long term recombination and deflagration.

Most pressing challenges in light of PAR hydrogen safety was recognized the study of PARs behavior under ex-vessel conditions including the combined effect of oxygen starvation, steam, carbon monoxide and iodine [2,3,6,7,9].

An ample set of the R&D work have been performed for understanding and quantitative characterization of performance this type of the PARs and their safety limits. There is no, however, a clear definition and generally agreed and accepted list of the key PAR parameters, which are governing its performance and safety use [1–5]. The purpose of the PAR standardization is to develop approaches to the establishment of uniform requirements for PARs, which could sever as the basis for PAR performance and safety limits quantification. On the other hand PARs testing should be performed under univocal and traceable initial and boundary conditions. Currently, the test methods and programs to verify the design characteristics of PARs installed at Russian NPPs are in the stage of agreement with regulatory body [5]. In order to develop such test methods and program, it is reasonable to use foreign experience, but there is still no unified approach to PARs testing reproducible at various experimental facilities. The paper presents a tentative to define criteria for comparing different PAR systems.

2 PARs Deactivation factors and their impact on parameters, critical for PAR performance and safety

The possible PAR safety criteria are strongly influenced by many factors such as the atmosphere conditions (pressure, temperature, gaseous composition, etc.) [3, 4, 9–12], thus PAR is a complex system. Consequently it is very difficult to propose only a single value for the criteria for all possible conditions, scenarios and PARs types (Fig. 1). Therefore, to justify the PARs safety it is proposed to use standard procedures for analyzing complex systems (system analysis, systems approach). In these approaches, there are significant differences between parameters, indicators and criteria, i.e. for terms of an interconnected triad of concepts - a parameter, an indicator and a criterion should be understood on well-developed scientific and methodological basis for the analysis of complex systems.

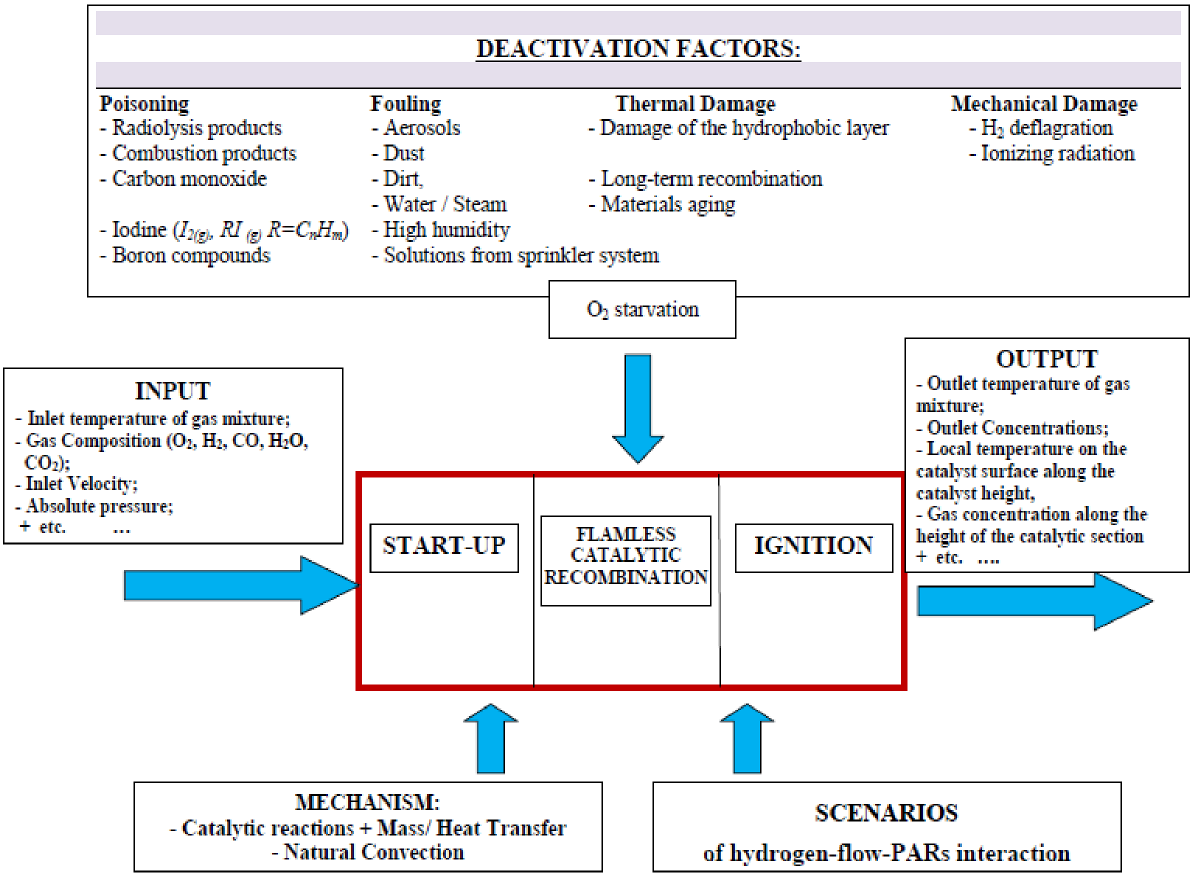

Figure 1: Deactivation factors and parameters, important for PARs performance and safety

When analyzing PARs safety, it is proposed to clearly establish which parameters (technological, organizational, etc.) are selected from all available ones (measurements, experience, expert opinion, etc.) and why exactly they are taken as safety indicators of the PARs under accident conditions. It is proposed to first justify the choice of those indicators from the mass of available parameters, according to the values of which it will be possible to evaluate changes in PARs safety.

The PAR efficiency reduction under realistic severe accident scenarios should be considered for the formalization of PAR qualification

The deactivation of PARs because of their exposure to poisonous environment in particular inside the NPP containment is an important concern of ensuring nuclear and hydrogen safety [6–12]. These deactivation factors may effect to parameters, important for PAR performance and safety (Fig. 1).

Based on the analysis of the published literature on PARs [7–12], PARs may be exposed to several deactivation factors as during NPP normal operation and at accidents. Such a deactivation may occur through different mechanisms and could in principle affect the start-up behavior up to the full loss of catalytic activity [7–12]. In this context, the goal of this paper is to define a minimal set of parameters of the PARs, which can be regarded as important for PARs performance and safety and which may be used as a possible reference for PAR qualification testing and for assessment of hydrogen mitigation efficiency under challenging boundary conditions of severe accidents, e.g. the effect of carbon monoxide in the ex-vessel phase or the oxygen starvation effect.

3 PARs Baseline States, Important for the Safety of Light Water Reactor

The main characteristics that determine the procedure and modes of using PARs as part of safety systems for removal of hydrogen during accidents at NPPs are [1–12]:

- start-up characteristics,
- hydrogen recombination performance,
- threshold volume concentration of hydrogen, which characterizes the transition from the flameless recombination mode to the ignition mode with the exit of an open flame outside the PAR housing (“ignition” threshold).

In accordance with such approach, when establishing standardized requirements for the characteristics and properties of PARs of a particular design and standard size, this report considers the following main states that determine the ability of PAR to mitigate the risk of hydrogen explosions: START-UP, FLAMLESS CATALYTIC RECOMBINATION and CATALYTIC IGNITION.

When describing PARs start-up behavior, it is proposed to distinguish between two types of processes that determine this state, namely,

- "start of catalytic recombination processes", i.e. transition from the inactive state of the catalytic surface of PAR elements to low-intensity self-sustaining catalytic reactions on the surface, caused by the entry of a vapor-hydrogen-air mixture with a hydrogen concentration exceeding the lower concentration limit of catalytic oxidation at the PAR input and
- “gas-dynamic (hydrodynamic) start of the recombiner itself ", defined as transient process of formation of a stable, self-sustaining convection flow ("chimney effect"), i.e. the transition from the inactive state of the PAR catalytic elements to heat release due to a self-sustaining catalytic reaction on the surface, the intensity of which is sufficient for the formation and called "chimney effect"). For a fixed height of the gas-dynamic path of the PAR system and the specified geometric characteristics of the catalytic element cassettes, the "chimney" effect appears for steam-hydrogen-air mixtures with a hydrogen concentration exceeding the lower concentration limit of hydraulic start PAR the power of

the catalytic heat release provides a hydraulic support to the oxidation products, which exceeds the difference in the values of the hydrostatic pressure of the external atmosphere in the inlet and outlet sections).

For the basic state “Flameless catalytic recombination at rated performance” the safe operation of PARs in an accident conditions / hydrogen presence, may be characterized by:

- integral (kg/sec) and specific capacity (kg/m^{2}sec) - PAR rate of flameless hydrogen recombination;
- integral values of the pulse of the steady-state gas jet of reagents (in the inlet section PAR) and recombination products (in the outlet section PAR);
- integral heat dissipation power.

As PARs testing parameters may be suggested:

- inlet gas-mixture temperature to the PAR casing,
- inlet hydrogen concentration to the PAR casing,
- surface temperature at the lower part of the catalytic section,
- surface temperature at the upper part of the catalytic section,
- gas temperature above the catalyst housing inside the PAR,
- outlet gas temperature to the PAR casing,
- outlet hydrogen concentration to the PAR casing,
- inlet velocity (flow) of the gas-mixture to the PAR casing,
- concentration of steam in the gas-phase,
- oxygen concentration in the gas-phase,
- carbon monoxide concentration in the gas-phase.

The concentration limit of "catalytic ignition" is determined through two possible mechanisms:

a) "internal mechanism", which is caused by formation of a self-sustaining flame near the "hot spots" of the catalyst, its propagation inside the PAR, leaving the PAR casing and further propagation regardless of the processes inside the PAR,
b) "external mechanism", which is caused by the separation of the catalytic particle from the substrate, its removal outside the PAR casing, entering the area of the PVAC, in which the concentration and temperature are sufficient for catalytic self-heating of an individual particle, ignition of the gas mixture and flame propagation independent of PAR.

So state of "catalytic ignition" of a steam-gas mixture (when the PARS safety limits are exceeded) can be characterized by:

- lower concentration limit of volumetric ignition of a vapor-hydrogen-air mixture caused or induced by heterogeneous catalytic oxidation of hydrogen on the surface of catalytic elements;
- delay of catalytic particle separation or of exit of the flame outside the PAR protective casing after exceeding the hydrogen limiting concentration in the PAR inlet section.

4 Conclusion

The need of a systematic approach to the determination of functional states and processes (modes of operation) of PARs is shown.

The proposed approach seems to be useful for standardizing the requirements for PARs based H_2 mitigation system in the nuclear industry and hydrogen energy and for the development of experimental testing techniques for recombiners.

PARs testing may be required to be performed under univocal and traceable initial and boundary conditions. A minimal set of the parameters of the PARs as a technical system and its environment has been proposed for their performance and safety standardization purposes. The proposed set of parameters is subject of discussion. It should be taking into account the fact that regulatory requirements for installation of PARs based H_2 mitigation system may be specific for different countries.

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