DEVELOPMENT OF ALTERNATE METHODS OF DETERMINING INTEGRATED SMR SOURCE TERMS

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EXECUTIVE SUMMARY

The Nuclear Energy Institute (NEI) Small Modular Reactor (SMR) Licensing Task Force (TF) has been evaluating licensing issues unique and important to iPWRs, ranking these issues, and developing NEI position papers for submittal to the U.S. Nuclear Regulatory Commission (NRC) during the past three years. Papers have been developed and submitted to the NRC in a range of areas including: Price-Anderson Act, NRC annual fees, security, modularity, and staffing. In December, 2012, NEI completed a draft position paper on SMR source terms and participated in an NRC public meeting presenting a summary of this paper, which was subsequently submitted to the NRC.

One important conclusion of the source term paper was the evaluation and selection of high importance areas where additional research would have a significant impact on source terms. The highest ranked research area was iPWR containment aerosol natural deposition. The NRC accepts the use of existing aerosol deposition correlations in Regulatory Guide 1.183, but these were developed for large light water reactor (LWR) containments.

Application of these correlations to an iPWR design has resulted in greater than a ten-fold reduction of containment airborne aerosol inventory as compared to large LWRs. Development and experimental justification of containment aerosol natural deposition correlations specifically for the unique iPWR containments is expected to result in a large reduction of design basis and beyond-design-basis accident source terms with concomitantly smaller dose to workers and the public. Therefore, NRC acceptance of iPWR containment aerosol natural deposition correlations will directly support the industry's goal of reducing the Emergency Planning Zone (EPZ) for SMRs.

Based on the results in this work, it is clear that thermophoresis is relatively unimportant for iPWRs. Gravitational settling is well understood, and may be the dominant process for a dry environment. Diffusiophoresis and enhanced settling by particle growth are the dominant processes for determining DFs for expected conditions in an iPWR containment. These processes are dependent on the area-to-volume (A/V) ratio, which should benefit iPWR designs because these reactors have higher A/Vs compared to existing LWRs.

INTRODUCTION

The objective of this project is to evaluate relevant aerosol deposition experimental data and analytical correlations that were generated since 1993 for relevance to iPWRs. In addition, each of the natural aerosol removal phenomena (i.e. coagulation, condensation, phoretic, and diffusive deposition) will be analyzed for applicability to expected geometries, dimensions, and post accident transient thermal-hydraulic conditions in iPWR containments. If determined to be appropriate, a new set of experiments to support iPWR unique conditions will be developed. In addition, the applicability of correlations and conclusions in NUREG/CR-6189 for natural aerosol deposition to iPWRs will be assessed. If necessary, with new experimental data, the project may recommend the revision of correlations that model natural deposition mechanisms for iPWR applicability.

The tasks that were performed for this project are:

Task 1: Develop a range of iPWR containment design and post-accident transient thermal hydraulic conditions.

Results - a review of common containment features and accident parameters expected to affect aerosol behavior was conducted with three of the existing iPWR designs. This generic model was used by the remaining tasks to ensure the work was relevant to the expected design conditions of the proposed iPWRs

Task 2: Complete review of all available U.S. and international post-1993 aerosol deposition test data for applicability to iPWR containment post-accident conditions and geometries.

Results - The Project reviewed 23 experiments that have been conducted to validate post-accident reactor containment aerosol models that are not currently considered in regulations. The project also reviewed the relevance to IPWRs on each test based on the important phenomena for IPWRs.

Task 3: Complete review of correlations for coagulation, condensation, phoretic, and diffusive deposition mechanisms and evaluate applicability to iPWR containment design and expected post-accident conditions.

Results - The project investigated the relative importance of settling, thermophoresis, diffusiophoresis, and enhanced settling due to condensational particle growth on the deposition of aerosol in a containment. The deposition velocity and hence the decontamination factor depends greatly on the steam concentration. Without significant steam in the containment, settling alone is a slow but dominant deposition process for particles larger than a micrometer in diameter. With steam, two phenomena may occur that significantly increase the decontamination factor. First, steam can condense on colder walls, and the steam concentration gradient forces particles to the wall. This diffusiophoresis process is independent of particle size and increases significantly with increasing A/V and increasing steam mole fraction. The second phenomenon with steam is the potential for growing particles by condensation on to the particles. This may occur due to a supersaturated condition, or if the particle is water soluble. Water soluble material have a lower water vapor pressure just above the particle, and can remove water from the atmosphere even for unsaturated environments. In either case, the DF after about 2 hours can be more than a factor of 10 for expected atmosphere and wall temperatures, A/V greater than about 1 m-1, and steam mole fractions of 0.1. For more detailed analysis a thermal-hydraulics calculation is needed to determine the conditions in the containment.

Based on the results in this work, it is clear that thermophoresis is relatively unimportant for iPWRs. Gravitational settling is well understood, and may be the dominant process for a dry environment. Diffusiophoresis and enhanced settling by particle growth are the dominant processes for determining DFs for expected conditions in an iPWR containment. These processes are dependent on the area-to-volume (A/V) ratio, which should benefit IPWR designs because these reactors have higher A/Vs compared to existing LWRs. The steam concentration can be well modeled with MELCOR and provides input to models of diffusiophoresis and enhanced settling.

Task 4: Evaluation of need for additional iPWR containment aerosol tests and revisions to aerosol deposition correlations for iPWRs

Results - This project developed a set of experiments that will, for the first time with emphasis on IPWRs, experimentally evaluate several aerosol deposition processes. The thrust of these experiments will verify the diffusiophoresis and hygroscopic effects for a range of conditions that are appropriate for current IPWR designs. Prior work, notably the LWR Aerosol Containment Experiments (LACE) and AeRosol Trapping In a Steam generator (ARTIST) Project experiments, were designed to collect data for traditional LWR designs. The purpose of this work is to improve the understanding of aerosol behavior in high risk accident situations. The experiments proposed by this project will be used in iPWR risk assessments studies for both containment bypass and in-containment failure events.

The range of experiments proposed here examines the result of severe accidents releasing radionuclides as aerosols to the containment and includes the effects of aerosol transport, entrainment and decontamination. The results from these experiments will increase the understanding of the decontamination factors for iPWRs, providing a knowledge base to decrease the excess conservatisms currently used in projected source terms and related dose rates for iPWR designs.

RESULTS AND DISCUSSION

Currently, there are four Integrated Pressurized Water Reactor (iPWR) designs (a type of small modular reactor or SMR) being developed in the U.S. with planned CY 2015-2016 license applications to the USNRC. A unique iPWR design feature that can significantly affect design basis and beyond-design-basis accident radiological source terms is its relatively small containment volume. The iPWR containment volume is about two orders of magnitude smaller than that of current generation large PWRs. The smaller volume has concomitantly smaller horizontal and vertical dimensions and a larger surface area to volume ratio as compared to large PWR containments. In some iPWR designs, the containment is an evacuated steel vessel which is designed to accommodate higher LOCA pressures than large PWR containments. In addition to the physical reduction in containment size, some iPWR designs incorporate a steel containment that is immersed in a large pool of water for the removal of decay heat passed through the steel containment.

The large thermal gradient between the containment and the pool during a LOCA can lead to stratification of particulates at the boundary, impacting fission product transport and atmospheric dispersion. This phenomenon is complicated by the temporal dependence on particulate sizes that subsequently impact removal phenomenon. Many modern severe accident codes assume instantaneous fluid mixing inside the containment during and after a pipe break. This approximation holds true in the large containment volume of current PWRs. The expected dimensions and increase equipment/structure density inside of containment will decrease the accuracy of such approximations.

In the case of some iPWR designs, high pressure vent or recirculation valves are used to release/return cooling water between the integral reactor vessel and the containment volume. By accounting for the containment wall juxtaposition to such valves, fission product aerosol plating phenomenon and possible aerosol jetting scenarios can be more accurately simulated. All iPWR containments have no spray, fan cooler, or ice condenser systems for airborne radioactivity reduction. USNRC Regulatory Guide (RG) 1.183, Appendix A, Section 3.2 allows for airborne radioactivity (aka aerosol) containment natural deposition credit. RG 1.183 refers to NUREG/CR-6189 and its models in the RADTRAD computer code as acceptable containment natural process aerosol removal models. These models are based on experimental and analytical data from 1978 through 1993 and were developed for large PWR and BWR designs of 1000 MWt to 4000 MWt core thermal power. The significantly different iPWR containment volumes, surface areas, aerosol flow velocities, drop heights, and other physical features will have different aerosol natural deposition characteristics than current large PWRs. Extrapolation of current natural containment aerosol models to iPWR conditions can significantly affect the accident source term which is the only means by which airborne radioactivity can be reduced in-containment for these designs.

NUREG/CR-6189 identifies the following natural in-containment aerosol removal phenomena: coagulation (composed of gravitational, Brownian, turbulent diffusion, and turbulent inertial components); condensation (composed of the free molecular, continuum and transition regimes); sedimentation; phoretic (composed of diffusiophoresis and thermophoresis components); and diffusive deposition. Many thermal-hydraulic parameters are assumed to be in the range that applies to large LWRs in NUREG/CR-6189. A final phenomenon that could prove of interest in the integrated thermal-hydraulic behavior of iPWRs (as compared to current LWRs) is the thermal source term in-containment fission product movement. This phenomenon has arguably received inadequate attention though such movement could contribute up to a quarter of the heat load.

The objective of this project was to evaluate relevant aerosol deposition experimental data and analytical correlations that were generated since 1993 for relevance to iPWRs. In addition, each of the natural aerosol removal phenomena (i.e. coagulation, condensation, phoretic, and diffusive deposition) were analyzed for applicability to expected geometries, dimensions, and post accident transient thermal-hydraulic conditions in iPWR containments. A new set of experiments to support iPWR unique conditions was developed. In addition, the applicability of correlations and conclusions in NUREG/CR-6189 for natural aerosol deposition to iPWRs was assessed. If necessary, with new experimental data, the project may recommend the revision of correlations that model natural deposition mechanisms for iPWR applicability.

This project identified post-1993 available experimental data as well as additional experimental data needs and analytical correlation requirements to properly model unique design features and transient containment post-accident thermal-hydraulic behavior in iPWRs. This project is also expected to benefit current large LWRs by identifying more recent experimental data that can be used to justify improved analytical correlations for modeling containment natural aerosol deposition mechanism that apply to large LWR containments as well as iPWR containments. Such experimental and analytical revisions are expected to result in a more realistic calculation of containment aerosol natural deposition and concomitant reduction of source term for both design basis (intact containment) and beyond-design-basis (delayed containment failure) accident sequences.

Based on the results in this work, it is clear that thermophoresis is relatively unimportant for iPWRs. Gravitational settling is well understood, and may be the dominant process for a dry environment. Diffusiophoresis and enhanced settling by particle growth are the dominant processes for determining DFs for expected conditions in a iPWR containment. These processes are dependent on the area-to-volume (A/V) ratio, which should benefit iPWR designs because these reactors have higher A/Vs compared to existing LWRs.