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Proposed methodology for Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building

César Serrano[a,*], Gonzalo Jimenez[b], Mª del Carmen Molina[a], Emma López-Alonso[b], Daniel Justo[b], J. Vicente Zuriaga[c], Montserrat González[c]

[a] Iberdrola Ingeniería y Construcción, S.A.U., Avda. de Manoteras 20 Edif.C, 28050 Madrid, Spain
[b] Universidad Politécnica de Madrid (UPM), Spain
[c] Iberdrola Generación Nuclear, Paraje El Plano s/n., 46625 Cofrentes (Valencia), Spain

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ABSTRACT

The *Stress Tests* accomplished by the European nuclear plants assume to be a complementary and comprehensive review of the safety of nuclear facilities, taking into account the events occurred in Fukushima Daiichi. The analysis of Passive Autocatalytic Recombiners (PARs) installation in Cofrentes NPP (BWR Mark III, 1092 MWe) was a requirement emerged from those tests and developed by Iberdrola Engineering and Construction jointly with Universidad Politécnica de Madrid (UPM). The study established a methodology for location and number of PARs for being installed to minimize the risk arising from an hydrogen release and its distribution in containment building during a severe accident (SA). In this paper, the implementation of this methodology was deeply analyzed for Cofrentes NPP.

The proposed methodology presented herein for PARs installation analysis is divided in four steps: identification of the most limiting scenarios to be simulated with a severe accident code (MAAP4) in order to obtain mass and energy sources (step 1); hydrogen distribution analysis in containment with a 3D containment code (GOTHIC 8.0) (step 2 and 3); and PAR sizing and location analysis (step 4). The most limiting scenarios chosen for a BWR were: Station Blackout (SBO); Total Loss of Feed Water (TLOFW); and Loss of Coolant Accident (LOCA). Several sensitivity analyzes of different PAR sizes and configurations were accomplished, and the most suitable PARs configuration was determined. This optimal configuration consisted in a total of 53 PARs: 47 units placed inside the containment and 6 units in the drywell. For data analysis, an in-house code was developed, providing combustion and deflagration data in a clear and accurate way, showing the combustion windows and their span.

The proposed methodology was established as accurate enough for analysing PARs installation within containment applied to a BWR Mark III. The fact of having a very detailed 3D GOTHIC model allowed creating a strategy of implementation based on the preferred hydrogen pathways and areas of accumulation.

1. Introduction

During a severe accident (SA) in a Light Water Reactor (LWR), large quantities of hydrogen could be generated during the degradation of the reactor core and released into the containment atmosphere. The hydrogen combustion in the containment building represents one of the most significant hazards that could compromise the containment integrity (Kljenak et al., 2012), in fact, different hydrogen combustion events occurred during TMI-II (Kemeny et al., 1979) and Fukushima accidents (NEA, 2013). The latter drawn again the world's attention to the hydrogen combustion risk management (NRC, 2014), launching new international projects (Nishimura et al., 2015). Experiments conducted before 2011 are being reviewed under the new light of Fukushima events (Gupta, 2015; Bentaib et al., 2015).

The methodology posed herein establishes the Passive Autocatalytic Recombiner (PAR) installation, answering the regulatory requirements emerged after Fukushima Daiichi accident (NEA, 2011). The project comprises the hydrogen control during a SA by developing a safety demonstration analysis, which includes the implementation of optimized PARs configuration in containment building.

The PAR performance is based on hydrogen recombination with the oxygen present in the containment atmosphere using certain

* Corresponding author.
E-mail addresses: css@iberdrola.es (C. Serrano), gonzalo.jimenez@upm.es (G. Jimenez), jvzuriaga@iberdrola.es (J.V. Zuriaga).

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metals as catalysts. This method is totally passive and requires studies that might accurately predict the hydrogen pathways to ensure an unimpaired PARs performance. The use of this technology is the most extended strategy to reduce the hydrogen before it could reach flammable concentrations during a SA, particularly during those accidents with loss of electric power supply.

Therefore, a correct simulation of local hydrogen distribution is critical to assess the hydrogen risk adequately (IAEA, 2011). Such a project requires a code able to simulate SA phenomenology, to reproduce 3D containment geometries and PAR performance and; thus, to obtain a more reliable safety analysis.

In order to select the most appropriate tools for this type of analysis, there are several publications that set guidelines to take into account hydrogen distribution and PAR implementation. The IAEA TECDOC-1661 (IAEA, 2011) provides guidance and support in SA management, implementing various strategies regarding hydrogen mitigation. These strategies include the use of catalytic recombiner for hydrogen concentration reduction. Furthermore, this guidance presents a possible PAR configuration including number and location. The use of CFD codes is recommended. The PARSOAR project is a project on hydrogen risk assessment in nuclear power plant containment, focusing on SA risks and development of countermeasures for 'defence-in-depth' (Bachellerie et al., 2003). One of the objectives of this project is to elaborate a handbook aimed at guiding the implementation of hydrogen recombiners in nuclear power plants. After the number and location of these recombiners are defined, a demonstration of the efficiency of the PARs system installation should be carried through by comparing the sequences with and without recombiners, in order to quantify the reduction of the combustion risk. A code with 3D capabilities is essential to simulate complex containment geometry. Finally, the technical reports from the OECD/NEA bring an exhaustive overview of the main simulation tools for hydrogen risk problems, (NEA, 1999) (NEA, 2015).

Three approaches are normally taken when simulating hydrogen management in containment buildings: lumped parameter codes, Computational Fluid Dynamics (CFD) codes and containment codes with 3D capabilities. Also a combination of the previous ones is possible.

The lumped parameters codes, such as MAAP or MELCOR, are more appropriate to simulate large number of SA sequences and phenomenology such as core degradation or hydrogen generation. Nevertheless, those codes cannot predict some of the details of local gas mixing (NEA, 2015). Some studies include hydrogen distribution simulations and combustion risk evaluation using lumped parameter codes and geometrical simplifications. For instance, the study done by (Huang, 2013) in which MELCOR code is used to perform a Passive Autocatalytic Recombiner (PAR) installation analysis in CANDU6 reactors.

On the other hand, CFD codes are able to accurately reproduce 3D thermal–hydraulic containment phenomenology during a SA (NEA, 2015). The capabilities of CFD codes to evaluate hydrogen distribution are intensively assessed in (NEA, 1999), (NEA, 2007). Simulations of large scale facilities with commercial CFD codes are a very challenging task, even though having some successful studies in the past (Martín-Valdepeñas et al., 2007), (Bawens and Dorofeev, 2014), (Prabhudharwadkar et al., 2011), considering the difficulty of simulating the wall condensation and at least three species (air, H_2, and steam) in a large volume of a typical reactor containment (60,000–70,000 m^3). The problem of simulating accurately the wall condensation is that the CFDs need extended modeling capabilities and, usually, very fine computational meshes (NEA, 2014), thus making the calculation of a long SA too demanding computationally. However, some researchers have successfully calculated the wall condensation for geometries simpler than the whole containment (Mimouni et al., 2011).

The use of 3D containment codes, such as GOTHIC, for safety demonstration analyzes has been repeatedly established as a useful tool for hydrogen distribution within the containment and capable to determine local and global hydrogen concentration with a reasonable precision (NEA, 2015). In particular, GOTHIC code has several additional advantages over commercial CFD codes for these issues: it is used for design base accident analyzes, it has several validated wall-condensation models, such as DLM-FM (EPRI, 2012b) and it has all necessary tools for simulations of hydrogen management and distribution with adequate accuracy for location of PARs in SA conditions. Additionally, GOTHIC implements its own recombination model based on efficiency. The 3-D capabilities of GOTHIC to simulate basic flows, and in detail, hydrogen flows for containment analysis, is extensively investigated (EPRI, 2012b), through tests carried out in facilities like PANDA, CSTF, BFMC or CVTR. Dr. Andreani and Dr. Paladino at PSI accomplished a large validation effort against light gas experiments (Paladino et al., 2008; Andreani et al., 2009, 2012; Andreani and Smith, 2003; Andreani and Erkan, 2010; Andreani et al., 2010; Andreani and Paladino, 2010).

Regarding previous analyzes for PARs sizing and location, one of the first analysis is performed for a Belgian NPPs. In this analysis of hydrogen release and distribution, the implementation of PARs is confirmed as a preventive solution (Snoeck and Centner, 1995). A computer code was designed to stablish the PAR efficiency considering hydrogen control systems such as igniters, PARs and containment inertization. The final catalyst area able to prevent hydrogen concentration, which could lead to containment failure, is obtained.

In Germany, the analyzes carried out by Breitung et al. at KIT (Breitung, 1997; Breitung and Royl, 2000; Royl et al., 2000) set a methodology for hydrogen risk and mitigation analysis in SA scenarios using several codes, such as GASFLOW or COM3. The methodology consists of several steps that include the selection of scenarios, hydrogen sources, mitigation and distribution; and finally, combustion regimes analyzes. This methodology is implemented in two German design PWR containments (Royl et al., 2000). An evolution of this methodology is applied later on in the licensing process of EPR in the UK, (HSE, 2011b, 2013; Dimmelmeier et al., 2012). In this case, MAAP4 code is used as a basis code for simulating SA cases, using COCOSYS for cases that need more detail. The author use GASFLOW for the most penalizing scenarios. Cases involving supersonic deflagrations or detonations were simulated with another code called COM3D. KIT researchers also conduct comparative calculations between MELCOR and GASFLOW for calculating hydrogen distribution in a KWU-PWR containment (Szabó et al., 2012).

In Canada, the study from (Chan, 2003) uses GOTHIC to model containment thermal hydraulics and hydrogen transport for licensing of PAR installation of CANDU reactors. GOTHIC is also used for licensing US-APWR reactor of Mitshibishi in USA (Seto, 2010).

In the UK, for the AP1000 licensing process, the calculation of hydrogen generation is performed with GENNY (Westinghouse proprietary code), MELCOR and MAAP4 (HSE, 2011a).

In Croatia, there are different studies for PAR implementation in Krsko NPP conducted by Grgic et al. (2012, 2014a,b)). In these studies, mass and energy sources are obtained using MAAP code and a 3D GOTHIC containment model is developed to predict hydrogen distribution, in order to reach the level of detail needed.

In Hungary, Téchy et al. evaluate hydrogen combustion risk during a SA in Paks NPP (VVER-440) containment type (Téchy et al., 2013). The code used for hydrogen distribution is GASFLOW and the study includes recombiner operation analyzes.

In the Netherlands, Visser et al. (2013) present an ANSYS Fluent analysis of hydrogen distribution and the use of PARs as a mitigation option. The analyzes obtained are compared with the experiment carried out in the large-scale THAI facility in order to

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