Annals of Nuclear Energy 120 (2018) 509–515

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Mitigation of source term in suppression pools: Large uncertainties in predictability ☆

L.E. Herranz *, R. Iglesias, J. Fontanet

Unit of Nuclear Safety Research, CIEMAT, Av. Complutense 40. 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 9 November 2017
Received in revised form 1 June 2018
Accepted 5 June 2018

Keywords:
Fukushima accident
Nuclear safety
Pool scrubbing
Jet regime

ABSTRACT

The Fukushima accident has revived the interest of suppression pools as a passive way to scrub radioactivity from the gas reaching the aqueous volume in case of a severe accident. However, modeling of pool scrubbing is far from being mature. This paper focuses on the scrubbing occurring at the nearby of the injection point and, by illustrating how far from observations prediction can be, it highlights the importance of developing proper models at this region of the pool. To do so, a specific simple ASTEC model has been set-up and a jet scrubbing database has been gathered from the open pool scrubbing literature by picking suitable tests in which all the key initial and boundary conditions were recorded and reported. In particular, low-submergence experiments with high injection velocity experiments have been chosen to address what is known as jet scrubbing (i.e., scrubbing at the inlet region when particles are carried in the pool by a gas submerged jet).

1. Introduction

Suppression Pools were reminded to be a key safety feature of BWR technology by the Fukushima accident (Nuclear Emergency Response Headquarters, 2011). Their performance, though, had been profusely investigated back in the 70′s and 80′s, both as an energy and mass sink (Patterson, 1979; Su, 1981) and later in the 80′s and 90′s as an effective filter for fission products and aerosols (Escudero et al., 1995). Current investigations of the three accidents occurred at the Fukushima-1 site (Herranz et al., 2015a,b; Pellegrini et al., 2015) are highlighting that pools might have strongly affected the accidents unfolding and the resulting source term to the environment.

Recent investigations (Herranz et al., 2014) have pointed out that despite the progress achieved through previous research, there are still knowledge gaps concerning safety-significant phenomena that might dominate radioactive mitigation within aqueous ponds. Among them a few examples may be mentioned: high injection velocities of the carrier gas (i.e., jet injection regime), gas rise hydrodynamics under both bubbly regime (low gas velocity) and churn-turbulent flow (high gas velocity) or the effect of submerged structures. These and other phenomena have been either barely studied in the past or investigated in a non-systematic way, so that no sound model and/or correlation development has been feasible. Some of these phenomena are being studied accounting the results produced by the EU-PASSAM project of the 7th Framework Programme of EURATOM (Lind et al., 2015).

The present paper aims at assessing the ASTEC 2.0 code (Chatelard et al., 2014) capability for modeling pool scrubbing. In particular, the code ability to predict particles retention at the nearby of the injection point at high gas injection velocity, is to be checked against the experimental data available. To do so, a peer review of the database has been previously conducted and the specific useful experiments chosen and fully characterized accordingly with the modeling needs. Given the integral nature of ASTEC, the model built-up to run the code in a sort of stand-alone way is to be also described. This work is part of the CIEMAT contribution to the EU-CESAM project of the 7th Framework Programme of EURATOM.

2. Background

Removal of contaminating particles and/or vapours from a carrier gas passing through an aqueous pond is known as pool scrubbing. The scrubbing or filtration efficiency (η) is usually expressed in terms of the Decontamination Factor (DF), which is defined by the ratio of the aerosols mass entering (m_{in}) and leaving (m_{out}) the pool (or the filtration system):

☆ This work has been done in the frame of EU CESAM project of the EURATOM 7th Frame Work Program.
* Corresponding author.
E-mail address: luisen.herranz@ciemat.es (L.E. Herranz).

https://doi.org/10.1016/j.anucene.2018.06.010
0306-4549/

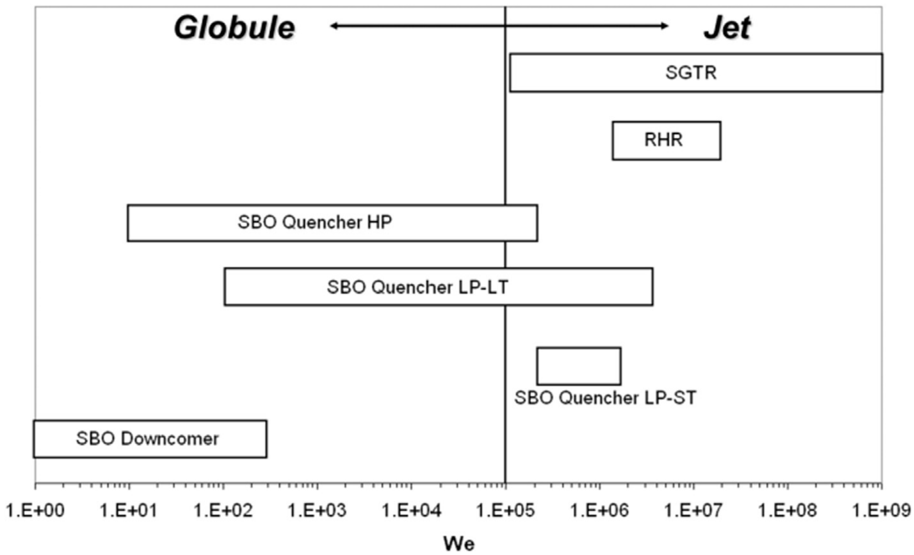

Fig. 1. Map of accident sequences as a function of the injection regimes (SGTR-Steam Generator Tube Rupture, SBO – Station Blackout, RHR-Residual Heat Removal).

$$DF = \frac{m_{in}}{m_{out}} = \frac{1}{1-\eta}$$

Based on the different nature of hydrodynamic and vapour/aerosol phenomena governing the pool scrubbing decontamination, the carrier gas pathway through the aqueous volume is split into three regions: injection, rise and pool surface. Consistently, the overall DF may be written as a multiplication of individual DFs:

$$DF = DF_{inj} \cdot DF_{rise} \cdot DF_{sur}$$

At the injection zone in the pool, the mechanical as well as the thermal gas-liquid interaction determine the scrubbing process. The gas composition and velocity are key variables in this region. The inlet gas regime is usually classified according to the non-dimensional Weber number ($We = \frac{\rho_l \cdot D_{inj} \cdot v_{inj}^2}{\sigma}$) as: jet regime ($We \geq 10^5$) and globule regime ($We < 10^5$), where ρ_l is the pool liquid density, D_{inj} is the injector diameter, v_{inj} is the exit velocity of the gas, and σ the pool liquid surface tension (Flanigan et al., 1983). Under the jet regime liquid drops are entrained in the gas bulk and decontamination through inertial and non-inertial droplet-particles and droplet-vapours interactions is enhanced. At moderate or low gas velocities a globule forms and grows attached to the injection point; until globule detaches, a number of mechanisms contribute also to contamination removal, but their net effect is less than under jet regime. Regardless injection regime, whenever partial steam pressure in the gas is higher than saturation pressure at pool temperature, steam condensation enhances scrubbing. During gas rise through the pool, hydrodynamics heavily affects scrubbing efficiency. Hydrodynamic phenomena in this region (i.e., globule break-up, swarm formation, gas internal circulation, etc.) have been traditionally described through laws governing the bubbly flow regime; however, as gas velocity increases other more stochastic 2-phase flow regimes may develop (i.e., churn-turbulent flow). At the pool surface, bubbles rupture causes micro-droplets. Some of them can be entrained by the gas flow while the others fall back due to their size by gravity. These entrained droplets transport very fine aerosol particles as well as dissolved fission products.

During the 80′s some pool scrubbing codes were developed: SPARC90, BUSCA and SUPRA. In fact, current integral severe accident codes, like MELCOR and ASTEC, do have integrated adaptations of the SPARC code (Owczarski and Burk, 1991). Extensive data-predictions comparisons have since been set (Fischer, 1998; Herranz and Fontanet, 2009), but a systematic validation process has not been feasible due to shortcomings in the available database (Herranz et al., 2014).

In-code implemented models are necessarily based on hypotheses and approximations, some of whom are far simpler than reality. For example, the application of globule formation model to high gas injection velocities, though, is not suitable since anticipated gas-liquid and droplets-particles interactions are drastically different (Berna et al., 2016). Unfortunately, separate effects data are often not available or are too uncertain, so that specific comparisons of model estimates and data cannot be reliably set (uncertainties in pool scrubbing models might result in factors around 100 in the containment radioactivity levels according to Fischer-1998). Therefore, a systematic validation of codes and models would require building up a suitable database for this purpose. This is particularly true for the decontamination near the injection point under high injection velocities (i.e., jet regime), although recently some tentative modeling has been proposed (Berna et al., 2016; Herranz et al., 2013), although it is still in an initial development phase.

3. Data base on "jet scrubbing

As shown in Fig. 1, in some of the most risk-significant severe accident sequences fission products are carried to aqueous ponds at high injection velocities characteristic of submerged jets. Given the high impact of inertial mechanisms at the injection nearby under such conditions (i.e., most radioactive mass is highly likely to be trapped at this pool zone), a thorough validation of the specific codes formulation for such region (DF_{inj}) is essential for analytical tools to gain some credit. For this purpose, a peer review of pool scrubbing database has been carried out. As no specific separate effect tests on "jet scrubbing" have been conducted to the best knowledge of the authors, a number of criteria have been set to choose those experiments from which at least indirect/qualitative insights on these phenomena might be gained:

- High gas velocities ($We \geq 10^5$); target condition of this work.
- Low submergence; minimization of any DF_{rise} contribution to DF, so that measured DFs would mainly correspond to DF_{inj}.