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Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior

Final Project Summary for the U.S. Department of Energy

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Timothy Beville, Program Manager
Office of Nuclear Energy
U.S. Department of Energy

EPRI Project Manager
R. King

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Pittsburgh Technical LLC.
The Hastings Group, LLC
LPI, Inc.

NOTE

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The following organizations, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Pittsburgh Technical LLC.
9687 Babcock Blvd.
Allison Park, PA 15101

Principal Investigator
Sola Talabi Ph.D.

The Hastings Group, LLC
1915 Ewing Avenue, Suite 3
Charlotte, NC 28203

Principal Investigator
Peter Hastings

LPI, Inc.
36 Main Street
Amesbury, MA 01913

Principal Investigator
Gregory Zysk

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ABSTRACT

Under assumed severe accident conditions, a nuclear reactor’s containment vessel provides a defense-in-depth function by preventing radionuclide particle release. This is achieved by creating a physical barrier and by decontamination (removal of aerosolized particles produced during the accident). Decontamination occurs through active mechanical systems (where applicable) and passive natural occurring phenomena. Due to their comparatively higher containment surface area to volume ratios when compared to large light water reactors (LWRs), the integrated pressurized water reactor (iPWR) subcategory of small modular reactors (SMRs) has design features that increase the significance of the passive decontamination factors, due to the following natural occurring phenomena: gravitational settling, thermophoresis, diffusiophoresis, and impaction due to convective flows. The purpose of this study is to provide estimates for the decontamination associated with these phenomena. Specifically, these results provide decontamination factors associated with the thermal-hydraulic and geometric parameters that characterize iPWRs, based on the experimental work documented in this report.

Keywords

Integrated pressurized water reactor (iPWR)
Small modular reactor (SMR)
Aerosol
Decontamination
Passive containment
Phoresis

REPORT SUMMARY

It has been evaluated that the radiological source terms associated with a Small Modular Reactor (SMR) may be significantly different from that associated with a Large Light Water Reactor (LLWR) (EPRI 3002004218). Source terms are influenced by radionuclide inventory in the core, and the in-containment vessel environment, including the geometry. SMR designs with an integrated containment vessel (CV), called Integrated Pressurized Water Reactors (iPWR) have CV volumes that are significantly smaller than LLWRs. Currently in the US, there are four major iPWR designs that have been advertised, i.e., by NuScale, BWX Technologies (mPower), Westinghouse, and Holtec. International designs include SMART (Korea) and CAREM (Argentina).

A typical iPWR CV volume is about an order of magnitude smaller than that of LLWRs and, consequently, this creates a larger deposition surface area to volume ratio, which is a parameter that supports in-vessel particle deposition for higher ratios. The surface deposition is further enhanced for iPWRs immersed in water, due to the creation of a thermal gradient and condensation on the CV wall surface. The thermal gradient creates three effects that enhance deposition mechanisms: thermophoresis due to a difference in temperature, diffusiophoresis due to a difference in steam concentration, and convective flows due to the temperature difference between the hotter reactor vessel (RV) wall and the cooler CV wall. Gravitational settling as a deposition mechanism has also been identified as potentially being more significant for iPWR designs with relatively clean stainless-steel CVs, which may result in higher aerosol densities due to reduced or eliminated interaction with concrete and debris in the vessel. These identified deposition mechanisms are passive in nature and are particularly significant for iPWRs because these designs have largely eliminated some of the active mechanical systems such as containment vessel sprays.

Prior studies (EPRI 3002004218) suggest that these passive mechanisms are likely to result in higher post-accident decontamination factors (DF) as compared with those assumed for LLWRs. The objective of this study, performed in collaboration with the U.S. Department of Energy, is to develop estimates of the aerosol removal rates associated with the passive deposition mechanisms for an expected range of geometric and thermal-hydraulic parameters that are characteristic of iPWR designs. These aerosol removal rates are used to calculate DFs. To capture a wide range of thermal-hydraulic and design parameters for iPWR designs, the aerosol removal rates are determined with the use of an experimental test loop and CFD simulations. The experimental test loop provides for results over a range of iPWR design parameters and benchmarks the CFD model, which is then used to provide estimates for a wider range of parameters.

The study has two major parts, which include: 1) Development of the technical basis to estimate iPWR aerosol decontamination factors with experiments and CFD simulations, and 2) Development of iPWR aerosol decontamination factor estimates based on execution of experiments and CFD simulations.

Following are the executive summaries from the two final reports completed for this project. The final reports are publicly available at no cost from www.epri.com.

Deliverable Number: 3002010491

Product Type: Technical Report

Product Title: Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior: Phase 2a - Technical Basis and Test Plan for Experimental Testing and Computational Fluid Dynamics Analysis

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PRIMARY AUDIENCE: iPWR designers and safety analysis professionals.

SECONDARY AUDIENCE: Regulatory agencies.

KEY RESEARCH QUESTION

Due to their comparatively higher containment surface area to volume ratios when compared to large light water reactors (LWRs), the integrated pressurized water reactor (iPWR) subcategory of small modular reactors (SMRs) includes design features that increase the significance of the passive decontamination factors, due to the following natural occurring phenomena; gravitational settling, thermophoresis, diffusiophoresis, and impaction due to convective flows. The increase in potential decontamination factors opens the possibility for a reduced public exposure in accident scenarios.

EPRI released a Phase I study in 2014, EPRI 3002004218, Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior, Phase 1 – Test Plan Development, that identified the critical natural deposition mechanisms and examined the potential for reduced source terms.

The purpose of this continuing study (Phase 2) is to provide estimates for decontamination associated with these phenomena.

RESEARCH OVERVIEW

This study builds on the Phase 1 study, with an objective to develop estimates of the decontamination factors associated with the natural deposition mechanisms. Estimation of the decontamination factors is performed by experimentally measuring the aerosol decontamination rates associated with the natural deposition mechanisms along with simulation of these mechanisms with a computational fluid dynamics (CFD) code. This interim report provides the details for experimental test planning and preliminary CFD analysis

KEY FINDINGS

This report presents the outcomes of the first part of the study, development of the technical basis to estimate iPWR aerosol decontamination factors with experiments and CFD simulations. The major outcomes include development of a CFD model; an experimental test plan; and the design, fabrication, and commissioning of an experimental test loop. A summary of the activities and critical documents associated with these outcomes is presented in this report.

The final outcomes of this study will include the estimates of the decontamination factors associated with the natural deposition mechanisms, based on experiments being conducted at the time of issuance of this document

WHY THIS MATTERS

This work will assist the nuclear industry by providing improved analytical correlations to model aerosol decontamination for iPWR-specific, post-accident, thermal-hydraulic environments and design configurations. Improved correlations are expected to result in a more realistic calculation of containment aerosol natural deposition.

HOW TO APPLY RESULTS

Users may apply the results of this work, in concert with a coming and subsequent final report by modification or development of CFD models to estimate design specific aerosol decontamination factors.

LEARNING AND ENGAGEMENT OPPORTUNITIES

EPRI is performing this work in collaboration with the U.S. Department of Energy. The final report containing experimental results is targeted for early 2018.

EPRI CONTACTS: Ron King, Program Manager, rking@peri.com

PROGRAM: Advanced Nuclear Technoloy

IMPLEMENTATION CATEGORY: Reference - Technical Basis

Deliverable Number: 3002013032

Product Type: Technical Report

Product Title: Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior: Phase 2b – Results and Analysis

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PRIMARY AUDIENCE: iPWR designers and safety analysis professionals.

SECONDARY AUDIENCE: Regulatory agencies.

KEY RESEARCH QUESTION

Due to their comparatively higher containment surface area to volume ratios when compared to large light water reactors (LWRs), the integrated pressurized water reactor (iPWR) subcategory of small modular reactors (SMRs) has design features that increase the significance of the passive decontamination factors, due to the following natural occurring phenomena: gravitational settling, thermophoresis, diffusiophoresis, and impaction due to convective flows. The increase in potential decontamination factors opens the possibility for a reduced public exposure in accident scenarios.

EPRI released a Phase I study in 2014, EPRI 3002004218, Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior, Phase 1 – Test Plan Development, that identified the critical natural deposition mechanisms and examined the potential for reduced source terms.

EPRI released an additional study in January 2018, EPRI 3002010491, *Advanced Nuclear Technology: Integrated Pressurized Water Reactor (iPWR) Containment Aerosol Deposition Behavior – Phase 2a: Technical Basis and Test Plan for Experimental Testing and Computational Fluid Dynamics Analysis*. This study provided the requirements definition and technical basis for examining iPWR aerosol deposition mechanisms and estimating decontamination factors using experimental data and CFD simulations.

This Phase 2b report provides results for the final phase, which includes an estimation of iPWR decontamination factors based on a series of experiments and CFD simulations.

RESEARCH OVERVIEW

This study builds on the Phase 1 and Phase 2a studies, with an objective to develop estimates of the decontamination factors associated with natural deposition mechanisms. Estimation of the decontamination factors is performed by experimentally measuring the aerosol decontamination rates associated with the natural deposition mechanisms along with simulation of these mechanisms with a computational fluid dynamics (CFD) code. This final report provides the iPWR decontamination factors, along with the process by which they are determined, which includes details for experimental tests conducted and CFD simulations.

KEY FINDINGS

The results of this study indicate that the iPWR decontamination factors are significantly higher compared to larger, more traditional containments, and in the range of decontamination factors for containment vessel spray systems in large reactors.

This important finding is substantiated by additional findings related to the significance of deposition mechanisms that contribute to the higher decontamination factor. Specifically, convective flow was identified as an additional and significant particle transport and deposition mechanism, while thermophoresis and diffusiophoresis are also shown to be more significant for iPWRs due to higher thermal and steam concentration gradients, respectively.

WHY THIS MATTERS

This work will assist the nuclear industry by providing improved analytical correlations to model aerosol decontamination for iPWR-specific, post-accident, thermal-hydraulic environments and design configurations. Improved correlations are expected to result in a more realistic calculation of containment aerosol natural deposition.

HOW TO APPLY RESULTS

Users may apply the results of this work by modification of existing methods or development of CFD models to estimate design specific aerosol decontamination factors.

LEARNING AND ENGAGEMENT OPPORTUNITIES

EPRI performed this work in collaboration with the U.S. Department of Energy.

EPRI CONTACTS: Ron King, Program Manager, rking@peri.com

PROGRAM: Advanced Nuclear Technoloy

IMPLEMENTATION CATEGORY: Reference - Technical Basis

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