Analytical Approaches for Investigating Sodium Aerosols in Fast Reactors

Pooja Kumari*
(Research Scholar) School of Applied Science, Sanskriti University Mathura U.P.
Dr. S. Shekhar**
(Co-Supervisor & Assistant Professor) Department of Physics, Maharishi Vishwamitra College Buxar, VKSU Ara Bihar
Ratna Bhaskar***
(Research Scholar) School of Applied Science, Sanskriti University Mathura U.P.
Dr. D. S. Tomar**
(Supervisor & DEAN Science) School of Applied Science, Sanskriti University Mathura U.P.

1 INTRODUCTION

The concept of An Analytical Approaches On Sodium Aerosols For The Fast Reactor. Fast reactors were one of the first types of reactors built. New SFR designs have been created for the Generation IV Nuclear Energy Systems project. The goals of these new designs are to explore non-traditional applications of nuclear energy while developing new reactor designs that meet the demand for clean and reliable power generation and also focus on enhanced safety and the reduction of cost and proliferation risks. Many of these new reactor concepts involve reactors that use recycled fuels or metallic fuels, like the SFR [1].

2 REFERENCE SFR DESIGN

With public and political resistance to a national radioactive waste repository in the United States, consideration has been given in recent years to develop reactors that can convert long-lived radioisotopes found in spent nuclear fuel to short-lived ones.

SFRs could play a large part in the burning of actinides found in spent light water reactor (LWR) fuels. By burning a substantial portion of the spent fuel not only would the amount of waste needing to be stored in a repository be drastically reduced, but a considerable amount of energy would be produced as well [3].

3 TECHNOLOGY NEUTRAL FRAMEWORK

The U.S. Nuclear Regulatory Commission (NRC) previously published a document detailing “feasibility studies for a risk-informed and performance-based regulatory structure for future plant licensing,” called NUREG-1860. This report identifies a framework for the purpose of guiding future nuclear plant licensing procedures based on a risk-informed approach that is independent of the type of plant. In addition to the current license process, as described in Part 50 of Title 10 of the Code of Federal Regulations (10 CFR 50), this new technology-neutral approach will make the licensing process more efficient and effective for newer plant designs [8]. The technology neutral framework (TNF) approach strives to implement risk-informed, performance-based, defense-in-depth, and flexible framework for licensing future nuclear facilities. This TNF specifically incorporates probabilistic risk assessment (PRA), frequency consequence curves, and deterministic information to effectively identify licensing basis events (LBE).

4 METHODOLOGY

Several key events can occur in an SFR that in turn affect the source term. While the reactor is in operation, noble gases and volatile radionuclides that escape from the fuel are retained within the pin either in the sodium bond (sodium internal to the pin that assures good heat transfer between the surface of the pin and the cladding), airborne in the pin gas plenum, or deposited on a surface [5]. During a pin failure the noble gases and airborne radionuclide aerosols and vapors escape from the pin, along with molten fuel and sodiumbonded nuclides, and form a bubble within the fuel assembly. This bubble breaks up into smaller bubbles as it rises into the sodium pool. Most of the nuclides will be scrubbed and mixed with the sodium in the pool but a fraction of these bubble-trapped aerosols and vapors are expected to escape into the cover gas region above the pool. In all of the scenarios analyzed in this thesis, it has been assumed that the primary system barrier has failed.

5 RESULTS AND DISCUSSION

As discussed in Chapters 2 and 3, there are several key events that affect the consequences of accident scenarios in SFRs. The four barriers that prevent radioactive material from being released to the environment are the fuel matrix, cladding, primary system, and containment. Only if all four of these barriers fail will a substantial amount of radioactive material be released in an accident. Since the sodium in the primary system is radioactive, it can contribute to the source term in accident scenarios involvingrelease from fuel or in events in which there is no release from fuel. The containment and primary system alone are the only two barriers preventing primary system sodium from being released. Thus, events in which only radioactive sodium is released to the environment are expected to be more likely than those involving release from fuel. As shown below, however, the offsite consequences from sodium releases are relatively minor.

The sodium pool in effect acts as an additional barrier in that it acts as a scrubberthat reduces the release of radionuclides released from the fuel. The following sections will discuss the cases analyzed for this research and the results of those analyses.

Metal Fuel Model

Historically there has been more effort in studying the behavior of oxide than metallic fuels in severe accidents. The metallic fuel considered for this research is a mixture of U-15Pu-10Zr. The melting point of this fuel is 1590 K, much less than the melting point of LWR fuel [5]. It should be noted that the noble gases are expected to bea major contributor to the dose in many SFR accident scenarios as their solubility in sodium is very small and they are not subject to containment deposition processes.

Iodine, normally a high contributor to offsite dose in LWR accidents, is expected to be negligible in metallic-fuel accidents as it forms a low volatile compound with the fuel, UI_3. Cesium, on the other hand, has a boiling point of 944 K and is expected to be present in the plenum of fuel pin as a volatile vapor during normal operation. Cesium isotopes are likely to be the primary contributor to offsite consequences in the highest consequence scenarios in which primary system and containment retention mechanismsare ineffective. Tellurium and other volatile gases are also potentially significant contributors. Tellurium reacts with sodium, however. Any tellurium captured in the sodium pool is unlikely to be subsequently released.

5.1 Characteristic Accident Scenarios

Each of the characteristic accident scenarios investigated for SFRs along with the scenario type (non-energetic, energetic, core uncovery), containment status (intact or failed), details of the release characteristics, and descriptions of the assumed mode of primary system failure (limited or gross failure) are described in Table 1. In each of the cases described it has been assumed that the primary system has failed. This failure, as described in Chapter 2, can be considered limited as for a seal failure in the deck structure, or gross if the deck structure has been destroyed. For characteristic core uncovery situations it has been assumed that there would be a gross failure of the primary system, also with the deck destroyed. In the uncovery scenarios, the nuclides are released directly from the core to either the containment, if it is intact, or to the environment, if thecontainment has failed.

Table 1 SFR Characteristic Accident Scenarios for Metallic Fuel

Scenario Type	**ContainmentStatus**	**Release Characteristics**	**Primary System Failure Type**	**Failure Details**
Non-Energetic	Intact	Substantial fuel melt, treat as TOP with failureto SCRAM. Pool scrubbing. Primary failed.	Limited ---------- Gross	Major seal failure in deck --------------- Primary system fail, deck gone
Non-Energetic	Failed (1 m² hole)	Substantial fuel melt, treat as TOP with failureto SCRAM. Pool scrubbing. Primary failed.	Limited ---------- Gross	Major seal failure in deck --------------- Primary system fail, deck gone
Energetic	Intact	Fuel melting, energetic event. Treat as TOP with failure to SCRAM. Limited pool scrubbing.	Limited ---------- Gross	Major seal failure in deck --------------- Primary system fail, deck gone
Energetic	Failed (1 m² hole)	Fuel melting, energetic event. Treat as TOP with failure to SCRAM. Limited pool scrubbing.	Limited ---------- Gross	Major seal failure in deck --------------- Primary system fail, deck gone
Core Uncovery (oxidized)	Intact	Core uncovered 4 hours. Oxidizing environment.	Gross	Primary system failed, no deck structure
Core Uncovery (oxidized)	Failed (1 m² hole)	Core uncovered 4 hours. Oxidizing environment.	Gross	Primary system failed, no deck structure

For each characteristic accident scenario described in Table 3, analyses were performed with the RCS computer code to determine the source term to containment. The results of those calculations are provided in Reference [17] and the radionuclide input to MELCOR can be viewed in Appendix A. For these cases, MELCOR analyses were performed and offsite doses calculated. The results are presented in Table 2.

Table 2 Offsite Doses for Characteristic Accident Scenarios for Metallic Fuel

Scenario Type	**Containment Status**	**Radionuclides**	**Gross Primary Failure Dose (rem)**	**Limited Primary Failure Dose (rem)**
Non-Energetic	Intact	Na NG Cs **Total**	3.8E-4 0.61 8.3E-3 **0.62**	3.5E-5 0.25 6.4E-3 **0.25**
Non-Energetic	Failed	Na NG Cs **Total**	7.0E-3 52 0.82 **53**	3.3E-4 10.6 0.19 **11**
Energetic	Intact	Na NG CsTe Low Vol. **Total**	3.8E-4 1.5 3.3 0.10 2.0 **6.9**	3.3E-5 0.63 4.3 0.13 2.6 **7.6**
Energetic	Failed	Na NG CsTe Low Vol. **Total**	3.7E-3 520 3.1E3 97 1.9E3 **5.7E3**	2.4E-4 510 3.1E3 97 1.9E3 **5.7E3**

Core Uncovery (oxidized)	Intact	NaNGI Cs Low Vol. **Total**	3.7E-4 1.3 0.34 0.36 0.55 **2.6**	--
Core Uncovery (oxidized)	Failed (1 m² hole)	NaNGI Cs Low Vol. **Total**	6.7E-3 12 4.1 4.3 6.6 **29**	--

The TNF, as described in Chapter 3, provides values for the acceptable frequency of licensing basis events (LBEs) for varying levels of offsite consequences. The Frequency-Consequence curve, as shown previously in Figure, illustrates that a scenario having a dose greater than 500 rem must have a frequency of less than 1E-7 per year with high confidence.

For non-energetic scenarios in which the containment remains intact with gross-failure of the primary system the driving force for radionuclide release is greater than observed for the case with limited primary system failure. This is due to the higher rate of sodium release to the containment and oxidation of this sodium. The comparison of pressure behavior over time in the containment between gross failure and limited failure scenarios can be seen in Figure 1.

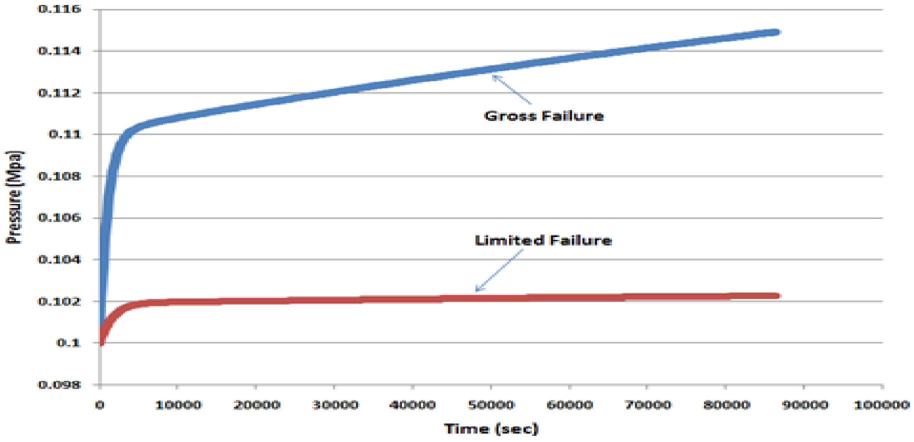

Figure 1 Containment Pressure for Non-Energetic Event for Cases with Gross Failure and Limited Failure of the Primary System

Figure 2 shows the mass of cesium airborne in the containment over time for the non-energetic accident scenario with intact containment and a gross primary system failure. The masses are separated into different aerosol size bins based on the aerosol diameter. The cesium aerosol enters the containment from the cover gas region with a mass median diameter of 0.5 microns, which is in the respirable range. Over time the cesium aerosols agglomerate with the sodium oxide aerosols, which are at a much higher concentration, resulting in the large cesium/sodium oxide agglomerates to fall out and deposit by gravitational settling [7].

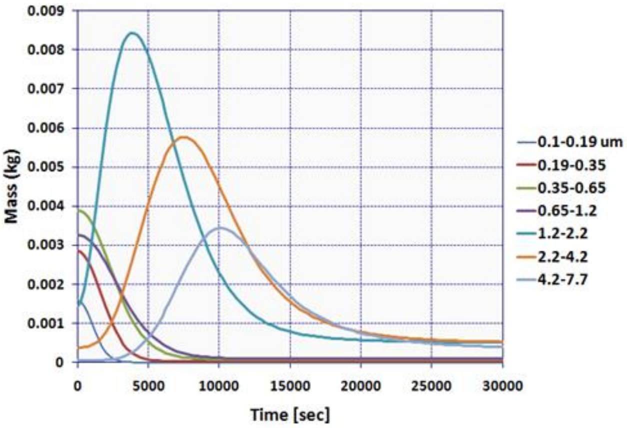

Figure 2 Mass of Cesium in Aerosol Size Bin in Containment Versus Time

Figure 3 depicts the mass of cesium aerosols airborne versus deposited as a function of time. Because there is a continual source of cesium to the containment an equilibrium is established between the rate of introduction of cesium and the rate of deposition leading to a constant mass airborne. The airborne mass of cesium aerosol is subject to leakage to the environment. The amount leaked over the 24-hour period is too small to be seen in the figure.

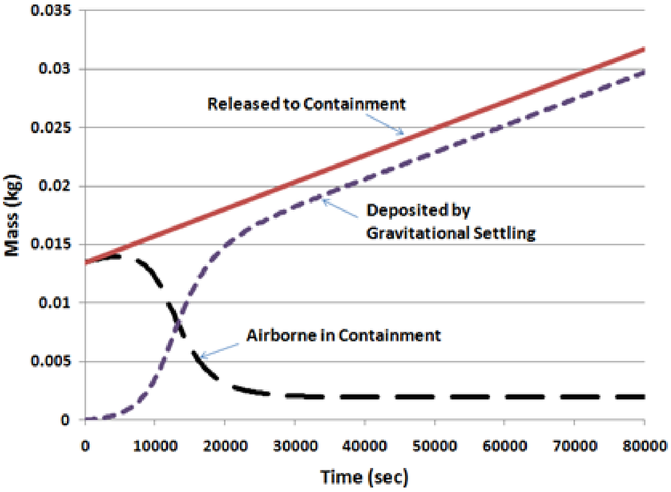

Figure 3 Deposition of Cesium in Containment

For those non-energetic accident scenarios, it can be noted that the doses observed are dominated by the noble gases being released. The doses are less than might be expected because the release of radionuclides from the fuel is small and the overlying pool of sodium is effective in capturing aerosols that are released from the fuel. The contribution of radioactive sodium to offsite dose is small. Other than noble gases, because of its volatility cesium is likely to be the principal contributor to offsite doses.

The cesium that does escape the pool is largely deposited within the containment due to the agglomeration of cesium aerosols with sodium oxide aerosols. Thus sodium has a major impact on offsite doses. On the one hand, energy release from sodium oxidation provides the driving force for release from containment. On the other hand, the co-agglomeration of fission product aerosols with sodium oxide aerosols enhances the deposition of fission product aerosols by gravitational settling.

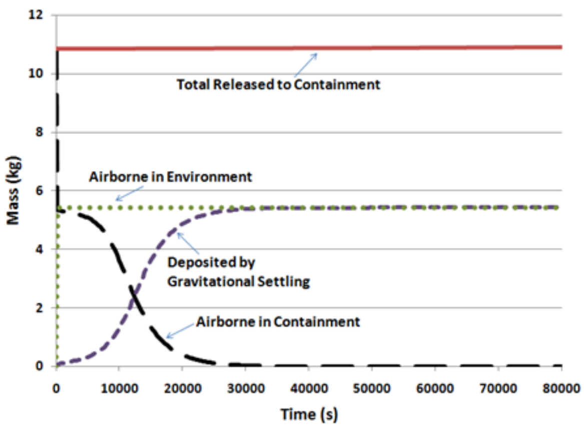

Figure 4 Cesium Transport During Energetic Event

For all other cases, as seen in Table 2, the offsite dose consequences are much less than the energetic case with containment failure. For the energetic case with an intact containment, the dose is reduced significantly. The dose consequence is slightly less than 25 rem. Twenty-five rem is the design basis limit for site dose calculations, which are performed with a severe-accident release of radionuclides to the containment with the containment leaking at its design basis leak rate. The scenario in which the core is uncovered and the containment is failed has a surprisingly small offsite dose considering the magnitude of release to the containment. Even though the leak area modeled is quite large (1 square meter), there is very little driving force for release to the environment. Thus, radionuclides released from the reactor coolant system largely settle to the floor of the containment before they can leak to the environment. One of the principal reasons for analyzing the core uncover scenario was to evaluate whether the oxidation of metallic fuel would lead to a large release of low volatility radionuclides.

This was found to not be the case. Although the low volatility group is a significant contributor to offsite consequences, it does not dominate off-site consequences.

Table 3 Risk of Early Fatalities and Latent Cancer Fatalities for Characteristic AccidentScenarios [7]

Scenario Type	Containment Status	Early Fatality Risk (OneMile)	Latent Cancer Fatality Risk (TenMile)
Non-Energetic	Intact	0	2E-13
Non-Energetic	Failed	0	1E-11
Energetic	Intact	0	1E-14
Energetic	Failed	2E-9	2E-11
Core Uncovery	Intact	0	6E-12
Core Uncovery	Failed	0	2E-11

The risk of early fatality was calculated for an individual living within one mile of the plant while the latent cancer fatality risk was found for an individual living within ten miles of the plant. The NRC's safety goals established by the QHOs are that there should be less than 5E-7 annual risk of early fatalities for those within one mile of a facility and less than 2E-6 annual risk of latent cancer fatalities for those within ten miles. Figure 5 shows the risks associated with each characteristic accident scenario, from Table 3, along with the QHO limits. For most scenarios, there are no early fatalities observed. As indicated in Figure 5, all of the scenarios would satisfy the QHO goals by very wide margins.

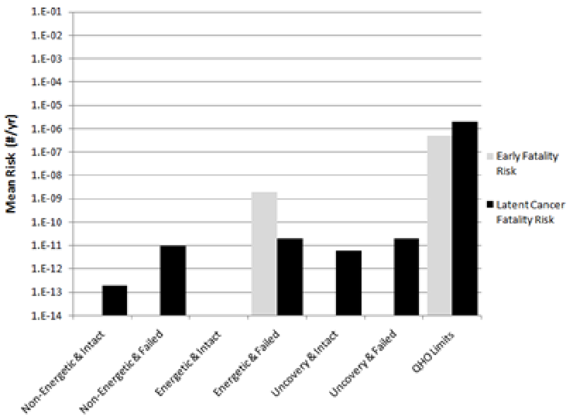

Figure 5 Risk Results for Early Fatalities and Latent Cancer Fatalities from Characteristic Accident Scenarios

5.2 Scenario Sensitivity Studies

In order to observe the effects of smaller containment volumes, filtered vents, and containment failure mode assumptions, several additional cases were modeled. The details of these studies can be seen in Table 4 with the changes added to the characteristicaccident scenarios in bold.

Table 4 Scenario Sensitivity Studies for Metallic Fuel

ScenarioType	Containment Status	Release Characteristics	Primary System Failure Type	FailureDetails
Non-Energetic	Intact	Substantial fuel melt, treatas TOP with failure to SCRAM. Pool scrubbing. Primary failed. **Small volume.**	Limited	Major sealfailure in deck
Non-Energetic	Failed (1 m² hole)	Substantial fuel melt, treatas TOP with failure to SCRAM. Pool scrubbing. Primary failed. **Small volume.**	Limited	Major sealfailure in deck
Non-Energetic	Failed **(Containment gone)**	Substantial fuel melt, treatas TOP with failure to SCRAM. Pool scrubbing. Primary failed.	Gross	Release from cover gas to environment
Energetic	Failed **(Containment gone)**	Fuel melting, energetic event. Treat as TOP withfailure to SCRAM. Limited pool scrubbing.	Gross	Release from covergas to environment

The subsequent offsite dose consequences for these additional scenarios can be seen in Table 5.

Table 5 Offsite Doses for Scenario Sensitivity Studies with Metallic Fuel

Scenario Type	Containment Status	Details	Radionuclides	Failure Dose (rem)
Non-Energetic	Intact	Small volume,Seal failure indeck	Na NG Cs **Total**	9.8E-5 10 1.7E-2 **10**
Non-Energetic	Failed (1 m² hole)	Small volume.	Na NG Cs **Total**	8.8E-4 27 3.7E-1 **27**
Non-Energetic	Failed	Containment gone, Release from cover gas to environment	Na NG Cs **Total**	1.1 400 19 **420**

Energetic	Failed	Containment gone, Release from cover gas toenvironment	Na NG CsTe Low Vol. **Total**	2.1 1.0E3 6.3E3 1.9E2 3.9E3 **1.1E4**

For the non-energetic case with limited failure, intact containment and small containment volume (4.43E3 m^3) the total dose calculated was around 10 rem. In the original case with the larger containment volume (2.86E4 m^3) the total dose observed was only 0.25 rem. The larger dose observed with the smaller volume case is due to the containment being more easily pressurized resulting in a larger driving force for release of radionuclides to the environment.

The case involving a non-energetic scenario with limited failure, failed containment, and small containment volume the total dose was around 27 rem. The original case with the larger containment volume had a dose consequence of 11 rem. The smaller volume associated with this case allows for a larger pressure-related driving force resulting in a larger release of radioactive material.

5.3 Model Sensitivity Studies

A number of sensitivity studies were also completed to observe the effects on the offsite consequence of containment retention mechanisms. These studies include increasing the deposition surface area available in the containment, adding a pressure differential on the outside of the containment due to a 5 mph wind, modeling the variation in environmental pressure over 24 hours, and modeling the effects due to loss of oxygen when it is burned with sodium during an oxidation event (an effect that the MELCOR code is not capable of addressing directly). Table 8 shows the details of these sensitivity studies.

Table 6 Containment Model Sensitivity Analysis Cases

Scenario Type	Containment Status	Failure Type	Failure Details	Analysis Details
Non-Energetic	Intact	Limited	Major seal failure in deck	Containment floor area doubled to examine effects on deposition
Non-Energetic	Failed (1 m^2 hole)	Limited	Major seal failure in deck	Wind added:Pressure differential modeled for wind at 5 mph
Non-Energetic	Failed (1 m^2 hole)	Limited	Major seal failure in deck	Environment pressure variation of 15 Pa over 24 hours
Non-Energetic	Intact	Gross	Primary system failed, deck gone	Effect on pressure when oxygen is burned in containment

The offsite dose consequences for the sensitivity studies can be seen in Table 7.

The first sensitivity case investigated was altering the non-energetic scenario with limited failure and intact containment to have a larger containment floor area. The offsite exposure from cesium was found to be reduced by approximately 20% from 6.4E-3 to 5.1E-3 due to enhanced gravitational settling. There was also a minor reduction in the noble gas release, apparently as the result of additional heat transfer to structure.

The case with the 5 mph wind against the outside of the failed containment was modeled by creating a 2.94 Pa pressure differential between the environment and a second pseudo environment. The wind was modeled to flow in and out of the containment through two 0.5 m^2 holes. The effect of this 5 mph wind on the offsite consequence is significant. A dose of 11 rem was obtained in the original case modeled with no wind. However when the wind was added to the model, the offsite consequence increased to 3.9E2 rem. Thus, depending on the size and location of breaches in the containment outside wind can have a significant effect in providing a driving force for release.

The last sensitivity study investigated the effects on the pressure and offsite consequences when oxygen from the containment is removed at the same rate sodium is inserted on a molar basis, simulating the effects of oxygen consumption in a sodium fire.The effect on pressure over time can be seen in Figure 6.

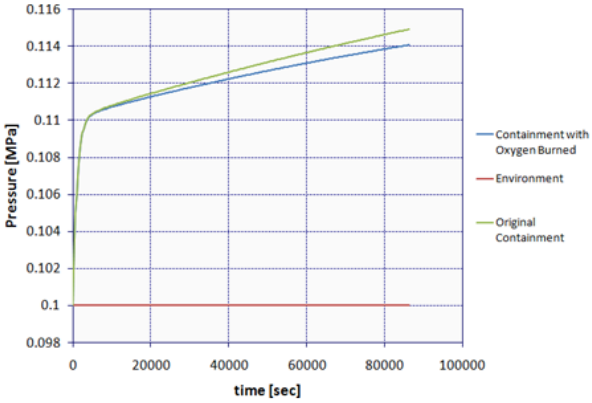

Figure 6 Pressure Over Time for Non-Energetic Event with Intact Containment

The pressure when the oxygen is burned in the containment appears to increase at a slower rate than when oxygen is not being removed. Overall the pressure over 24 hours is lower for this sensitivity study. The offsite dose is reduced accordingly, decreasing from 0.62 rem to 0.61 rem. This slight decrease is due to the fact that there is a lower driving force for release with the lower containment pressure during this scenario.

Overall since the pressure is only decreased slightly, the change in dose is very small.

Table 7 Offsite Doses for Containment Model Sensitivity Cases

Scenario Type	Containment Status	Details	Radionuclides	Failure Dose(rem)
Non-Energetic	Intact, Seal Failure	Containment floor area doubled to examine effects on deposition	Na NG Cs **Total**	2.9E-5 0.23 5.1E-3 **0.24**
Non-Energetic	Failed, Seal Failure (1 m^2 hole)	Wind added:Pressure differential modeled for wind at 5 mph	Na NG Cs **Total**	6.6E-2 380 8.0 **3.9E2**
Non-Energetic	Failed Seal Failure,(1 m^2 hole)	Environment pressure variation of 15 Pa over 24 hours	Na NG Cs **Total**	3.3E-4 11 1.9E-1 **11**
Non-Energetic	Intact, Gross Failure	Effect on pressure when oxygen is burned in containment	Na NG Cs **Total**	3.8E-4 0.60 8.2E-3 **0.61**

5.4 Oxide Fuel Model

Several of the same characteristic accident scenarios were also modeled with oxide fuel. Only limited failure cases consisting of a seal failure were modeled for most cases, since the objective of examining oxide fuel was only to determine whether there would be substantial differences from the same cases with metallic fuel. . The core uncovering scenarios, however, were only modeled as a gross failure of the deck structure. The details of the cases that were studied using oxide fuels can be seen in Table 8.

Table 8 SFR Characteristic Accident Scenarios for Oxide Fuel

ScenarioType	**Containment Status**	**Primary SystemFailure**
Non-Energetic	Intact	Major seal failure in deck
Non- Energetic	Failed (1 m^2 hole)	Major seal failure in deck
Energetic	Intact	Major seal failure in deck
Energetic	Failed (1 m^2 hole)	Major seal failure in deck
Core Uncovery (oxidized)	Intact	Primary system failed, no deckstructure
Core Uncovery (oxidized)	Failed (1 m^2 hole)	Primary systemfailed, no deck structure

For each characteristic accident scenario using oxide fuel described in Table 10, analyses were performed with the RCS computer code to determine the source term to containment. The results of those calculations are also provided in Reference [17] and the radionuclide inputs to MELCOR can be seen in Appendix A. For these cases, MELCOR analyses were performed and offsite doses calculated. The results are presented in Table 9.

Table 9 Offsite Consequences for Characteristic Accident Scenarios in Oxide Fuel

Scenario Type	**ContainmentStatus**	**Radionuclides**	**Failure Dose(rem)**
Non-Energetic	Intact	Na NG Cs I **Total**	3.5E-5 0.25 2.9E-3 7E-4 **0.25**
Non-Energetic	Failed	Na NG Cs I **Total**	3.3E-4 11 8.0E-2 1.2E-2 **11**
Energetic	Intact	NaNG CsI Te Low Vol. **Total**	3.3E-5 0.63 4.3 4.0 1.2E-1 2.5 **12**
Energetic	Failed	NaNG CsI Te Low Vol. **Total**	2.4E-4 512 3.1E3 3.2E3 9.7E1 1.93E3 **8.9E3**
Core Uncovery	Intact	NaNG CsI Te Low Vol. **Total**	3.5E-4 1.3 2.1E1 2.0E1 6.2E-1 3.2 **46**
Core Uncovery	Failed	NaNG CsI Te Low Vol. **Total**	6.6E-3 12 2.5E2 2.4E2 7.4 3.9E1 **5.5E2**

For the oxide fuel cases with a non-energetic accident occurring, like with the metallic fuel cases, the noble gases dominate the dose consequences. The doses obtained for these cases with primary system seal failures are nearly equal to the doses seen for thesame cases that use metallic fuel.

For the energetic case with the intact containment a dose of 12 rem is obtained.

This is slightly higher than the 7.6 rem dose observed in the same case with metallic fuel. For the energetic case with failed containment a dose of 5.7E3 rem was seen using metallic fuels but was higher, 8.9E3 rem, for the oxide fuel.

For the cases in which a core uncovering accident has occurred the dose consequences observed for the oxide fuel is substantially higher than those observed for the metallic fuel. For a core uncovery situation with intact containment the dose calculated is approximately 46 rem and when the containment is failed the dose is around 5.5E2 rem. These doses are larger than the respective 2.6 rem and 29 rem estimated for the metallic fuel cases by more than an order of magnitude. Because oxide fuel melts at a higher temperature, it would not be surprising to observe higher source terms in severe accidents in SFRs, particularly with regard to the contribution of iodine. However, it is important to recognize the substantial uncertainties associated with the source terms for both metallic and oxide fuels in SFR environments. It would be inappropriate to conclude based on the results of these analyses that the severity of severe accident consequences for an oxide-fueled SFR are significantly greater than for a metal-fueled design.

6 CONCLUSIONS AND FUTURE WORK

Several accident scenarios were investigated including those with non-energetic events, energetic events, and core uncovery situations. For each event type, analyses were performed for scenarios in which the containment was either failed or intact and in which the primary system failure mode was either gross or limited in size. The calculated offsite dose consequences were then compared to the Technology Neutral Framework (TNF) Frequency-Consequence curve to determine the permissible frequency of these varying accident scenarios.

Overall, the most likely accident scenarios that could occur in an SFR are non-energetic accidents consisting of substantial fuel melt under the overlying sodium pool. For these cases the doses observed are less than the comparable LWR accident scenarios. This is because the release of radionuclides from the metallic SFR fuel is small and the sodium pool is successful in scrubbing the aerosols that are released from the fuel. The doses from the non-energetic cases are dominated by the noble gases with the contribution of radioactive sodium to offsite dose being small. Cesium is also likely to be a principal contributor to offsite doses due to its volatility although a large fraction of the cesium that escapes the pool becomes deposited within the containment due to the agglomeration of cesium aerosols with sodium oxide aerosols. Therefore sodium has both positive and negative impacts on offsite doses. The energy released during sodium oxidation provides the driving force for release from containment. However, the co- agglomeration of fission product aerosols with sodium oxide aerosols enhances the deposition of fission product aerosols by gravitational settling.

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