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An Approach to Determine a Defensible Spent Fuel Ratio

U.S. Department of Energy, Office of Nuclear Energy Fuel Cycle Technologies Program – Material Protection, Accounting and Control Technologies

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An Approach to Determine a Defensible Spent Fuel Ratio*

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Abstract

Sabotage of spent nuclear fuel casks remains a concern nearly forty years after attacks against shipment casks were first analyzed and has a renewed relevance in the post-9/11 environment. A limited number of full-scale tests and supporting efforts using surrogate materials, typically depleted uranium dioxide (DUO_2), have been conducted in the interim to more definitively determine the source term from these postulated events. In all the previous studies, the postulated attack of greatest interest was by a conical shape charge (CSC) that focuses the explosive energy much more efficiently than bulk explosives. However, the validity of these large-scale results remain in question due to the lack of a defensible Spent Fuel Ratio (SFR), defined as the amount of respirable aerosol generated by an attack on a mass of spent fuel compared to that of an otherwise identical DUO_2 surrogate. Previous attempts to define the SFR have resulted in estimates ranging from 0.42 to 12 and include suboptimal experimental techniques and data comparisons. Different researchers have suggested using SFR values of 3 to 5.6. Sound technical arguments exist that the SFR does not exceed a value of unity. A defensible determination of the SFR in this lower range would greatly reduce the calculated risk associated with the transport and dry storage of spent nuclear fuel.

Currently, Oak Ridge National Laboratory (ORNL) is in possession of several samples of spent nuclear fuel (SNF) that were used in the original SFR studies in the 1980's and were intended for use in a modern effort at Sandia National Laboratories (SNL) in the 2000's. A portion of these samples are being used for a variety of research efforts. However, the entirety of SNF samples at ORNL is scheduled for disposition at the Waste Isolation Pilot Plant (WIPP) by approximately the end of 2015. If a defensible SFR is to be determined for use in storage and transportation security analyses, the need to begin this effort is urgent in order to secure the only known available SNF samples with a clearly defined path to disposal.

* This report fulfills the DOE/NE FCT M2 milestone M2FT-14SN0405041, "Cask Sabotage Gaps Report." This work was performed under the work package FT-14SN040504, "Concepts and Approaches," by Sandia National Laboratories.

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ACRONYMS

AED	Aerodynamic Equivalent Diameter
BCL	Battelle Columbus Laboratory
Cat	Category (of special nuclear material)
CFR	Code of Federal Regulations
DUO_2	Depleted Uranium Oxide
DOE	U.S. Department of Energy
ECF	Explosive Component Facility
EF	Enhancement Factor (of volatile fission products)
FEW	Fuel Element Waste
GC-MS	Gas Chromatography Mass Spectroscopy
HED	High Energy Device
HfO_2	Halfnium Oxide (Hafnia)
IAEA	International Atomic Energy Agency
ICP-MS	Inductively Coupled Plasma – Mass Spectroscopy
INL	Idaho National Laboratory
ISFSI	Independent Spent Fuel Storage Installation
LRRI	Lovelace Respiratory Research Institute
MPACT	Material Protection Accounting and Control Technologies
MTHM	Metric Tonnes of Heavy Metal
NAS	National Academy of Sciences
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
ROM	Rough Order of Magnitude
RMWMF	Radioactive and Mixed Waste Management Facility
RPSD	Radiation Protection Sample Diagnostics
RRF	Respirable Release Fraction
SFR	Spent Fuel Ratio
SPRF	Sandia Pulsed Reactor Facility
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories

TSR	Technical Safety Requirements
WGSTSC	(International) Working Group for Sabotage Concerns of Transport and Storage Casks
WIPP	Waste Isolation Pilot Plant

1 INTRODUCTION

Sabotage of spent nuclear fuel casks remains a concern nearly forty years after attacks against shipment casks were first analyzed and has a renewed relevance in the post-9/11 environment. A limited number of full-scale tests and supporting efforts using surrogate materials, typically depleted uranium dioxide (DUO_2), have been conducted in the interim to more definitively determine the source term from these postulated events. In all the previous studies, the postulated attack of greatest interest was by a conical shape charge (CSC) that focuses the explosive energy much more efficiently than bulk explosives. However, the validity of these large-scale results remain in question due to the lack of a defensible Spent Fuel Ratio (SFR), defined as the amount of respirable aerosol generated by an attack on a mass of spent fuel compared to that of an otherwise identical DUO_2 surrogate. Previous attempts to define the SFR in the 1980's have resulted in estimates ranging from 0.42 to 12 and include suboptimal experimental techniques and data comparisons. Because of the large uncertainty surrounding the SFR, the SFR remains a target of criticism by nuclear safety advocates. Credible arguments exist that the SFR does not exceed a value of unity [Philbin, *et al.*, 2002]. A defensible determination of the SFR in this lower range would greatly reduce the calculated risk associated with the transport and dry storage of spent nuclear fuel.

The most recent effort was conducted at Sandia in the 2000's but did not test spent fuel. A detailed review and error propagation analysis of this Sandia effort lead to a proposed improved apparatus and procedure [Lindgren and Durbin, 2009]. These improved methods outline an approach to determine a statistically defensible SFR and are the basis for the test program described in this report.

Currently, Oak Ridge National Laboratory (ORNL) is in possession of several samples of spent nuclear fuel (SNF) that were used in the original SFR studies in the 1980's and were intended for use in the effort at Sandia National Laboratories (SNL) in the 2000's. A portion of these samples are being used for a variety of research efforts. However, the entirety of SNF samples at ORNL is scheduled for disposition at the Waste Isolation Pilot Plant (WIPP) by approximately the end of 2015. If a defensible SFR is to be determined for use in storage and transportation security analyses, the need to begin this effort is urgent in order to secure the only known available SNF samples with a clearly defined path to disposal.

This gaps analysis report was funded by the Department of Energy (DOE) Fuel Cycle Materials Protection, Accounting, and Control Technologies (MPACT) program. The goals of this report are to explore the current knowledge base on the SFR, propose an improved experimental apparatus and procedure, and explore program costs and logistics. This report represents these efforts.

1.1 A Brief History of Spent Fuel Sabotage Testing

A number of studies have been commissioned over four decades to estimate the source term and subsequent results of exposure from postulated attacks. In the late 1970's, a conservative

[*] This report fulfills the DOE/NE FCT M2 milestone M2FT-14SN0405041, "Cask Sabotage Gaps Report." This work was performed under the work package FT-14SN040504, "Concepts and Approaches," by Sandia National Laboratories.

analysis was published by SNL [DuCharme *et al.*, 1978], also known as the "Urban Study"). Due to lack of experimental data, this study used expert judgment to define the amount of material released by an attack in downtown Manhattan. As a result the US Nuclear Regulatory Commission (NRC) imposed new regulations requiring increased security for shipments of spent fuel to protect against sabotage events.

In response to the perceived conservatisms in the original Urban Study, a second analysis was conducted in an attempt to refine the assumptions made in the original assessment [Finley, *et al.*, 1980]. The estimated releases from this new study were 14 times lower than reported in the Urban Study, but the NRC did not relax the interim regulations on the transportation of spent fuel.

Acknowledging the lack of experimental data in this technical area, the NRC and DOE both funded parallel test programs to determine the source term from full-scale and scaled casks. The costs and safety requirements to conduct the full-scale tests with actual spent fuel would have been prohibitive. Therefore, the test planners at SNL chose to conduct the full-scale tests with fuel rods filled with surrogate pellets made of DUO_2 [Sandoval, *et al.*, 1983]. DUO_2 was chosen in an attempt to best match the mechanical response of spent fuel interacting with a high energy device (HED). This substitution appears justified because spent fuel contains approximately 90% by mass of U-238 dioxide. However, actual spent fuel pellets contain several properties unique to irradiated fuel such as fission products, a fragmented structure, and embrittled cladding. The ability to scale the results of the full-scale sabotage tests for expected releases from actual spent fuel required the measurement of a SFR. Again, the SFR is defined as the ratio between the spent fuel respirable aerosol mass released to the DUO_2 surrogate respirable aerosol mass released under other otherwise identical, disruptive conditions. Subsequent large scale tests conducted by SNL and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS, German Reactor Safety Authority) also elected to use DUO_2 as a fuel surrogate, further increasing the importance of the SFR for accurate source term interpretation [Philbin, *et al.*, 1988 and Pretzsch and Lange, 1994].

Two parallel programs, one at Battelle Columbus Laboratories (BCL) and another at Idaho National Engineering Laboratory (INL), were conducted in the early 1980's to obtain the SFR but resulted in inconclusive results. A follow-on effort was conducted in the 2000's at SNL, but funding was discontinued prior to testing with spent fuel.

1.1.1 Idaho National Laboratory SFR Efforts

In support of the full-scale testing program [Sandoval, *et al.*, 1983], the DOE directed INL to measure the SFR. Testing was conducted using two conjoined 55 gallon drums, one for the CSC and the other for a target rodlet of DUO_2 or SNF [Alvarez, *et al.*, 1982]. Both chambers were equipped with aerosol sampling equipment (see Figure 1.1). The lower chamber (target) was also inspected post-test for large and deposited debris. Three DUO_2 shots and 2 SNF shots were conducted during the course of testing yielding a SFR = 0.53 to 5.6.

The higher SFR value was a result of questionable wet sieving technique and assumed a single mode distribution, although available data show multimodal distributions are more likely. This method was employed because a tray containing the disassembled cascade impactor stages from the DUO_2 shots was accidentally dropped before analysis, erasing the identity of the individual

stages. Due to limited budget and schedule, the INL investigators were forced to extrapolate to the respirable range by wet sieving the bulk debris. The validity of this method was questioned at the time by the researchers but was ultimately allowed as an acceptable conservatism.

The lower SFR value is also suspect because the DUO_2 from the bulk filters was not determined through radiological techniques but was measured from the total mass of the sampling filters. The accuracy of balances in this range and the amount of handling of the sample filters raise questions about the validity of the calculated DUO_2 mass used for the SFR determination.

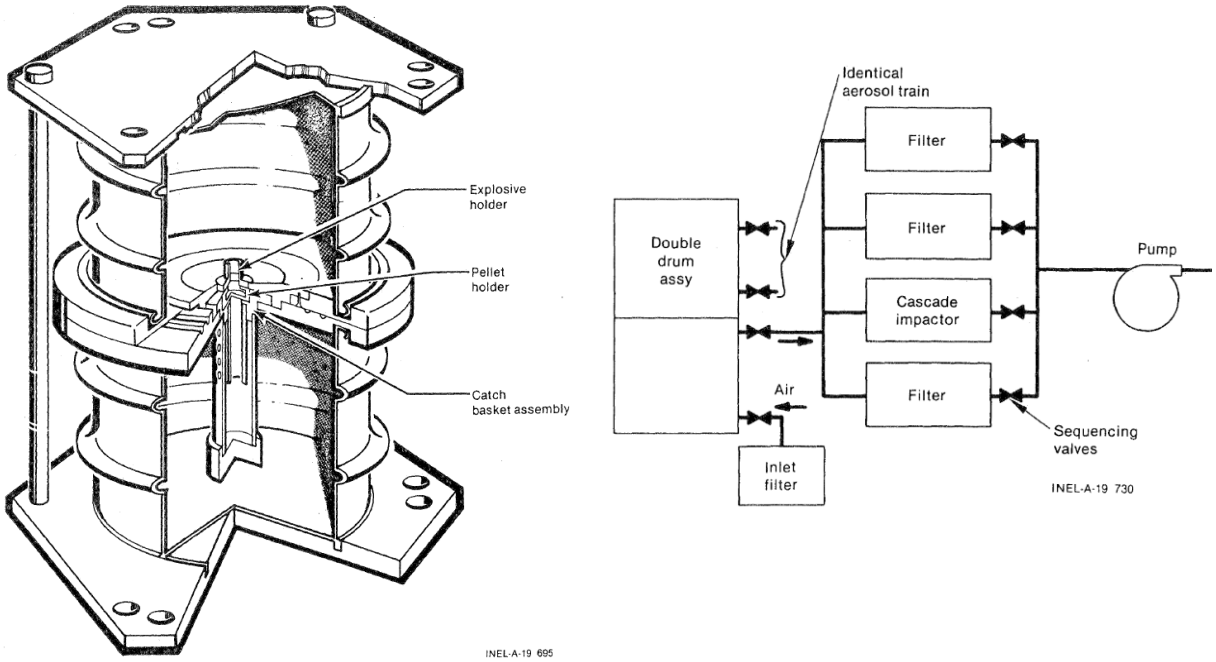

Figure 1.1 Drawing of the INL test chamber design (left) and aerosol sample train (right). (From Alvarez, *et al.*, 1982 Figures 4-6 and 4-8)

The major details of the INL tests are listed below.

- SFR = 5.6 (wet sieving), 0.53 (bulk filter)
- DUO_2 shots, 2 SNF shots (H.B. Robinson 15x15 PWR, 28 GWd/MTHM)
- Small targets (1 rodlet, 0.6 in. length SNF, 10.4 g of SNF)
- Small CSC (1.1 g explosives)
- CSC disrupted the entire target
- Aerosol collection by cascade impactors and bulk filters
- Aerosol samples significantly contaminated with soot
- Cascade impactor data for DUO_2 shots lost after a tray containing the impactor stages was dropped

- Extrapolation of wet sieving data to respirable range due to loss of cascade impactor data was recognized as highly inaccurate

1.1.2 Battelle Columbus Laboratories SFR Efforts

At the same time as the INL and early SNL efforts, the NRC sponsored a semi-independent research effort at BCL [Schmidt, *et al.*, 1981 and Schmidt, *et al.*, 1982]. The primary goal of the BCL investigation was to directly characterize the source term arising from a CSC attack on a shipping cask, not to measure the SFR. The test series involved firing a CSC against various configurations of a scaled shipping cask and measuring the amount of material blown from the cask interior in the form of debris and aerosols (see Figure 1.2). In the course of testing, the investigators at BCL conducted one DUO_2 shot comparable to four SNF shots. However, the SFR values (0.42 to 12) determined from these results raise questions about the repeatability of the test setup. In particular, the availability of a single DUO_2 shot for SFR calculations introduces distinct statistical uncertainty beyond that already demonstrated by the range of SFR values when the SNF shots demonstrated such poor repeatability.

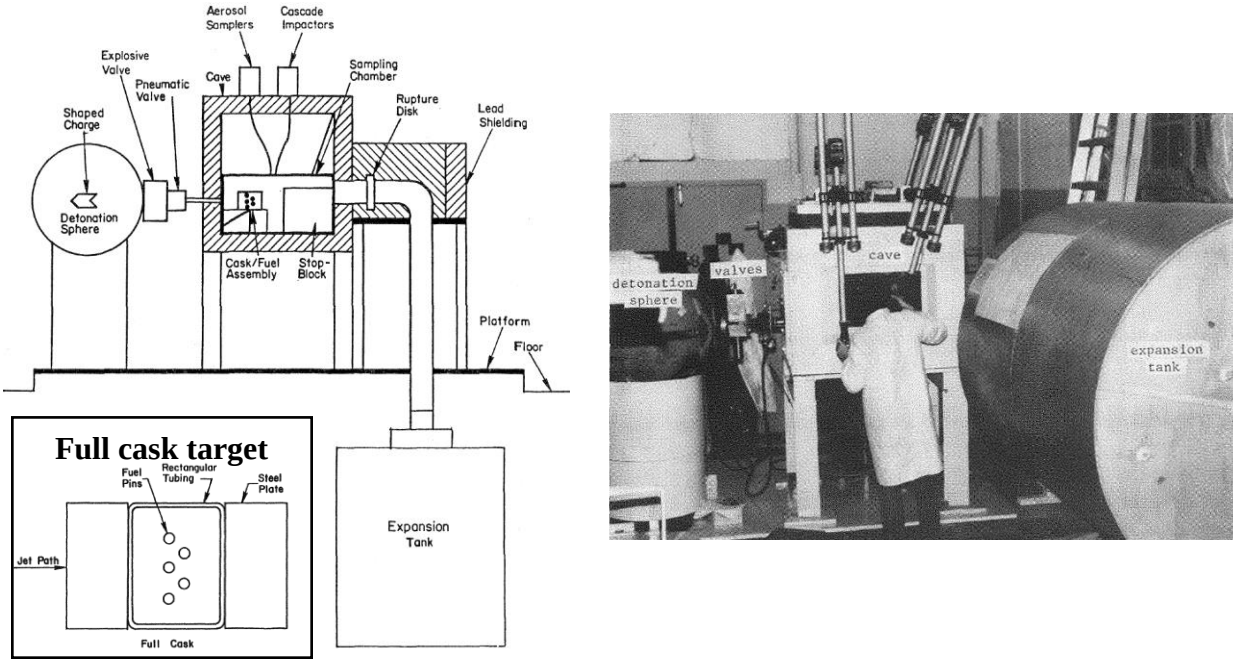

Figure 1.2 Schematics of the BCL target (lower left inset) and overall apparatus layout (upper left). Photograph of the apparatus (right). (From Schmidt, *et al.*, 1982 Figures 3-6, 3-1, and 3-2)

The major details of the BCL tests are listed below.

- SFR = 0.42 (SNF bulk filter to DUO_2 cascade impactors), 3 to 12 (bulk filter)
- 1 DUO_2 shot, 4 SNF shots (H.B. Robinson 15x15 PWR, 33 GWd/MTHM)
- Large targets (5 rodlets, 4 in. length SNF, 348 g of SNF)
- Large CSC (450 g explosives)
- Aerosol collection by cascade impactors and bulk filters

- Soot contamination limited by explosive valve separating explosive and aerosol chambers
- Focus on overall release from scaled cask with different boundary conditions
- Determination of SFR was a secondary goal

1.1.3 Sandia National Laboratories SFR Efforts

In the early 2000's, DOE and NRC partnered to reexamine the SFR by sponsoring a new test program at SNL [Molecke, *et al.*, 2008]. Like the two efforts before, this program intended to subject targets of both DUO_2 and SNF to shock loadings from a CSC. This testing effort resulted in three DUO_2 shots, as well as several shots with CeO_2. However, funding was cancelled before any shots with SNF could be conducted. Figure 1.3 shows several photographs of the SNL testing apparatus and associated equipment. This program identified many of the issues from the previous BCL and INL testing and sought to correct them.

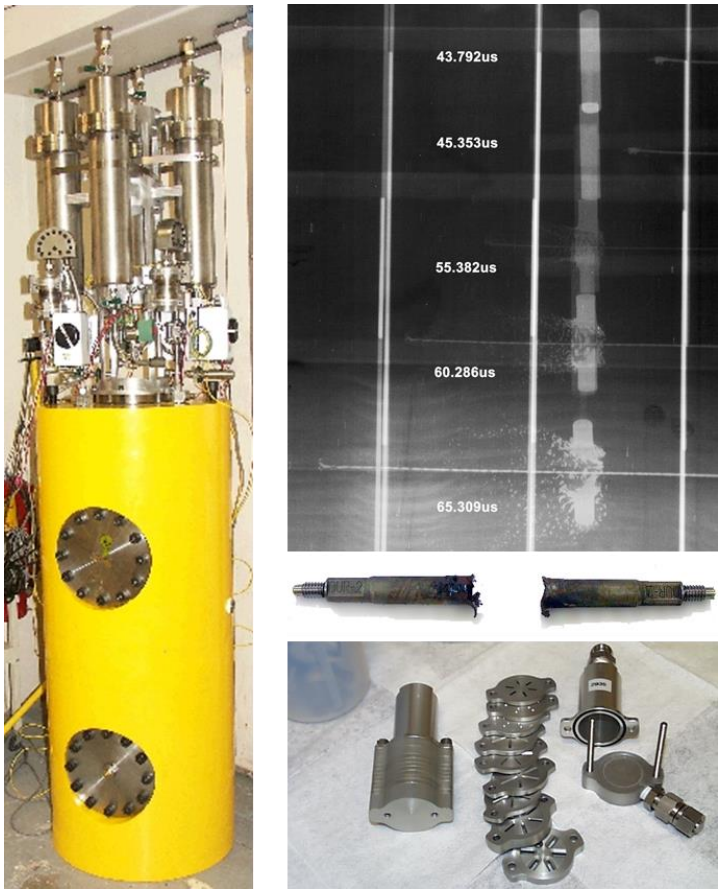

Figure 1.3 Photographs of the SNL apparatus (left), a complete and disassembled Marple cascade impactor (lower right), a disrupted target rodlet (middle right), and a target under assault (upper right). (From Molecke, *et al.*, 2008)

The major details of the SNL tests are listed below.

- SFR = Undetermined (No SNF shots)

- DUO_2 shots, No SNF shots (6 planned – 3× H.B. Robinson 15x15 PWR, 67 GWd/MTHM and 3× Surry 15x15 PWR, 36 GWd/MTHM)
- Intermediate targets (1 rodlet, 2.17 in. length SNF, 41.6 g of SNF)
- Intermediate CSC (72 g explosives)
- Aerosol collection by cascade impactors
- Heavy soot contamination on aerosol samples
- Water condensation in sample lines likely caused large experimental uncertainty and underestimates of respirable aerosols

A detailed review and error propagation analysis of the previous Sandia effort lead to a proposed improved test apparatus and test procedure [Lindgren and Durbin, 2009]. The parameters found to contribute the most error were the aerosol sample train loss, the average sample pressure measurement, the sample collection time, the number of moles of gas injected into the aerosol chamber in the pressure equilibration process, and the total disrupted mass. Aerosol loss in the sampling system contributes the most error and uncertainty to the determination of respirable release fraction (RRF). The test program proposed in the remainder of this report is based on these earlier SNL test plans with the improvements identified in the error propagation analysis as well as the lessons learned from the INL and BCL efforts.

Specifically, the most relevant lessons learned from previous SFR testing are the following.

- INL – Minimize the size of both the target and CSC such that the target is completely disrupted. This reduces the required robustness of the experimental chamber but more importantly minimizes the activity of spent fuel that needs to be handled. Second, the disrupted mass is known *a priori* by disrupting the entire target.

- BCL – Incorporate a fast-acting valve between the explosive chamber and the aerosol chamber in order to minimize the flow of soot and moisture into the aerosol chamber. Carbon particles (soot) can overwhelm the aerosol cascade impactors with deleterious effects. Furthermore, water vapor generated during the combustion of the explosives can condense in the aerosol sampling lines and leads to significant errors in the calculation of the respirable release fraction.

- SNL – Design test vessels for disposal. Vessels are designed to fit inside a 55 gallon drum to accommodate disposal at the WIPP site.

2 PROPOSED SPENT FUEL RATIO TESTING

A new series of tests are proposed to provide a defensible SFR. These tests will involve two fuel types, a high-burnup (H.B. Robinson 67 GWd/MTHM) and low-burnup (Surry 36 GWd/MTHM). Testing the two distinct fuel types will provide an important measure of the potential effect of burnup on the SFR. Samples of both fuel types are currently in the possession of ORNL. These fuel rod samples, which were generated in commercial nuclear reactors, are not considered "commercial" nuclear fuel as they were created for use as DOE-owned research material. As such, these materials are eligible for disposal at the WIPP as Fuel Element Waste (FEW) and are currently scheduled for disposal by the end of 2015. If the proposed SFR testing is conducted, SNL would ultimately send the SNF-contaminated test vessels and aerosol sampling equipment to the WIPP site for disposition as well. Figure 2.1 shows the idealized disposition path for the SFR targets and is meant to demonstrate the chain of custody of the samples, not the actual transport path. A well-defined plan for disposition is a strength of the proposed testing.

Figure 2.1 Idealized disposition path of SNF test samples.

This type of testing requires the expertise of personnel at several specialized facilities. Figure 2.2 shows the four key facilities used in the proposed SFR testing. The function and activities of

each of these installations are described in more detail later in this chapter. These key facilities and organizations include the following:

- Explosive Components Facility (ECF)
- Radiation Protection Sample Diagnostics (RPSD)
- Sandia Pulsed Reactor Facility (SPRF)
- Radiological and Mixed Wasted Management Facility (RMWMF)
- Lovelace Respiratory Research Institute (LRRI – not shown in Figure 2.2)

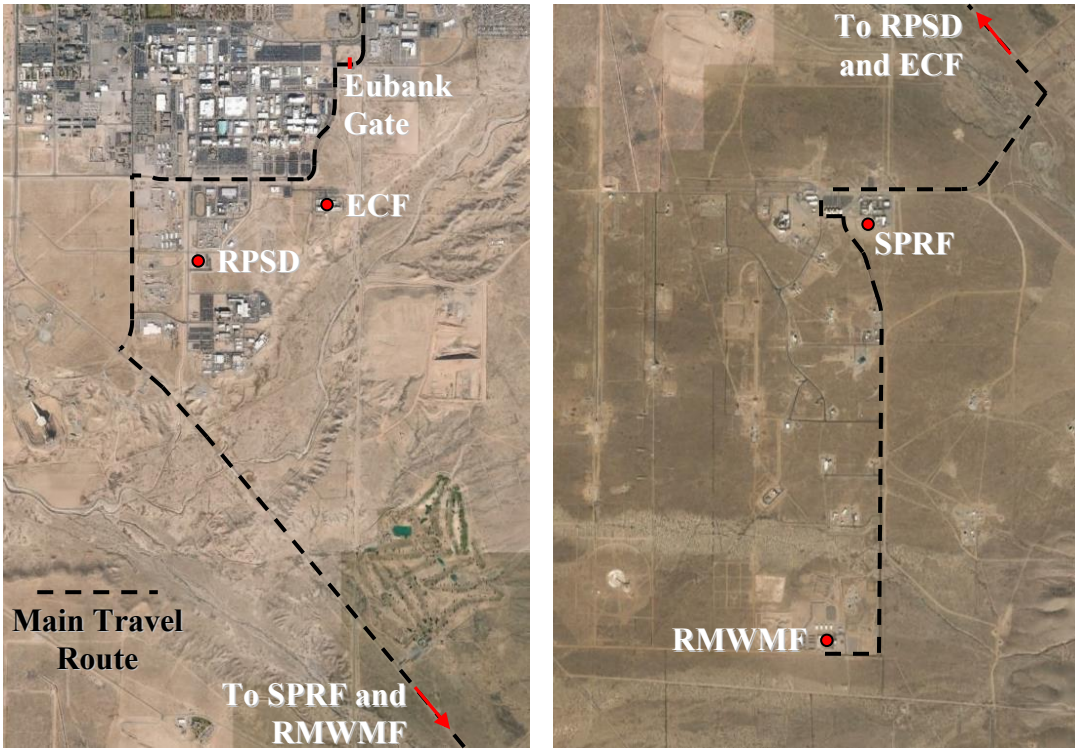

Figure 2.2 Identification of major facilities for the proposed SFR testing.

The major steps of the proposed testing are shown next.

- Targets fabricated at ORNL and transported SPRF for storage.
- Test vessels and CSC's transported from ECF to SPRF.
- Target and CSC loaded into vessel at SPRF. CSC detonated and aerosols collected.
- Contaminated vessel and aerosol samplers transported to RMWMF.
- Aerosol samples digested in acid solution at RMWMF.
- Diluted aerosol digestions transported to RPSD.
- Gamma and alpha spectroscopy and ICP-MS conducted on samples at RPSD.

- Vessel and other contaminated hardware packaged for transport to WIPP at SPRF.

2.1 General Description of the Proposed Testing

Figure 2.3 shows a conceptualization of a double-chamber test vessel that incorporates experimental improvements gleaned from reviews of previous SFR efforts. This conceptual design illustrates the functional components of the test vessel but is not a final design. The final design may evolve significantly in order to accommodate a fast-acting valve with access for charge removal or system depressurization.

Initially, (Figure 2.3a) the explosive chamber is charged with one atmosphere of krypton, the aerosol chamber is charged with one atmosphere of argon. A rupture disk keeps the gases separated. The sample train is pressurized with helium to the anticipated chamber pressure at the time of sample collection. A thermal conductivity sensor in the sample system reads the high thermal conductivity of helium. If required, the entire chamber and sample system is heated to the expected dew point of the aerosol sample to prevent moisture condensation.

When the CSC is detonated (Figure 2.3b) the jet disintegrates the fuel rodlet releasing aerosols. Some combustion gases are explosively injected into the aerosol chamber along with the CSC jet. The majority of the combustion products and energy are released into the krypton in the explosive chamber. The krypton mixture in the explosive chamber reaches a higher temperature and pressure than the argon mixture in the aerosol chamber.

This causes the gas in the explosive chamber to violently flow into the aerosol chamber mixing krypton and more combustion gases into the aerosol-laden argon until the fast-acting valve closes (Figure 2.3c). The fast-acting valve is intended to limit this influx of combustion gases and prevent the carbon soot from overloading the aerosol collection devices. Next, the concentration of aerosols and gases in the aerosol chamber is established.

After the temperatures in the aerosol chamber equilibrate (~15 seconds), the sample valves are opened (Figure 2.3d). A constant sample flow is drawn through the cascade impactor into a vacuum reservoir connected to the sample system through a critical flow orifice. The pressure in the sample system and the aerosol chamber are approximately equal so there is no sudden pressurization of the sample system to compromise the aerosol sample. Aerosol-laden gas is drawn into the sample system and displaces the helium. When the sample gas reaches the impactor, the thermal conductivity sensor detects the lower thermal conductivity of the krypton argon mixture, which denotes the start time of sampling.

After the desired sampling time, the sample valves are closed. The gas collected in the gas sample bottle is analyzed for nitrogen, krypton, argon and carbon dioxide. The carbon dioxide and nitrogen provides a tie to all gaseous combustion products through the reaction stoichiometry. The relative concentrations of N_2, Ar, Kr, and CO_2 together with the initial amount of Ar loaded into the aerosol chamber and the dew point measurement of the aerosol sample stream allows the calculation of the initial moles of aerosol-laden gas.

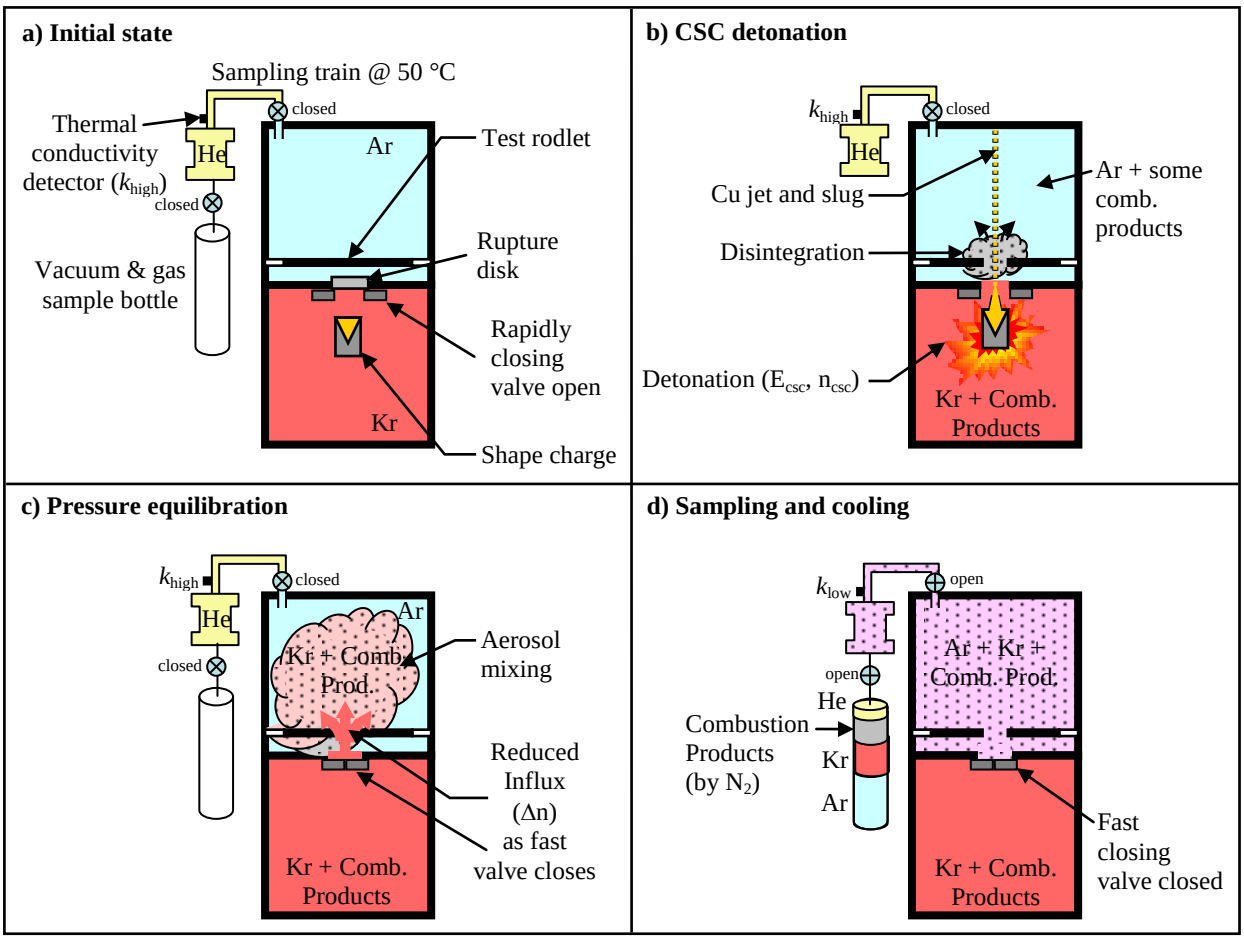

Figure 2.3 Sequencing and details of an improved experimental setup for measuring the SFR.

There are a number of important constraints to consider in the design of the double chamber test vessel:

- The overall dimensions of the test vessel must accommodate disposal at WIPP. This means that the maximum outer diameter of the vessel is less than 22.5 in. in order to fit in a standard 55 gallon drum, which is then loaded into a RH-TRU 72-B payload canister. The vessel will be designed such that two or ideally three test vessels will fit within one transport cask.
- The test vessel must be designed and certified for use with the chosen CSC and the expected vessel overpressure. Technical Area V safety guidelines require a factor of safety that is twice that required by the ASME Boiler and Pressure Vessel Code. The test vessel design must be proof tested by detonating the proper amount of explosive within the vessel that will produce twice the stress generated by the design CSC.
- The test vessel design must accommodate the installation and operation of a fast acting normally open valve. The valve will be sized to allow the passage of the CSC jet and subsequent slug but close in less than 10 ms (0.01 s) or before appreciable amounts of combustion products flow from the explosive chamber into the aerosol chamber. The

valve is not required to maintain containment of the radioactive aerosols between the chambers. The size of the valve must allow for proper stand-off between the CSC and the target. The CSC will likely be mounted close or directly to the valve. If an explosive or pyrotechnic valve is used, accommodation may be required to allow removal of the valve charge prior to disposal in the unlikely event of a misfire. If a pressure driven valve is used accommodation may be required to allow depressurization of the valve prior to disposal.

- The test vessel design must accommodate the direct manual installation of a spent fuel target from a custom designed container in the SPRF.
- Other design features of the test vessel include a replaceable CSC jet stop block that does not incorporate plastics, lifting points, and penetrations. These penetrations include aerosol sampling ports, chamber gas purge, and leads for CSC and fast acting valve operation.

2.2 Oak Ridge National Laboratory (Target Design and Fabrication)

ORNL will be tasked with developing a procedure to defuel rod segments, weld end plugs, and seal weld the SNF targets. The rod segments will be identified as to the source rod and rod location. A small sample of the spent fuel removed from the rod in the fabrication process will be reserved as a calibration standard for use in the development and verification of analytical procedures. The fabricated fuel rod segments will be installed in custom shielded containers and shipped to Sandia. A final selection on the shipping cask has not been made, but several candidates (e.g. 9975) with active certificates of compliance (CoC) exist. The CoC for any chosen cask would likely need to be updated to reflect the contents of the SNF targets. The rod segment and end plug design must accommodate the direct manual installation of a spent fuel target from the custom shielded containers into the aerosol chamber at the SPRF.

Figure 2.4 shows a drawing of the target design from the previous SNL program. The proposed targets would be similar but would have less SNF per target, 1 to 3 pellets of fuel (0.6 to 1.8 in.) as opposed to 4 pellets (2.17 in.). Also, the proposed targets would not be pressurized as was intended for the previous target design. The design for the Surry targets would also contain 1 to 3 pellets of SNF. Next, the radiological contents and dose rates for the proposed targets are assessed for the H.B. Robinson targets. Because the burnup is lower and the fuel is older, the Surry targets are not explicitly treated but are expected to be lower activity than the H.B. Robinson targets.

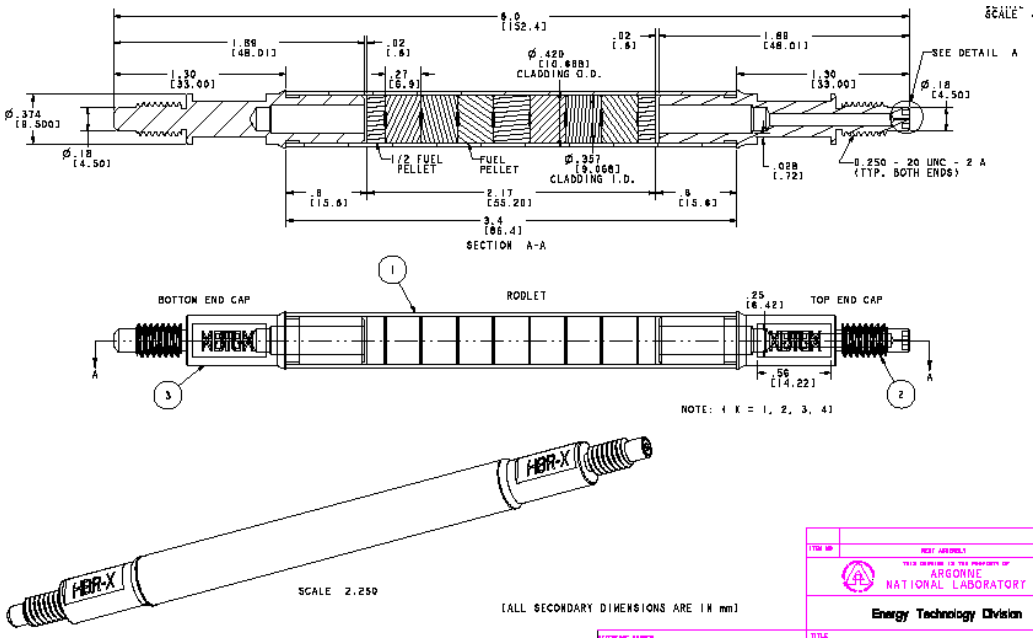

Figure 2.4 Previous SNL H.B. Robinson spent fuel rodlet design. (From Molecke *et al.*, 2008)

The proposed targets are comprised of up to three pellets of SNF from the H.B. Robinson power reactor. Each test will contaminate a test vessel, a series of sampling devices/sampling train (cascade impactors and bulk filters), and the vacuum bottles. The overall activities of each contaminated element are summarized below. Details of these estimates are given in Appendix A.

- Test target and vessel – 12 Ci (Pre- and post-detonation)
- Maximum sampling devices/sampling train (combined) – 0.6 Ci (Post-detonation)
- Realistic sampling devices/sampling train (combined) – 0.16 Ci (Post-detonation)
- Vacuum bottles (combined) – 0.06 Ci (Post-detonation)

The dose rates associated with these activities are estimated below based on the A_1 quantity (assumes gamma-exposure dominates).

- Test target and vessel – 0.05 Sv/h (5 rem/h)
- Maximum sampling devices/sampling train (combined) – 2.5 mSv/h (250 mrem/h)
- Realistic sampling devices/sampling train (combined) – 0.67 mSv/h (67 mrem/h)
- Vacuum bottles (combined) – 0.023 mSv/h (2.3 mrem/h)

Note that each test may employ multiple sampling devices. Therefore, the individual device activity and dose rate would scale by the number of devices, assuming equal collection amongst the devices. Also, the cascade impactors include several stages for successively smaller

particles. If these stages are isolated from each other after initial disassembly, the stage sample would contain a subset of the overall device radioactivity.

2.3 Explosive Components Facility (Explosives Design and Surrogate Testing)

The Explosive Components Facility (ECF) includes 96,000 ft^2 of laboratories, diagnostic centers and performance facilities for the research and development of advanced explosive technology ideal for the purposes of this study. Three tasks will be completed at the ECF. The CSC for use in testing will be selected and characterized. The integration of the fast-acting valve is also expected to occur at the ECF. Finally, the majority of the non-radioactive shots will be conducted at the ECF.

The size of the CSC must be optimized to minimize the amount of explosives but still powerful enough to completely disrupt the fuel rod target. The mass of explosives used in the CSC and the design of the test vessel are coupled. A test vessel with thinner walls can be used with a smaller explosive. The size of the CSC also determines the optimal standoff from the target, typically 5 to 6 charge diameters. The shorter standoff for a small CSC influences the test vessel design especially if a fast acting valve is placed between the aerosol sampling and explosive chambers. The fuel segment target design size and the CSC design size are also coupled and must be determined in conjunction with each other. The CSC jet timing and interaction with the target will be visualized and evaluated using flash x-ray imaging in initial testing with surrogates at the ECF.

The introduction of combustion products into the aerosol chamber causes a number of problems. First, abundant soot particles can overload the aerosol impactor stages and reduce separation efficiency. The sampling time must be reduced to limit the total particle load on the separation stages. The reduced sampling time also reduces the amount of fuel aerosols collected and thus the detection sensitivity of the method. Second, typical explosives used in CSCs such as HMX contain hydrogen, which produces water as a combustion product. If the dew point of the gas in the aerosol chamber is raised above the temperature of the test vessel and aerosol sampling system, the condensation that occurs in the vessel and sample train will significantly affect the aerosol measurement results. Finally, the total moles of gas in the aerosol chamber at the time of sampling are a crucial piece of information. The variability of the amount of gas injected into the aerosol chamber from the CSC detonation and subsequent flow from the explosive chamber needs to be quantified.

Characterization of the individual test components and integrated apparatus will be conducted using surrogate targets (both hafnia, HfO_2, and DUO_2). The testing using the Zircoloy clad HfO_2 surrogate targets will be less complicated because HfO_2 does not present toxicity or radiological hazards. The HfO_2 target testing will be used to refine the experimental procedures and develop statistics on the repeatability of the overall approach. Testing with the DUO_2 targets is complicated by the toxicity and slight radioactivity of depleted uranium. The test vessel and aerosol sample train will need to be decontaminated between tests.

The basic steps for conducting a test are:

1. Ready the test vessel. Install a new valve if single-use valves are used. Otherwise arm valve.
2. Install the aerosol sampling systems.
3. Install the surrogate target.
4. Install the CSC
5. Ready the data acquisition and control systems.
6. Conduct test shot.
7. Remove aerosol impactors for processing
8. Open test vessel chambers and clean out debris and make ready for next test.

2.4 Lovelace Respiratory Research Institute (Aerosol Sampling)

LRRI will be contracted to provide support for the design and characterization of the aerosol sampling systems. The design of the aerosol sampling system depends on the moles of aerosol laden gas contained inside the aerosol chamber, the concentration of aerosol present in the gas and the desired aerosol size cuts to be collected. The aerodynamic diameter size cuts depend on the flow rate drawn through the impactor, and the sampling time depends on when the stages begin to become overloaded with particles. Minimization of soot laden combustion gases from the explosive chamber into the aerosol chamber will allow longer sampling times and increase the sensitivity of the measurement.

An important step in reducing the uncertainty in the aerosol measurement is to conduct a calibration of the sample system. The calibration of both the sample train and cascade impactor should be performed using a well-known fluorometric method [Rader, *et al.*, 1991]. In this method, monodisperse oleic acid oil droplets generated with the vibrating orifice aerosol generator are tagged with trace amounts of a fluorescent dye (uranine) and introduced into the sample train and impactor. After the test, the sample train and impactor are disassembled and oleic acid/uranine deposits on various component surfaces are collected in solution and quantified fluorometrically to determine where a given sized particle was captured or lost. The characterization would be performed under the experimental initial conditions including the imposed noble gas atmospheres. The high temperature and pressure conditions may also be simulated for increased accuracy.

2.5 Sandia Pulsed Reactor Facility (SNF Testing)

The SPRF is a small research reactor facility located in Technical Area (TA) 5 at SNL near Albuquerque, New Mexico. The facility is designed for operation of fast pulsed reactors and low power critical experiments. The SPRF is a Hazard Category II nuclear facility and contains several Category III Special Nuclear Materials Material Balance areas. The primary mission of the SPRF is to provide capabilities for the performance of low power/low enrichment criticality experiments and criticality safety training for the DOE complex. A secondary mission is to provide facilities to support other experiment activities performed by SNL (*e.g.* fissionable material handling in experiment preparation and performance).

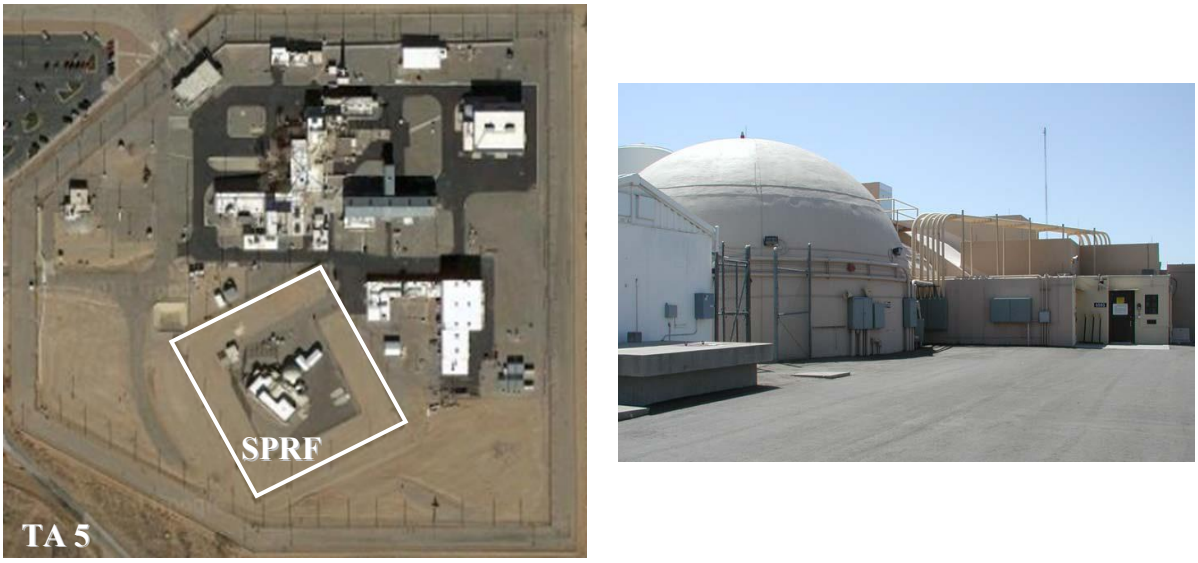

Figure 2.5 Aerial photograph (left) and ground-level photograph (right) of the SPRF.

In order to conduct these tests at SPRF, several modifications to the current facility technical work document are required. First, a safety basis supplement to institute technical safety requirements (TSR) level controls for this experiment will be produced. These controls will be a "safety significant" containment, which will have to be designed by explosive group to withstand internal projectiles and twice the maximum pressure expected from the detonation. The explosives cannot be mixed with or contiguous (touching) the radioactive material. An explosives license for the SPRF will also need to be obtained. In addition, a readiness review will need to be conducted to address the new activities.

The test chamber will be made ready at SPRF. First, the aerosol sampling system will be installed onto the aerosol chamber, and then the fast-acting valve and CSC will be installed by explosive technicians into the explosive chamber. The test chamber will then be placed inside of the shield cask. The spent fuel target will be directly inserted into the aerosol chamber from the transport shield. After the shot, the entire experimental chamber will be transported to the RMWMF for removal and processing of the aerosol sampling.

After the aerosol system has been removed, the test chamber will be returned to SPRF for storage. The details of the contaminated vessels' storage will depend on the radiation levels measured on the vessels. Packaging in the RH-TRU 72-B transport casks for disposal to WIPP will be conducted at SPRF.

2.6 Radioactive and Mixed Waste Management Facility (SNF Aerosol Sample Preparation)

Operations at RMWMF regularly include the sorting, treatment, storage, packaging, and shipping of radiological, mixed, and transuranic (TRU) waste forms. Figure 2.6 shows a photograph of the entire RMWMF facility and a photograph of typical glove box operations. Once the test has been conducted in SPRF and the test vessel has been transported to the RMWMF, personnel will separate the cascade impactors/gas cylinder assemblies from the experiment vessel using glove bags/sleeves. In addition, the assembly will be vented into the

Building 6920 ventilation system through a HEPA filter attached to the experiment vessel. This will leave the vessel at ambient pressure, a crucial requirement for disposal at WIPP. Personnel will separate the gas cylinder from the cascade impactor or bulk filter. The aerosol-laden media will be transferred into the glove box. In the glove box, personnel will remove the filters from the aerosol samplers and place them in containers for portable gamma spectroscopy measurements. Containers with filters will be decontaminated, surveyed out of the glove box, and transferred to RPSD for gamma spectroscopy measurements. The empty experiment vessel will be inspected for transportability and transferred back to SPRF for storage. The vessel will be removed from the shield cask at SPRF so the cask can be re-used in the next shot.

Figure 2.6 Aerial photograph (left) and glove box operations (right) at the RMWMF.

After gamma spectroscopy measurements are completed, filters will be returned to the glove box. Filters will be removed from the container, transferred to capsules, mixed with strong acid, and loaded into carousels for microwave digestion, where the entire sample is heated and dissolved into solution. Carousels will be returned to the glove box and the acid solution will be diluted to five liters per sample. Containers with the five liter aliquots will be inspected for transportability and transferred to RPSD for radiochemical analysis. RPSD will return residual liquid from the five liter aliquots to the RMWMF. Acids will be neutralized and solidified for disposition as low-level waste. Primary waste from the cascade impactors will be segregated and managed as remote-handled transuranic waste if necessary. If remote handling is required, the waste will returned to TA-V in 55-gallon drums for disposition with other remote-handled waste.

2.7 Radiation Protection Sample Diagnostics (Radiochemistry Analysis)

The RPSD provides radioactive analytical services to customers at SNL and other government agencies compliant with applicable standards and accreditations. These sevices include gamma spectroscopy, alpha spectroscopy, inductively coupled plasma mas spectroscopy (ICP-MS), and gas chromatography mass spectroscopy (GC-MS).

Upon removal of the filter media from the cascade impactor, the analytical laboratory will perform non-destructive assay of the filter using portable gamma spectroscopy analysis. The goal of the gamma spectroscopy measurement is to quantify cesium and europium. This information could be used to establish the enhancement factor between the cesium and/or

europium and possibly the transuranics in the sample. For the DUO_2, the goal is to quantify the ^{238}U activity utilizing lower levels of activity thereby allowing for the use of environmental level sample preparation techniques.

Following gamma spectroscopy analysis, microwave digestion will be performed on the media using strong acids. The digestate will then be diluted and passed through extractant resins for isotopic separations ($^{238/239}Pu$, ^{237}Np, ^{241}Am, $^{234/235/238}U$, and/or $^{242/243/244}Cm$) before analysis by alpha spectroscopy. The losses associated with sample preparation will be corrected by adding a radioactive tracer to ensure all preparation losses are accounted for during the digestion phase. The digestate will also be analysed for total uranium (^{235}U and ^{238}U) using inductively coupled plasma – mass spectrometery (ICP-MS) analysis. The same total uranium analysis will be performed on the aerosol samples derived from the spent fuel and DUO_2 targets in order to produce the best comparison for determination of the SFR.

2.8 Waste Isolation Pilot Plant (Waste Management)

The waste stream generated from this test program is anticipated to be newly-generated, remote-handled (RH), transuranic debris waste. This waste will consist of contaminated experimental vessels used in defense-funded experiments, which will qualify for disposal at WIPP. The vessels are constructed of greater than 90% metal with small amounts of other materials. The radiological characteristics will be well known as the fuel in the Fuel Experimental Waste (FEW) is from Oak Ridge National Laboratory with well documented isotopic data.

The experimental vessels will be constructed to fit into 55-gallon, WIPP-approved steel drums for disposal at the WIPP. The 55-gallon drums are not considered containment and are used to facilitate easier handling at WIPP. The final form of the FEW will have no sealed containers greater than four liters; contain no liquids, corrosives, flammables, or reactives (explosives). Any explosives used in the experiment will be demonstrated to have been expended and will be properly documented. All inner chambers will be vented through HEPA filters and demonstrated to be permanently at atmospheric pressure.

Sandia will coordinate with WIPP for characterization, certification, and disposal support of the experimental vessels prior to waste generation. Sandia will provide the Central Characterization Project (CCP) with the required information to prepare an Acceptable Knowledge Summary Report, a Radiological Report, and Certification Plan. Visual examination (VE) operators will observe and document the assembly, disassembly, and packaging. Dose-to-curie (DTC) operators will perform DTC measurements on the test vessels to meet WIPP characterization and certification requirements. After all experiments have been completed, the drums will be transported to WIPP for disposal.

3 BUDGET AND SCHEDULE OF PROPOSED SFR TESTING

The proposed SFR measurement project involves the careful coordination of several specialized facilities and groups of personnel. The entire effort will require a minimum of 4 years to complete. Recall that the SNF samples will only be available through the end of 2015, after which no alternative test materials exist. Two rough order of magnitude[†] (ROM) project budgets are presented for consideration. A ROM cost estimate is generally considered to have uncertainty bounds of -30% to +50%.

The first and lower budget estimate includes the minimum number of shots of both surrogates and SNF to produce a defensible SFR. This budget includes 3 shots each of H.B. Robinson and Surry fuel samples for a total of 6 SNF shots. Fifteen total surrogate shots would be conducted, 5 with DUO_2 and 10 with HfO_2. Table 3.1 gives the ROM budget and schedule for these SFR activities. The first year is spent preparing SNF targets, preparing reports to accept and dispose of the SNF targets, and designing the various testing components, most notably the test chamber and CSC. The second year sees the completion of SNF target fabrication as well as test system integration using HfO_2 targets. Year three includes activities to support all of the DUO_2 shots and half the SNF shots. Finally, the remainder of the SNF targets is consumed in the fourth year and disposal activities are completed. Table 3.2 presents further cost details of the minimal number of shots budget.

Table 3.1 Rough order of magnitude budget estimate and schedule for a SFR determination program with a minimal number of shots.

	Year 1	Year 2	Year 3	Year 4	Total
Primary Activities ⇒	Preparation	HfO_2 shots	DUO_2 & SNF shots	SNF shots & Disposal	
SNF Target Fabrication	$500,000	$510,000	$0	$0	$1,010,000
Explosives	$1,370,000	$491,000	$363,000	$18,000	$2,240,000
Aerosols	$259,000	$592,000	$416,000	$215,000	$1,480,000
SNF Shots	$200,000	$60,000	$310,000	$210,000	$780,000
SNF Sample Preparation	$50,000	$75,000	$393,000	$318,000	$840,000
SNF Analysis	$0	$16,000	$642,000	$432,000	$1,090,000
WIPP Disposal	$125,000	$0	$0	$984,000	$1,110,000
Project Management	$270,000	$395,000	$395,000	$420,000	$1,480,000
Project Administration	$194,000	$150,000	$176,000	$182,000	$700,000
Total	$2,970,000	$2,290,000	$2,690,000	$2,780,000	$10,730,000

[†] Contained herein is a Rough Order of Magnitude (ROM) cost estimate that has been provided to enable initial planning for this proposed project. This ROM cost estimate is submitted to facilitate informal discussions in relation to this project and is NOT intended to commit Sandia National Laboratories (SNL) or its resources.

Table 3.2 Detailed project costs for the SFR determination program with minimal number of shots.

Category	Fixed Cost	Unit Cost		# Samples		Cost/Test	# Tests		Total		Summary
SNF Target Fabrication											**ORNL**
Spent fuel target fabrication	$500,000					$85,000	6	targets	$510,000		$1,010,000
Explosives											**ECF**
CSC design	$100,000										$2,240,000
Explosive valve design	$150,000										
Timing & target disruption study	$500,000										
Chamber design & Cert	$500,000										
Chambers		$50,000	per chamber				8	chambers	$400,000		
Fast acting valves		$5,000	per valve				26	valves	$130,000		
CSC		$1,000	per CSC				36	CSCs	$36,000		
Surrogate Testing											
HfO_2		$25,000	per test				10	tests	$250,000		
DUO_2		$35,000	per test				4	tests	$140,000		
Spent Fuel Testing		$5,000	per test				7	tests	$35,000		
Aerosols											**LRRI**
System design	$150,000										$1,480,000
System calibration	$100,000										
Cascade impactors		$1,500		2	per test	$3,000	9	tests	$27,000		
Experimental setup						$5,000	21	tests	$105,000		
Data evaluation						$33,000	21	tests	$693,000		
Tech support contract		$100,000	per year				4	yrs	$400,000		
SNF Shots											**SPRF**
Safety Basis Supplement	$150,000										$780,000
Explosives license	$50,000										
Startup activities	$100,000										
Testing		$60,000	per test				7	tests	$420,000		
Lead shield containers						$5,000	12	lead pigs	$60,000		
SNF Sample Preperation											**RMWMF**
Facility modifications	$50,000										$840,000
Cask	$75,000										
Dry runs	$50,000										
Misc. tools	$25,000										
Sample digestion		$5,000	per sample	16	samples/test	$80,000	7	tests	$560,000		
Waste management	$75,000										
SNF Analysis											**RPSD**
HfO_2		$100	per sample	16	samples/test	$1,600	10	tests	$16,000		$1,090,000
DUO_2		$500	per sample	16	samples/test	$8,000	5	tests	$40,000		
Sample Preperation											
Microwave	$90,000										
Procedure development	$10,000										
Spent Fuel											
Procedure development	$50,000										
ICP-MS & alpha spec	$20,000	$5,000	per sample	16	samples/test	$80,000	6	tests	$480,000		
Gamma spectroscopy		$4,000	per sample	16	samples/test	$64,000	6	tests	$384,000		
WIPP Disposal											**WIPP**
AK report	$88,000										$1,060,000
Rad report	$37,000										
DTC	$90,000										
VE	$200,000										
Records/Doc service	$22,000										
Supplies	$12,000										
Labor	$450,000										
Travel	$100,000										
SPRF	$50,000										
Transport & consumables						$10,000	6	tests	$60,000		
Project Management											**Proj Management**
Technical management		$175,000	per year				4	yrs	$700,000		$1,480,000
Report		$175,000	per year				4	yrs	$700,000		
Travel		$20,000	per year				4	yrs	$80,000		
Project Administration	$702,000.0										
Total	**$4,500,000**								**$6,230,000**		**$10,730,000**

Utilizing a minimum number of shots comes with an associated technical risk. The program could likely suffer 1 or 2 outliers in the surrogate testing and perhaps 1 outlier in the SNF testing and still produce a drastically improved and definitive estimate of the SFR. However, the variance and resulting uncertainty of the SFR estimate would be drastically improved by increasing the number of shots by a factor of 2 while increasing the total project cost by a factor of 1.4. This "optimal-shot" proposal would use 6 H.B. Robinson, 6 Surry, 10 DUO_2, and 20 HfO_2 targets. Table 3.3 gives the ROM budget and schedule of a test program with twice as many shots. This estimate assumes that the personnel and facilities for testing in the minimal-shot proposal were utilized at availabilities of less than 50% and can accommodate twice as many shots in the same time frame. The project management remains the same based on the same four-year program duration. The WIPP disposal budget remains nearly the same because the disposal reports and inspections required for disposition are largely fixed costs. The cost of every other category of effort scales between 1.4 to 1.6 times more than the minimal-shot proposal with the exception of SNF analysis. This effort scales at 1.8 because the analysis costs are largely driven by the ICP-MS and gamma spectroscopy analyses after each SNF shot. Table 3.4 gives the cost details of the optimal-shot proposal.

Table 3.3 Rough order of magnitude budget estimate and schedule for a SFR determination program with an optimal number of shots.

	Year 1	Year 2	Year 3	Year 4	Total
Primary Activities ⇒	Preparation	HfO_2 shots	DUO_2 & SNF shots	SNF shots & Disposal	
SNF Target Fabrication	$500,000	$1,020,000	$0	$0	$1,520,000
Explosives	$1,370,000	$965,000	$755,000	$33,000	$3,120,000
Aerosols	$259,000	$978,000	$726,000	$328,000	$2,290,000
SNF Shots	$200,000	$60,000	$490,000	$390,000	$1,140,000
SNF Sample Preparation	$50,000	$75,000	$633,000	$558,000	$1,320,000
SNF Analysis	$0	$32,000	$1,114,000	$864,000	$2,010,000
WIPP Disposal	$125,000	$0	$0	$1,044,000	$1,170,000
Project Management	$270,000	$395,000	$395,000	$420,000	$1,480,000
Project Administration	$194,000	$247,000	$288,000	$255,000	$980,000
Total	$2,970,000	$3,770,000	$4,400,000	$3,890,000	$15,030,000

Table 3.4 Detailed project costs for the SFR determination program with optimal number of shots.

Category	Fixed Cost	Unit Cost		# Samples		Cost/Test	# Tests		Total		Summary
SNF Target Fabrication											**ORNL**
Spent fuel target fabrication	$500,000					$85,000	12	targets	$1,020,000		$1,520,000
Explosives											**ECF**
CSC design	$100,000										$3,120,000
Explosive valve design	$150,000										
Timing & target disruption study	$500,000										
Chamber design & Cert	$500,000										
Chambers		$50,000	per chamber				14	chambers	$700,000		
Fast acting valves		$5,000	per valve				47	valves	$235,000		
CSC		$1,000	per CSC				57	CSCs	$57,000		
Surrogate Testing											
HfO_2		$25,000	per test				20	tests	$500,000		
DUO_2		$35,000	per test				9	tests	$315,000		
Spent Fuel Testing		$5,000	per test				13	tests	$65,000		
Aerosols											**LRRI**
System design	$150,000										$2,290,000
System calibration	$100,000										
Cascade impactors		$1,500		2	per test	$3,000	15	tests	$45,000		
Experimental setup						$5,000	42	tests	$210,000		
Data evaluation						$33,000	42	tests	$1,386,000		
Tech support contract		$100,000	per year				4	yrs	$400,000		
SNF Shots											**SPRF**
Safety Basis Supplement	$150,000										$1,140,000
Explosives license	$50,000										
Startup activities	$100,000										
Testing		$60,000	per test				13	tests	$780,000		
Lead shield containers						$5,000	12	lead pigs	$60,000		
SNF Sample Preperation											**RMWMF**
Facility modifications	$50,000										$1,320,000
Cask	$75,000										
Dry runs	$50,000										
Misc. tools	$25,000										
Sample digestion		$5,000	per sample	16	samples/test	$80,000	13	tests	$1,040,000		
Waste management	$75,000										
SNF Analysis											**RPSD**
HfO_2		$100	per sample	16	samples/test	$1,600	20	tests	$32,000		$2,010,000
DUO_2		$500	per sample	16	samples/test	$8,000	10	tests	$80,000		
Sample Preperation											
Microwave	$90,000										
Procedure development	$10,000										
Spent Fuel											
Procedure development	$50,000										
ICP-MS & alpha spec	$20,000	$5,000	per sample	16	samples/test	$80,000	12	tests	$960,000		
Gamma spectroscopy		$4,000	per sample	16	samples/test	$64,000	12	tests	$768,000		
WIPP Disposal											**WIPP**
AK report	$88,000										$1,120,000
Rad report	$37,000										
DTC	$90,000										
VE	$200,000										
Records/Doc service	$22,000										
Supplies	$12,000										
Labor	$450,000										
Travel	$100,000										
SPRF	$50,000										
Transport & consumables						$10,000	12	tests	$120,000		
Project Management											**Proj Management**
Technical management		$175,000	per year				4	yrs	$700,000		$1,480,000
Report		$175,000	per year				4	yrs	$700,000		
Travel		$20,000	per year				4	yrs	$80,000		
Project Administration	$983,000.0										
Total	**$4,780,000**								**$10,250,000**		**$15,030,000**

4 SUMMARY

Sabotage of spent nuclear fuel remains a concern decades after attacks against spent fuel casks were first analyzed. A limited number of full-scale tests and supporting efforts using surrogate materials, typically depleted uranium dioxide (DUO_2), have been conducted in the interim to more definitively determine the source term from these postulated events. The conversion of these full-scale results to a realistic source term requires a relative measure of how DUO_2 and actual spent fuel respond to the same attack. The Spent Fuel Ratio (SFR) is defined as the mass of respirable aerosol generated by an attack on spent nuclear fuel (SNF) compared to that of an otherwise identical DUO_2 surrogate. Determination of the SFR has proven difficult. Attempts by Idaho National Laboratory and Battelle Columbus Laboratories in the 1980's generated SFR estimates with unacceptably large uncertainties. The most recent effort conducted at Sandia in the 2000's did not advance to the point of testing spent fuel. Past testing results provide estimates of the SFR ranging from 0.42 to 12 and include suboptimal experimental techniques and data comparisons. The large uncertainty in the SFR has led to continual criticism from nuclear safety advocates. A defensible SFR must be measured in order to accurately define source terms for security-related consequence analyses.

A new series of tests are proposed to provide a technically and statistically defensible SFR based on a review of earlier efforts and a detailed error propagation analysis [Lindgren and Durbin, 2009]. These tests will involve two fuel types, a high-burnup (H.B. Robinson 67 GWd/MTHM) and low-burnup (Surry 36 GWd/MTHM). The testing of the two fuel types will provide an important measure of the effect of burnup on the SFR. Samples of both fuel types are currently in the possession of ORNL and are the same used in the original SFR studies in the 1980's and were intended for use in a modern effort at Sandia National Laboratories (SNL) in the 2000's. These fuel rod samples, which were generated in commercial nuclear reactors, are not considered "commercial" nuclear fuel as they created for use as DOE-owned research material. As such, these materials are eligible for disposal at the Waste Isolation Pilot Plant (WIPP) and are currently scheduled for disposal by the end of 2015. If the proposed SFR testing is conducted, SNL would ultimately send the SNF-contaminated test vessels and aerosol sampling equipment to the WIPP site for disposition as well. A well-defined path to disposition is a strength of the proposed testing.

The major experimental improvements in the proposed test series learned as a result of previous testing efforts are:

- Minimize the size of the target and CSC
- Disrupt entire target such that the disrupted mass is known *a priori*
- Use a fast-closing valve to minimize the explosives-generated combustion gases in the aerosol chamber, thereby reducing soot contamination in the sampling system and preventing condensation
- Fill each experimental chamber with a unique noble gas to provide accurate initial conditions for aerosol concentration analysis

The determination of the SFR requires the use of highly specialized facilities and personnel for the design and safe handling of combined explosive and radioactive components. With the exception of the SNF rodlet fabrication at ORNL, SNL has the facilities and expertise for conducting all aspects of the required work including:

- Combine explosives with spent fuel in an available Hazard Category II nuclear facility
- Process aerosol samples in a radiological facility with shielded glove boxes and microwave digester
- Quantify radioactive samples with sophisticated sample preparation methods and analytical instrumentation
- Store contaminated test chambers until properly packaged and shipped directly to WIPP for remote handling disposal

The lower program budget estimate of $11M includes the minimum number of shots of both surrogates and SNF to produce a defensible SFR. This budget includes 3 shots each of H.B. Robinson and Surry fuel samples for a total of 6 SNF shots. The first year is spent preparing SNF targets, preparing reports to accept and dispose of the SNF targets, and designing the various testing components, most notably the test chamber and CSC. The second year sees the completion of SNF target fabrication as well as test system integration using HfO_2 targets. Year three includes activities to support all of the DUO_2 shots and half the SNF shots. Finally, the remainder of the SNF targets is consumed in the fourth year and disposal activities are completed. Utilizing a minimum number of shots comes with an associated technical risk. The program could likely suffer one or two outliers in the surrogate testing and perhaps one outlier in the SNF testing and still produce a drastically improved and definitive estimate of the SFR. However, the variance and resulting uncertainty of the SFR estimate would be greatly improved by doubling the number of shots while increasing the total project cost by only a factor of 1.4. This "optimal-shot" program is estimated to cost $15M.

A defensible SFR is badly needed for storage and transportation security analyses. This effort should be initiated now in order to secure the only known available SNF samples with a clearly defined disposition path.

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APPENDIX A: H.B. ROBINSON TARGET RADIOLOGICAL ASSESMENT

As part of the previous effort at SNL, the nuclear inventory of the proposed spent fuel targets from the H.B. Robinson reactor was characterized by program partners at GRS. The total activity of the spent fuel is dominated (> 99.6%) by a subset of 17 radioisotopes. Table A.1 gives the activity per metric ton of heavy metal (MTHM) of these dominant radioisotopes at three different times after offload (April 1995). The unabridged results of that isotopic assay are included in Table A.2 and include the relative activities for 229 radioisotopes. The GRS assay reported specific activities for discharge (t = 0 yr) and 8.5 yr after offload. The 20 yr activities are estimated by assuming an additional 11.5 yr decay time from the GRS assay. This 20 yr decay time gives the activity at the end of calendar year 2014.

The A_1 and A_2 quantities for a radioisotope or mixture of radioisotopes represent the activity of the sample source required to cause a dose rate of 0.1 Sv/h (10 rem/h) at 1 m from the source [IAEA, 2008]. The A_1 quantity is calculated assuming a sealed source, while the calculation of the A_2 quantity also allows for ingestion, inhalation, and immersion exposure pathways. The A_1 and A_2 quantities for the H.B Robinson fuel have values of 24 Ci and 0.4 Ci, respectively. The activity of a single pellet of the H.B. Robinson Fuel (length = 15.2 mm, pellet diam. = 9.3 mm, weight of metal (U) = 9.18 g) at the end of 2014 is estimated to be 3.9 Ci. Assuming the targets are fabricated using a maximum of three pellets, the total, single target activity is 12 Ci. For transport purposes, spent nuclear fuel is considered to be dispersable. Therefore, each target represents approximately 30 times the A_2 quantity and will require Type B transport packages. However, the A_1 quantity is more appropriate for the purposes of estimating unshielded dose rates for final sample handling because the internal and submersion pathways are eliminated from having a sealed target. These unmitigated dose rates are needed to determine if contact handling or remote handling are appropriate.

Table A.1 Subset of radioisotopes from H.B. Robinson fuel that dominate dose.

Nuclide	A/MTHM (Ci) (t = 0 yr)	A/MTHM (Ci) (t = 8.5 yr)	A/MTHM (Ci) (t = 20 yr)	A_1 (Ci)	A_2 (Ci)	A_{Pellet} (Ci)	A_{Target} (Ci)
AM 241	5.6E+02	2.5E+03	3.9E+03	2.7E+02	2.7E-02	3.6E-02	1.1E-01
BA 137M	1.6E+05	1.3E+05	1.0E+05			9.2E-01	2.7E+00
CM 244	3.6E+04	2.6E+04	1.7E+04	5.4E+02	5.4E-02	1.6E-01	4.7E-01
CS 134	2.9E+05	1.7E+04	4.1E+02	1.9E+01	1.9E+01	3.8E-03	1.1E-02
CS 137[a]	1.7E+05	1.4E+05	1.1E+05	5.4E+01	1.6E+01	9.7E-01	2.9E+00
EU 154	2.6E+04	1.3E+04	5.5E+03	2.4E+01	1.6E+01	5.0E-02	1.5E-01
EU 155	1.8E+04	5.5E+03	1.2E+03	5.4E+02	8.1E+01	1.1E-02	3.2E-02
KR 85	7.9E+03	4.6E+03	2.2E+03	2.7E+02	2.7E+02	2.1E-02	6.2E-02
PM 147	9.4E+04	1.0E+04	5.6E+02	1.1E+03	5.4E+01	5.2E-03	1.5E-02
PU 238	1.4E+04	1.4E+04	1.3E+04	2.7E+02	2.7E-02	1.2E-01	3.6E-01
PU 240	8.1E+02	8.4E+02	8.3E+02	2.7E+02	2.7E-02	7.7E-03	2.3E-02
PU 241	1.7E+05	1.2E+05	6.8E+04	1.1E+03	1.6E+00	6.3E-01	1.9E+00
RH 106	4.9E+05	1.4E+03	7.1E-01			6.5E-06	1.9E-05
RU 106[b]	4.7E+05	1.4E+03	7.1E-01	5.4E+00	5.4E+00	6.5E-06	1.9E-05
SB 125	6.2E+03	7.5E+02	4.8E+01	5.4E+01	2.7E+01	4.4E-04	1.3E-03
SR 90[c]	8.6E+04	7.1E+04	5.4E+04	8.1E+00	8.1E+00	5.0E-01	1.5E+00
Y 90	9.0E+04	7.1E+04	5.4E+04			5.0E-01	1.5E+00
TOTALS	2.8E+07	6.2E+05	4.3E+05	2.4E+01	4.1E-01	3.9E+00	1.2E+01

[a] A_1 and A_2 values for Cs 137 include Ba 137m.

[b] A_1 and A_2 values for Ru 106 include Rh 106.

[c] A_1 and A_2 values for Sr 90 include Y 90.

Table A.2 H.B. ROBINSON Reactor, Inventory, Mean Burn up 67 GWd/tU, GRS Cologne 12/18/03.

	Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]			Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]
Nuclide	Discharge	8,5 y Decay		Nuclide	Discharge	8,5 y Decay
H 3	2.52E+13	1.57E+13		HG206	6.43E-04	6.37E-04
BE 10	3.32E+05	3.32E+05		TL206	3.87E-02	3.83E-02
C 14	1.28E+10	1.28E+10		TL207	1.53E+05	6.46E+05
GE 71	8.87E+06			TL208	5.19E+08	1.53E+09
SE 79	2.42E+10	2.42E+10		TL209	8.37E+03	5.45E+03
KR 81	1.62E+04	1.62E+04		TL210	2.44E+00	5.12E+00
KR 85	2.92E+14	1.69E+14		PB209	3.97E+05	2.48E+05
RB 86	6.71E+13			PB210	2.92E+04	2.89E+04
RB 87	1.29E+06	1.29E+06		PB211	1.54E+05	6.48E+05
SR 89	8.53E+15	2.73E-03		PB212	1.45E+09	4.25E+09
SR 90	3.20E+15	2.62E+15		PB214	1.16E+04	2.44E+04

	Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]			Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]
Nuclide	Discharge	8,5 y Decay		Nuclide	Discharge	8,5 y Decay
Y 89M	1.29E+12	4.10E-07		BI208	2.15E-06	2.15E-06
Y 90	3.32E+15	2.62E+15		BI210	2.93E+04	2.90E+04
Y 91	1.23E+16	1.35E+00		BI210M	4.23E-07	4.23E-07
ZR 93	1.18E+11	1.18E+11		BI211	1.54E+05	6.48E+05
ZR 95	2.18E+16	5.88E+01		BI212	1.45E+09	4.25E+09
NB 92	1.10E+00	1.10E+00		BI213	3.80E+05	2.48E+05
NB 93M	5.40E+10	7.63E+10		BI214	1.16E+04	2.44E+04
NB 94	6.78E+06	6.78E+06		BI215	1.26E-01	5.30E-01
NB 95	2.17E+16	1.30E+02		PO210	2.47E+04	2.88E+04
NB 95M	2.14E+14	5.92E-01		PO211	4.61E+02	1.94E+03
MO 99	2.88E+16			PO212	9.27E+08	2.73E+09
TC 97	3.18E+01	3.18E+01		PO213	3.72E+05	2.42E+05
TC 99	7.72E+11	7.73E+11		PO214	2.93E+05	2.44E+04
TC 99M	2.52E+16			PO215	1.53E+05	6.48E+05
TC 98	3.78E+03	3.78E+03		PO216	1.45E+09	4.25E+09
RU103	3.02E+16	5.05E-08		PO218	1.16E+04	2.44E+04
RU106	1.73E+16	5.02E+13		AT217	3.80E+05	2.48E+05
RH103M	3.02E+16	5.04E-08		AT219	1.30E-01	5.46E-01
RH106	1.82E+16	5.02E+13		RN218	2.82E+05	
PD107	1.29E+10	1.29E+10		RN219	1.53E+05	6.48E+05
AG108	4.74E+09	1.34E+06		RN220	1.45E+09	4.25E+09
AG108M	1.58E+07	1.51E+07		RN222	1.16E+04	2.44E+04
AG109M	1.16E+16	1.16E+05		FR221	3.80E+05	2.48E+05
AG110	9.12E+15	9.74E+08		FR223	2.16E+03	9.10E+03
AG110M	4.09E+14	7.49E+10		RA222	2.82E+05	
AG111	1.56E+15			RA223	1.53E+05	6.48E+05
CD109	1.34E+07	1.16E+05		RA224	1.45E+09	4.25E+09
CD113	1.23E-03	1.25E-03		RA225	3.78E+05	2.48E+05
CD113M	1.65E+12	1.07E+12		RA226	1.16E+04	2.44E+04
CD115M	1.85E+13	2.12E-08		RA228	4.45E+00	7.98E+00
IN114	7.86E+11	7.31E-08		AC225	3.80E+05	2.48E+05
IN114M	5.38E+11	7.56E-08		AC226	9.30E+03	
IN115	3.85E-01	3.91E-01		AC227	1.54E+05	6.50E+05
IN115M	1.71E+14			AC228	4.35E+06	7.98E+00
SN117M	7.29E+11			TH226	2.82E+05	
SN119M	3.52E+12	5.43E+08		TH227	1.52E+05	6.37E+05
SN121M	2.42E+10	2.18E+10		TH228	1.43E+09	4.23E+09
SN123	5.95E+12	3.51E+05		TH229	2.47E+05	2.48E+05
SN125	2.16E+14			TH230	2.55E+06	4.61E+06
SN126	5.86E+10	5.86E+10		TH231	4.34E+10	6.55E+07
SB122	4.54E+13			TH232	7.76E+00	1.15E+01
SB124	2.71E+13	8.30E-03		TH234	1.13E+10	1.13E+10
SB125	2.30E+14	2.77E+13		PA230	2.89E+06	
SB126	8.72E+12	8.21E+09		PA231	2.24E+06	2.25E+06
SB126M	1.10E+13	5.86E+10		PA233	2.33E+10	2.07E+10

	Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]			Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]
Nuclide	Discharge	8,5 y Decay		Nuclide	Discharge	8,5 y Decay
SB127	1.71E+15			PA234M	1.15E+10	1.13E+10
TE123	1.58E-01	1.93E-01		PA234	2.02E+08	1.81E+07
TE123M	1.29E+12	1.89E+04		U 230	2.74E+05	
TE125M	2.97E+13	3.96E+12		U 231	2.95E+06	
TE127	1.70E+15	7.66E+05		U 232	2.89E+09	4.57E+09
TE127M	2.79E+14	7.82E+05		U 233	9.10E+05	1.67E+06
TE129	5.28E+15			U 234	2.04E+10	3.35E+10
TE129M	9.93E+14			U 235	6.54E+07	6.55E+07
TE132	2.23E+16			U 236	8.98E+09	8.99E+09
I 129	2.43E+09	2.43E+09		U 237	1.59E+16	1.03E+11
I 131	1.59E+16			U 238	1.13E+10	1.13E+10
I 132	2.31E+16			U 240	3.40E+11	2.13E+05
XE129M	9.57E+11			NP235	1.99E+09	8.76E+06
XE131M	1.79E+14			NP236	4.74E+05	4.74E+05
XE133	3.16E+16			NP237	2.04E+10	2.07E+10
CS134	1.07E+16	6.15E+14		NP238	1.39E+16	4.62E+09
CS135	3.31E+10	3.31E+10		NP239	4.24E+17	4.67E+12
CS136	1.62E+15			NP240M	1.82E+14	2.13E+05
CS137	6.11E+15	5.03E+15		NP240	2.04E+14	2.34E+02
CS132	9.80E+08			PU236	5.77E+10	7.33E+09
BA133	1.69E+05	9.66E+04		PU237	1.42E+11	4.84E-10
BA136M	2.45E+14			PU238	5.26E+14	5.29E+14
BA137M	5.80E+15	4.76E+15		PU239	1.19E+13	1.20E+13
BA140	2.62E+16			PU240	2.99E+13	3.09E+13
LA138	8.26E+00	8.26E+00		PU241	6.41E+15	4.29E+15
LA140	2.84E+16			PU242	2.87E+11	2.87E+11
CE139	9.71E+08	1.60E+02		PU243	2.16E+16	8.73E+05
CE141	2.39E+16			PU244	2.13E+05	2.13E+05
CE142	1.92E+06	1.92E+06		PU246	9.41E+07	1.61E+00
CE144	1.74E+16	9.05E+12		AM241	2.09E+13	9.20E+13
PR143	2.05E+16			AM242M	1.00E+12	9.62E+11
PR144	1.75E+16	9.05E+12		AM242	8.06E+15	9.58E+11
PR144M	2.28E+14	1.18E+11		AM243	4.67E+12	4.67E+12
ND144	1.25E+02	1.32E+02		AM245	1.06E+12	6.10E+02
ND147	1.02E+16			AM246	9.41E+07	1.61E+00
PM147	3.47E+15	3.80E+14		CM241	1.19E+09	
PM148	2.73E+15	9.38E-10		CM242	7.69E+15	8.07E+11
PM148M	7.29E+14	1.77E-08		CM243	6.94E+12	5.65E+12
SM147	1.74E+05	2.54E+05		CM244	1.34E+15	9.64E+14
SM148	4.82E+00	4.83E+00		CM245	1.61E+11	1.61E+11
SM149	1.59E-02	2.15E-02		CM246	1.15E+11	1.15E+11
SM151	1.80E+13	1.70E+13		CM247	8.73E+05	8.73E+05
EU152	5.84E+11	3.75E+11		CM248	6.12E+06	6.14E+06
EU154	9.53E+14	4.81E+14		CM249	1.29E+11	
EU155	6.65E+14	2.03E+14		CM250	6.25E+00	6.45E+00

	Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]			Activity per 1000 kg U [Bq]	Activity per 1000 kg U [Bq]
Nuclide	Discharge	8,5 y Decay		Nuclide	Discharge	8,5 y Decay
EU156	1.06E+16			BK249	3.60E+10	4.36E+07
GD152	3.80E-01	3.87E-01		BK250	6.26E+10	6.20E+01
GD153	2.71E+11	3.90E+07		BK251	6.88E+06	
TB157	1.37E+06	1.32E+06		CF249	3.48E+07	1.23E+08
TB160	7.75E+13	9.36E+00		CF250	1.10E+09	7.03E+08
TB161	3.31E+13			CF251	7.36E+06	7.32E+06
TB158	1.89E+07	1.82E+07		CF252	3.32E+09	3.56E+08
DY159	1.29E+06	4.41E-01		CF253	2.06E+08	
DY166	3.21E+11			CF254	2.75E+06	1.00E-09
HO166	1.37E+13			ES253	1.76E+08	
HO166M	1.35E+09	1.34E+09		ES254	1.48E+05	6.11E+01
ER169	4.44E+10			ES255	3.16E+05	
TM170	2.18E+10	1.19E+03		**TOTALS**	**1.04E+18**	**2.30E+16**
TM171	1.50E+09	6.99E+07				
TM172	4.16E+08					

A.1 Target and Test Vessel Dose Rate

The radiation emanating from an intact target or a contaminated test vessel is expected to be dominated by gamma rays. Based on the calculated A_1 quantity, the spent fuel target or used test vessel are estimated to give a gamma dose rate of approximately 0.05 Sv/hr (5 rem/hr). The contaminated test vessel will house the target within significantly thick steel walls. Therefore, this estimated dose rate may be overly conservative when considering handling of the test vessel both pre- and post-detonation.

A.2 Aerosol Sampler Dose Rate

Cascade impactors and bulk filters are being considered to capture information about the aerosol content of the post-detonation atmosphere in the test chamber. Both of these types of samplers require aerosol-laden gas to be drawn from the test chamber through the respective sampling device. The maximum amount of material aerosolized by the conical shaped charge is expected to be 5% of the total target mass or less. Earlier tests suggest this percentage ranges from 1 to 4 %. The sampling devices will not collect the entire aerosolized material, but the complete aerosolized target sample provides an upper limit that can be collected in the sampling devices for the purposes of these calculations. This assumed upper limit gives 0.6 Ci of total activity in the sampling devices and the sample train. The radioactivity will largely be concentrated in the sampling devices. This indicates that the gamma dose rate from these devices combined would be 2.5 mSv/h (250 mrem/h). Further assuming that 1) two cascade impactors and one bulk filter are used and 2) the samples are equally distributed through all three devices, gives an individual sampling device gamma dose rate of less than 1 mSv/hr (100 mrem/hr).

Realistically, only a fraction of the total aerosol will be collected during each test. Figure A.1 shows the total radioactive material collected in the sampling devices by activity assuming each sampling device draws at the same flow rate during the same collection time. For three devices

drawing at 10 liter/min (Total Sample Rate = 30 liter/min) for a sampling time of t_{sample} = 1 min, the total activity collected in the samplers would be 0.16 Ci. The associated gamma dose rate for all three devices together would be 0.67 mSv/h (67 mrem/h). The individual device dose rate would be 0.22 mSv/h (22 mrem/h). These dose rates can be adjusted to some degree to accommodate dose rates to workers if needed.

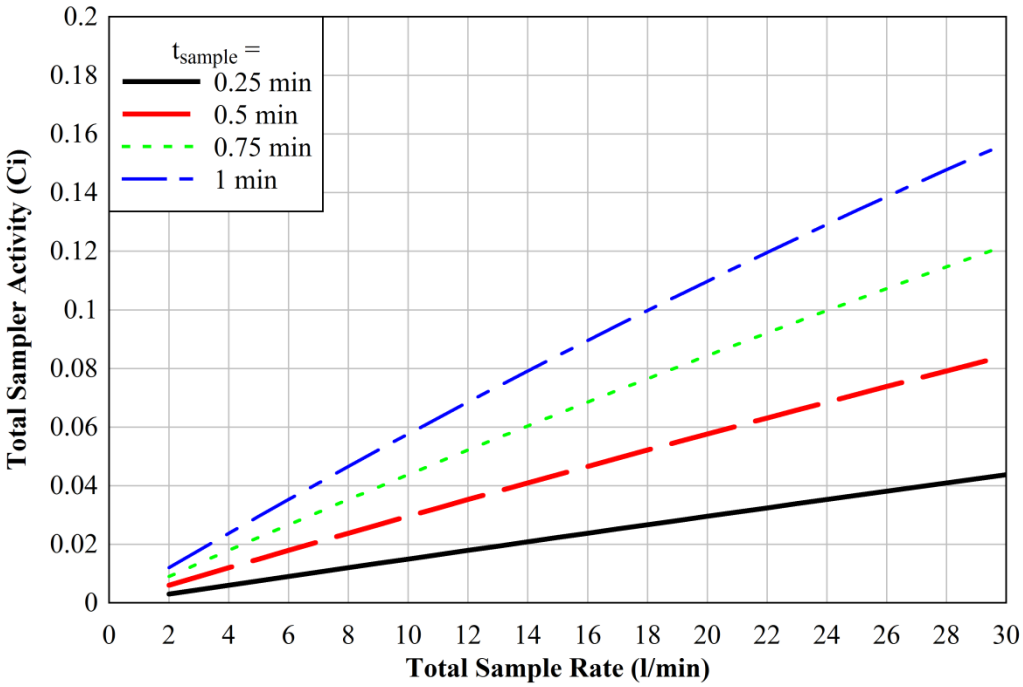

Figure A.1 Total activity of the sampling devices as a function of total sampling rate and collection time.

A.3 Vacuum Bottle Dose Rate

Almost all of the radioactive aerosol particles will be collected in the cascade impactors and bulk filters prior to the vacuum bottle. The last stage of the cascade impactors and the bulk filters are high-efficiency particle absorption (HEPA) certified, meaning they collect 99.97% or more of particles that have a size of 0.3 μm or larger. The amount of radioactive aerosols entering the vacuum bottles is therefore negligible. However, the radioactive gas, Kr-85, will be able to pass into the vacuum bottles. Assuming the entire inventory of Kr-85 is collected in the vacuum bottles, leads to an activity of 0.06 Ci. The combined dose rate from the Kr-85 is estimated to be 0.023 mSv/hr (2.3 mrem/hr). If multiple vacuum bottles are employed, the activity and consequently the dose rate would need to be divided by the number used to calculate for a single bottle.

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