

Review of Radionuclide Behavior in the Sodium Pool for MST Analysis

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1. Introduction

To get a license of a commercial nuclear power plant, it is essential to ensure the safety of the public and environment by providing protections against the release of radionuclides. As part of the process to prove the safety of a nuclear plant design, the source term is analyzed. Source term is defined as the release of radionuclides from the fuel and coolant into the containment, and subsequently to the environment, following a severe reactor accident where a significant portion of the reactor core has melted. Even though nuclear plant power source term analyses often used a deterministic, bounding, and conservative assessment of radionuclide release, regulations of nuclear plant source term have been developed to apply more realistically with the knowledge state and technics. The regulation of the source term for the Post Generation Sodium Fast Reactor is not yet determined which one is applied.

TID-14844 defined the source term for a maximum credible accident at an LWR based on the current state of knowledge at the time of its publication in 1962[1]. And NUREG-1465 addressed the limitations of TID-14844 by developing unique releases for BWRs and PWRs based on accident scenarios from NUREG-1150 and supplemental analyses[2]. NUREG-1465 also includes timed-releases with credit for engineered safety features along with uncertainty analyses. USNRC began formally addressing the use of mechanistic source terms (MSTs) in advanced reactor licensing with the issuance of SECY-93-092 following a request from the Commission for a review of the state-of-the-art of source term analyses [3].

For this MST analysis it is needed to assess radionuclide behavior released from the fuel fins to environment via containment. This paper presents only the radionuclide behavior in sodium pool to assess MST analysis.

2. Source Term History

2.1 MST analysis methodology

The MST calculation will be performed using parallel methodologies, as shown in Figure 1[4]. First, a mechanistic calculation, using available best-estimate tools (codes) and models, will attempt to realistically characterize the radionuclide release and offsite consequences of a severe accident. This calculation

includes the analysis of uncertainties and their impact on the resulting metrics. The transport of radionuclides during a severe accident can be divided into several phases, as shown in Figure 1. The accident begins and the fuel within the core is subsequently damaged. This is followed by the release of radionuclides from the damaged fuel, and their transport/retention in the sodium pool. From there, some radionuclides may migrate to the cover gas region, and subsequently to containment, and can be released to the environment. The final phase is the dispersion of radionuclides from the containment.

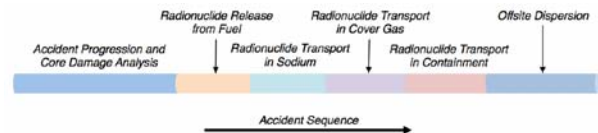


Figure 1. Source term analysis sequence [4].

2.2 Physical/Chemical Phenomena in Sodium Pool

The nomenclature shown in Figure 2 is used to represent the phase transitions of elements. This is important as radionuclides may change phases as they are released from the fuel pin and transport to relatively cooler regions in the sodium pool like structure or cover gas region. The vapor is used for a substance in the gas phase but at a temperature lower than its critical point. In the case of unsaturated vapor, saturation will occur near the cold surfaces, and deposition will begin. And aerosols are suppressed when passing through sodium pools. This is because the large rising bubbles of vapor will collapse or break up as they move upward through the pool of sodium. This breakup is a result of a combination of phenomena including condensation of sodium vapor, mechanical shearing on the upper internals, and reflected shock waves at the bottom of the reactor head.

In addition, mechanical deposition and adsorption may occur at different stages of radionuclide transport. The mechanical deposition is used to differentiate the deposition of particles onto surfaces due to gravitational settling, impaction/interference, diffusion, and thermophoresis from the phase change of deposition. And adsorption is used interchangeably with plate-out to refer to the adhesion of elements/compounds from a liquid or gas onto a surface. It is different from mechanical deposition since it implies a bonding between the surface and the adsorbed liquid or gas.

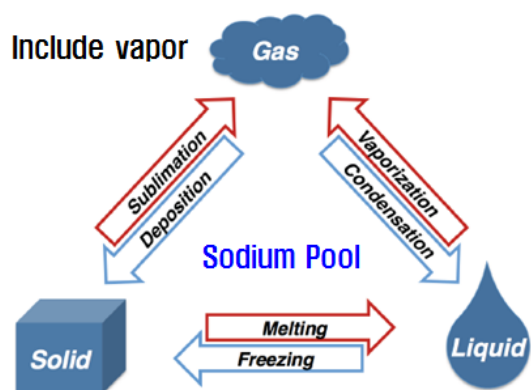


Figure 2. Phase Change Terminology [5].

2.3 Radionuclides Behavior in a Sodium Pool

The sodium pool may contain radionuclides from several sources, as shown in Figure 3, including activated sodium, corrosion products, tritium, and fission products from failed fuel pins.

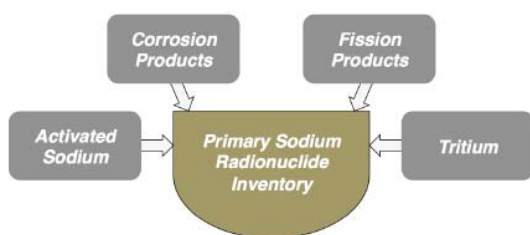


Figure 3. Radionuclides Sources in a Sodium Pool [5].

2.3.1 Activated Sodium

Natural sodium is composed entirely of the stable isotope ^{23}Na . The radioactive inventory in the sodium pool includes radioisotopes that are produced by activation of the stable isotope ^{23}Na by neutron absorption. Within the pool, ^{24}Na can be produced by the reaction $^{23}\text{Na}(n, \gamma)^{24}\text{Na}$. In smaller quantities, the longer-lived isotope ^{22}Na , a half-life of 2.6 years, can be produced by $(n, 2n)$ reactions. Impurities in reactor-grade sodium are not considered to have a significant effect on the activity levels [6]. And the possibility of a loss of coolant is potentially impacted with the inclusion of guard vessels for pool-type configurations.

2.3.2 Corrosion Products

Since type-300 stainless steel has historically used for constructing the core component, the activation of corrosion products is likely. In particular, the creation of ^{51}Cr , ^{54}Mn , ^{59}Fe , ^{58}Co , ^{60}Co , and ^{182}Ta are all possible [6].

2.3.3 Tritium

Tritium is produced by ternary fission in the fuel and

can be found in the sodium pool because of diffusion through the cladding [7]. Because the characteristic of tritium which is highly mobile to diffuse through structure, it is not a major concern. The level of tritium within the sodium pool depends on the operational conditions, plant layout, and hydrogen sources. For most pool-type SFRs, tritium may escape the sodium pool through transport to the cover gas, through the heat exchangers to the intermediate sodium loop, through structure, and by removal through the cold trap.

2.3.4 Fission Products

Fission products and fuel can also be found in the sodium pool after fuel pins are failed. These are stochastic fuel pin failures that have occurred due to structural imperfections, not due to core conditions outside of normal operation. The concern of the release is cesium and iodine, which have are high solubility in the sodium. Once released from the fuel pin, the behavior of radionuclides within the primary sodium is Complex.

During operation the largest contributor is the activity of ^{24}Na , however this ^{24}Na quickly diminishes due to its short half-life. Radionuclides, which are ^{22}Na , ^{131}I , ^{137}Cs , ^{134}Cs , and ^3H , may be the other main contributors. And these fission products are released from the failed fuel pins in the form of a gas/vapor or solid.

2.3.4.1 Vapors and Gas

Vapors and gases released from the failed fuel pins have differing fates depending on the vapor pressure and solubility of the particular element or compound in the sodium pool. Gases or vapors with high vapor pressure and low sodium solubility, like noble gases, will be directly transported to the cover gas region through the sodium pool. Some vapors may condense completely to the liquid phase when they contact with colder sodium. And then they could dissolve to the sodium pool or nucleate within a bubble. When vapor bubble nucleate and rupture the droplets into much finer droplets, some of these droplets may be of aerosol dimensions. The vapor recondensation is a major-phenomenon in the expansion and collapse of a small vapor bubble. For larger bubbles there is an important scale effect. It is likely that the bubble would undergo a few oscillations before it reaches the cover gas region. There is a mechanism that would reduce the fuel aerosol source term. Heat loss from the bubble to the cold surroundings would cause fuel vapor condensation as well as a reduction in the bubble pressure. If the heat loss is sufficiently large during the expansion and migration of the bubble, the bubble would collapse in the sodium pool before it rises to the cover gas region. If the bubble collapses due to condensation of the fuel vapor before it reaches to the cover gas region, all the

fuel vapor in the bubble would be harmlessly dispersed in the sodium pool [8]. The re-condensation rate is much decreased when the bubble contains non-condensable gas well mixed with the vapor, even considering turbulent motions. In a rising bubble the small aerosols remain suspended for a long time, therefore they are probably transferred to the cover gas region [9].

Other vapors with high solubility of the element or compound in sodium will directly dissolve in the sodium pool from the gas phase. Adsorption of the dissolved vapors onto structure in the sodium pool may occur.

2.3.4.2 Solid - Particulates

The phenomena of particulates released to a sodium pool are shown in Figure 4. Particulates that are released from the fuel pin could be entrapped within a vapor or gas bubble. These particulates may settle on or migrate to the surface of the bubble and interact with the sodium; the same outcome will occur if the bubble collapses as the vapor condenses when colder sodium is encountered. When the particle strikes the surface of the bubble, it can oscillate and finally float within the bubble (because of the interfacial, tension) or it can be transported into the cold liquid (sodium pool). For a particle at an Ar-Na interface, floating is found to be the most probable event (particles smaller than 2.6 mm float whatever the speed of impact) [9].

The particulates may dissolve in the primary sodium or become entrained in the moving sodium stream. The particular phenomenon that will be encountered by the particulate depends on whether compounds are formed and the solubility of the element/compound in sodium. From there, adsorption on structure may occur, especially in lower temperature regions of the primary system where dissolved radionuclides may precipitate. Mechanical deposition within the primary system is also a possibility, especially for entrained particles.

If temperature of the sodium pool changes to high, the radionuclides adsorbed onto structure can be redissolution. If the radionuclide deposited mechanically onto structure, resuspension may occur when flow condition adjacent to the structure change.

2.4 GAP analysis

Several gaps to analysis MST have been verified in models and data regarding some phenomena [10]. First, a gap is to determine what and how many radionuclides are included within the bubbles. There is no computational tool currently existing to analysis above phenomenon, even though it is very important to subsequent radionuclide release to the cover gas region.

Second is lack of information to analysis how many radionuclide are scrubbing and what affect the bubble and aerosol, when the bubble passes through the

sodium pool. And third is to determine the bubble diameter and particle size of the aerosols. The bubble diameter can be limited by hydrostatic pressure, and it is likely a conservative assumption, as smaller bubbles would aid in radionuclide removal.

Additionally there are not computational tools and sufficient experimental data to capture time effects of radionuclide vaporization, model the actual removal of radionuclides from bubbles, and determine kinetic effects within the sodium.

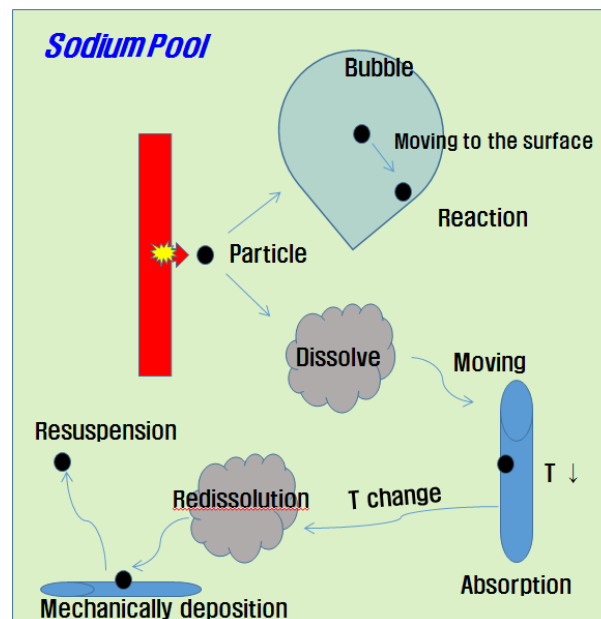


Figure 4. Phenomena of Particulates in a Sodium Pool

3. Conclusions

In the early 1990s, the USNRC began formally addressing the use of MSTs in advanced reactor licensing with the issuance of SECY-93-092. For this MST analysis it is needed to assess radionuclide behavior released from the fuel fins to environment via containment. This paper presents only the radionuclide behavior in sodium pool to assess MST analysis.

The sodium pool may contain radionuclides from several sources including activated sodium, corrosion products, tritium, and fission products from failed fuel pins. And these fission products are released from the failed fuel pins in the form of a gas/vapor or solid.

Several gaps to analysis MST have been verified. These Gaps in models and data regarding some phenomena result in uncertainties. Thus to reduce the uncertainties noted during the mechanistic source term calculation, and provide a more accurate source term assessment a determination of the data requirements for MST development should be formally made and additional experimentation is performed in support of MST development.

REFERENCES

- [1] J. DiNunno, R. E. Baker, F. D. Anderson, and R. L. Waterfield, "Calculation of Distance Factors for Power and Test Reactor Sites," TID-14844, 1962.
- [2] U.S. Nuclear Regulatory Commission, "Accident Source Terms for Light-Water Nuclear Power Plants," NUREG-1465, 1995.
- [3] U.S. Nuclear Regulatory Commission, "Issues Pertaining to the Advanced Reactor (PRISM, MHTGR, PIUS) and CANDU 3 Designs and their Relationship to Current Regulatory Requirements," SECY-93-092, 1993.
- [4] D. Grabaskas, M. Bucknor, J. Jerden, A. Brunett, "Regulatory Technology Development Plan - Sodium Fast Reactor: Mechanistic Source Term – Trial Calculation: Work Plan," Argonne National Laboratory ANL-ART-41, 2016.
- [5] D. Grabaskas, A. J. Brunett, M. Bucknor, J. Sienicki, and T. Sofu, "Regulatory Technology Development Plan - Sodium Fast Reactor: Mechanistic Source Term Development," Argonne National Laboratory ANL-ART-3, 2015.
- [6] International Atomic Energy Agency, "Fission and Corrosion Product Behaviour in Liquid Metal Fast Breeder Reactors (LMFBRs)," IAEA-TECDOC-687, 1993.
- [7] Osterhout, M., "Control of Oxygen, Hydrogen, and Tritium in Sodium Systems at Experimental Breeder Reactor II," UAC-41069, 1978.
- [8] D. H. Cho and D. W. Condiff, "Role of Fuel Bubble Phenomenology in Assessment of LMFBR Source Term," CONF-850410-Vol.2, 1985.
- [9] J.P. Breton, A. Lopicore, and A. Porrachia, "Expansion of a Vapor Bubble and Aerosols Transfer," CEA-CONF 5156, 1979.
- [10] D. Grabaskas, M. Bucknor, J. Jerden, A. Brunett, "Regulatory Technology Development Plan - Sodium Fast Reactor: Mechanistic Source Term – Trial Calculation," Argonne National Laboratory ANL-ART-49, 2016.