Nuclear Engineering and Technology 48 (2016) 870—880

Available online at ScienceDirect

Nuclear Engineering and Technology

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

Invited Article

Key Findings from the Artist Project on Aerosol Retention in a Dry Steam Generator

*Abdelouahab Dehbi**, *Detlef Suckow, Terttaliisa Lind, Salih Guentay, Steffen Danner, and Roman Mukin*

Nuclear Energy and Safety Research Department, Paul Scherrer Institute, Villigen, PSI 5232, Switzerland

ARTICLE INFO

Article history:
Received 31 May 2016
Accepted 3 June 2016
Available online 22 June 2016

Keywords:
Containment Bypass
Fission Product Retention
Steam Generator Tube Rupture

ABSTRACT

A steam generator tube rupture (SGTR) event with a stuck-open safety relief valve constitutes one of the most serious accident sequences in pressurized water reactors (PWRs) because it may create an open path for radioactive aerosol release into the environment. The release may be mitigated by the deposition of fission product particles on a steam generator's (SG's) dry tubes and structures or by scrubbing in the secondary coolant. However, the absence of empirical data, the complexity of the geometry, and the controlling processes have, until recently, made any quantification of retention difficult to justify. As a result, past risk assessment studies typically took little or no credit for aerosol retention in SGTR sequences. To provide these missing data, the Paul Scherrer Institute (PSI) initiated the **A**e**r**osol **T**rapping **I**n **S**team Genera**T**or (ARTIST) Project, which aimed to thoroughly investigate various aspects of aerosol removal in the secondary side of a breached steam generator. Between 2003 and 2011, the PSI has led the ARTIST Project, which involved intense collaboration between nearly 20 international partners. This summary paper presents key findings of experimental and analytical work conducted at the PSI within the ARTIST program.

1. Introduction

Despite improvements in steam generator (SG) design and in manufacturing and modes of operation, steam generator tube rupture (SGTR) events occasionally occur during pressurized water reactor (PWR) operation, which underlines the need to pay particular attention to these sequences. Steam generator tubing can undergo several degradation processes that can cause cracking, wall thinning, leakage, or even rupture [1]. A particular safety challenge arises from an SGTR in combination with other failures so that a core melt results by which radioactive fission products may be transported by

* *Corresponding author.*
E-mail address: abdel.dehbi@psi.ch (A. Dehbi).
http://dx.doi.org/10.1016/j.net.2016.06.001

a direct path to the environment. Sequences of this kind are referred to as "containment bypass" and, despite their low probability, they represent a significant or even dominant contribution to the overall public risk. Probabilistic safety assessments typically take little or no account of any retention of fission products on the SG secondary side [2], although the complex geometry of the tube bank, support plates, separators, and dryers provides a large surface area on which fission products may be trapped. The presence of liquid water in the SG bundle may further augment retention. However, the processes that control retention are complex and no reliable models or empirical data exist with which to perform assessments.

During 2000–2002, the Steam Generator Tube Rupture Project was performed within the European Union 5th Framework Program [3, 4]. The project generated a database on aerosol retention in PWRs and in VVR-type SGs, which allowed the verification and development of predictive models in support of accident management interventions in SGTR sequences. A primary outcome of the SGTR Project was that models for turbulent deposition, which dominates the removal mechanisms in dry conditions, are prone to substantial uncertainty. The project also showed that considerable aerosol retention can be expected, even with moderate water levels above the breach. In conclusion, the project indicated areas in which more data of separate effect nature are needed to provide a satisfactory understanding of aerosol removal phenomena in SGTR sequences.

Based on these outlined needs, an international collaborative project, called **A**e**r**osol **T**rapping **I**n **S**team Genera**T**or (ARTIST) Project, was performed between 2003 and 2011 and involved nearly 20 partners. The primary goal of the project was to experimentally determine aerosol and droplet retention in the SG within an eight-phase program. The experimental investigations were supported by analytical work and models were developed, based on the acquired experimental data. The final aim of the project was to gain an international consensus on the treatment of source term resulting from an SGTR.

As a prelude to the ARTIST Project, a reference calculation was performed to determine the boundary conditions for an assumed SGTR in a PWR, leading to core uncovery and melting and subsequent fission product release [5]. An SGTR with other failures leading to core damage was chosen as the base sequence because it is a major risk contributor in probabilistic safety assessment studies [2]. The calculations were performed using the SCDAP/RELAP5 code (INEEL, Idaho Falls, USA). In addition, fission product release was calculated using the SASPROG code (NRC, USA). The initiating fault in the calculations was a double-ended guillotine break near the bottom of one SG tube on the hot side. The operator assumedly does not reduce the primary side pressure, thereby resulting in the loss of coolant inventory, but the emergency coolant systems function normally.

The calculations showed that during fission product release, the primary pressure was ~0.5 MPa and the faulted SG secondary side pressure was 0.1 MPa. The break mass flow rate was ~900 kg/h at the time of interest, and the gas temperature was 1,000 K. These values were used to define the base–case boundary conditions for the ARTIST experimental program. Preservation of the jet momentum out of a one-diameter equivalent breach leads to a room temperature nitrogen (N_2) flow with a primary pressure of 3 bars discharging into the ambient environment. This translates into a gas flow rate of ~360 kg/h in the ARTIST mock-up. Under actual conditions, the carrier gas is superheated steam, which is too hot to condense on the structures. Hence, our use of N_2 gas as a surrogate is realistic and practical.

The chosen scenario is characterized by relatively small breach flows, and hence limited recirculation in the dry bundle. Other scenarios using a higher primary pressure will lead to higher flow rates, and hence higher recirculation, with potentially increased aerosol retention.

2. The ARTIST program phases

The ARTIST Project consisted of eight distinct phases, which are summarized as follows.

Phase I: Aerosol retention in SG tubes under dry conditions. In this phase, in-tube aerosol deposition/resuspension is studied under high flow conditions. Tube length, bend curvature, and aerosol type, size, and concentration are varied.

Phase II: Aerosol retention in the break vicinity under dry conditions. In this phase, aerosol deposition/resuspension at very high velocities is addressed. The break gas flow rate, break type (e.g., fish-mouth, double-guillotine) and aerosol size are varied.

Phase III: Aerosol retention in the bundle far from the break under dry conditions. The gas flow rate and aerosol size are varied.

Phase IV: Aerosol retention in the separator and dryer under dry conditions. This phase studies aerosol impaction and interception due to complex three-dimensional (3D) flows in the upper components of the SG. The gas flow rate and aerosol size are varied.

Phase V: Aerosol retention in the bundle section under flooded SG secondary side conditions when the break is submerged. This phase investigates aerosol scrubbing by the SG water pool and inertial impaction on the structures. The break flow rate, pool submergence, and aerosol size are varied.

Phase VI: Droplet retention in the separator and dryer sections under dry conditions. This phase deals with design basis accident (DBA)-type phenomena (i.e., the potential for "primary bypass") whereby a break at the top of the tube bundle sprays fine primary liquid droplets that may find their way into the environment through a stuck-open safety valve. In this phase, the carrier gas flow rates and droplet sizes are varied.

Phase VII: Integral tests. The seventh set of experiments is integral and is focused on aerosol retention in the whole model SG under dry conditions.

Phase VIII. Flooded separator. During this phase the secondary side is flooded up to the separator outlet, corresponding to the wide range of level measurement during SG filling. The additional effect of the SG separator internals on aerosol retention was studied.