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ARC-100 Reactor Security-by-Design Summary

September 2024

Changing the World's Energy Future

Robby Christian, Christopher Paul Chwasz, Scott E Ferrara, Robert Iotti, Ed Arthur, Irfan Ali

Idaho National Laboratory

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ARC	Advanced Reactor Concepts
CDA	Critical Digital Asset
DID	Defense in Depth
DL	Defense Level
DRACS	Direct Reactor Auxiliary Cooling System
EBR-II	Experimental Breeder Reactor II
FCMI	Fuel-Cladding Mechanical Interaction
FFTF	Fast Flux Test Facility
FRWG	Fast Reactor Working Group
FSF	Fundamental Safety Function
FUM	Fuel handling and Unhandling Machine
HVAC	Heating, Ventilation, and Air Conditioning
IAEA	International Atomic Energy Agency
I&C	Instrumentation & Control
IVTM	In-Vessel Transfer Machine
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
RCCS	Reactor Cavity Cooling System
RVACS	Reactor Vessel Auxiliary Cooling System
SeBD	Security by Design
SSeBD	Safety and Security by Design
SFR	Sodium-cooled Fast Reactor
SRS	Safety Reports Series
SSC	Structures, Systems, and Components
TEDE	Total Effective Dose Equivalent

EXECUTIVE SUMMARY

This report applies the security-by-design methodology developed in a previous National Nuclear Security Administration–sponsored work to the ARC-100, a sodium-cooled fast reactor (SFR) being developed by ARC Clean Technology, Inc (ARC). The report contains no proprietary information specific to the ARC-100 reactor. The insights developed in this report are high-level, and generally applicable to other sodium fast reactor designs. The information presented here is the result of a qualitative safety-based analysis and would not inform any potential adversary beyond what would be found in a docketed safety analysis report.

The scope of this present report covers ARC-100's reactor core, used fuel storage, and used fuel assembly wash station. These systems are also compared to a generic SFR design assumed in the previous study. The security assessment results show changes in structures, systems, and components (SSCs) safety importance relative to the generic SFR SSCs. However, the consequence assessment results are similar to a previously assessed generic SFR. Several SSCs have higher importance rankings than others, and it is recommended that protection efforts are prioritized for these SSCs.

This work will continue in the Fiscal Year 2025 for the remaining ARC-100 systems, including cesium trap, sodium cold trap, noble gas decay tanks (dewar bottles), and used fuel dry storage facility, to provide safety-and-security-by-design insights and recommendations on non-core systems. Results from this work will furnish a technical justification for the feasibility of these solutions for the ARC reactor's design and, where applicable, identify any regulatory benefits conferred by the proactive design aspect within a risk management framework. This initiative will contribute to a more secure design of the ARC reactor and support its licensing process.

CHAPTER 1

1. INTRODUCTION

Numerous advanced reactors of smaller scale will require a revised security strategy that takes into account their condensed form factors, distinctive features, and new regulatory frameworks. Lacking early implementation of security solutions that are technically solid and integrated into the design, the siting dilemma for small, advanced reactors will persist, potentially restricting their use and placement both domestically and internationally.

A previous work has proposed a method for integrating security-by-design (SeBD) and safety-and-security-by-design (SSeBD) into the early stages of nuclear facility development [1]. This approach allows reactor developers and regulators to enhance security measures, compare risk profiles of advanced reactor technologies, and ensure security features are embedded from the start, thus avoiding expensive modifications later. The method characterizes risk as the potential consequences vs. other factors that impact the ease or difficulty of an adversary achieving sabotage (and does not consider event frequencies). SeBD focuses on embedding security features to increase resistance to attacks while SSeBD integrates changes to bolster safety systems against attacks and prevent offsite releases due to adversarial actions. Understanding the unique security characteristics of ARs will help developers create reactors that are safer, more secure, and more cost-effective, benefiting utility operators and consumers worldwide.

This work implements the SSeBD methodology on the ARC-100 sodium-cooled fast reactor (SFR) designed by ARC Clean Technology, Inc. (ARC). ARC-100 is a 100-MWe pool-type SFR operating on a 20-year refueling cycle that has the potential to significantly reduce the quantity of long-term waste if the recycle of used fuel is allowed. The reactor design is rooted in the Experimental Breeder Reactor-II (EBR-II) program. The design is maturing rapidly and approaching the finalization of many key design attributes. ARC-100 is a scalable small modular reactor—several units can be grouped together to create larger generation hubs. ARC is looking to deploy the reactor internationally but focusing on an initial dual Canadian/U.S. deployment strategy. Both the U.S. and Canadian reactors employ the same nuclear island design; however, they differ in the power conversion unit where the Canadian design uses a superheated steam Rankine cycle while the U.S. version uses the supercritical CO_2 Brayton cycle. Therefore, this work will also benefit the Canadian reactor model.

This report summarizes the general SeBD and SSeBD methodology, applies the methodology on select systems and processes of ARC-100, and documents the findings in a publicly facing report. The insights provided in this report are preliminary. As the ARC design matures further and additional assessment tools become available, the fidelity of the safety analysis would provide greater details to inform the safe and secure operation of the facility. Specific insights and results of the analysis were captured in a separate non-public report for the reactor developer. This initiative will contribute to a more secure design of the ARC reactor and support its licensing process.

CHAPTER 2

2. METHODOLOGY

The methodology used to evaluate the ARC-100 design is defined as a security risk methodology and gives a process to determine qualitative ratings to potential offsite consequences of the release from radioactive sources, and the relative importance and vulnerability of safety systems during security events. The security risk methodology is technology neutral and flexible in the determination of bounding parameters, primarily the applied design basis threat and security program goals. For the evaluation of the ARC-100 U.S. design, the National Nuclear Security Administration (NNSA) International Nuclear Security generic design basis threat commonly used for international training courses was applied [2].

The methodology was developed under an NA-211 program in 2023–2024 to qualify security risks associated with advanced reactor technologies and develop a summary report and briefing materials to inform U.S. government entities, advanced reactor designers, and international partners in the deployment of safe and secure advanced reactors [1]. This methodology is focused on SSeBD characterization and qualification. The methodology identifies radiological sources in the design that are within the scope of assessment and qualifies their possible consequences, dispersibility, and barrier to release. Each radionuclide source's security is evaluated by examining the safety systems that support the fundamental safety functions (FSFs): control of heat removal, control of reactivity, retention of radionuclides, plus control of chemical interactions, their relative importance of protection by the security systems, and their vulnerability to attack. The result of this methodology is a heat-map of sources, and their safety systems qualified in their importance of protection and their relative vulnerability to adversary action. The methodology [1] is captured in Figure 2.1.

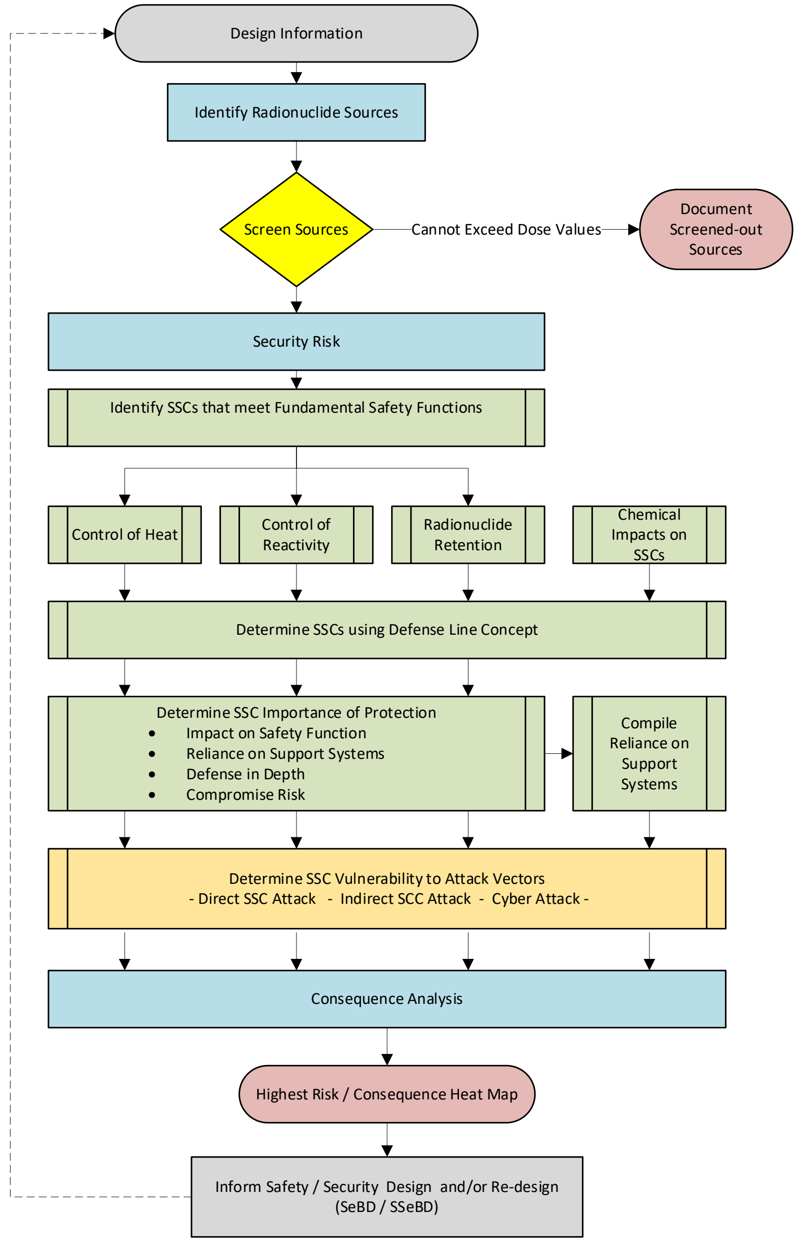

Figure 2.1. Security risk assessment methodology.

2.1. RISK CONSEQUENCE ASSESSMENT

The first step in the security risk methodology is the identification and screening of radiological sources that may need to be protected by the physical protection program. The identified sources are all of those that could pose a danger to the public given adversary initiated radiological sabotage, as the methodology is not intended to assess diversion or theft. Identified sources are qualified based on the maximum potential offsite dose impact, the possible dispersibility based on physical form, and the radiological control barriers that could retain the possible release of the source.

The maximum dose potential should be determined first to screen sources that would not exceed the dose thresholds used for the assessment. Considerations for interfacing or co-located radioactive sources should be taken into account (e.g., used fuel, waste processing, or storage). Those sources that screen into the methodology are assessed for dispersibility and barriers to release in the consequence assessment and then proceed to the security risk methodology. The consequence assessment results for each source that could be represented is a radar-plot-type diagram, as seen in Figure 2.2. The radar plot can quickly demonstrate the total risk of the radionuclide source through the area shown within the resulting triangle.

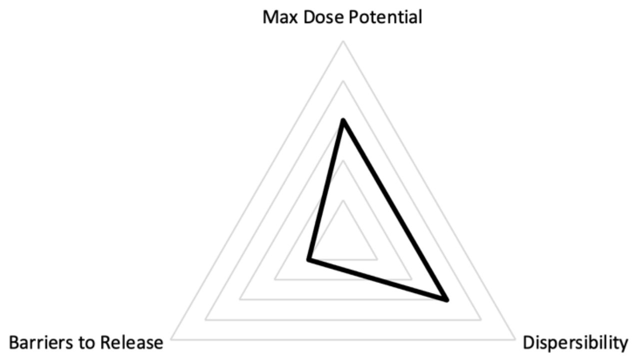

Figure 2.2: Example consequence assessment radar plot.

The qualification values associated with the radar plot are shown in Figure 2.3.

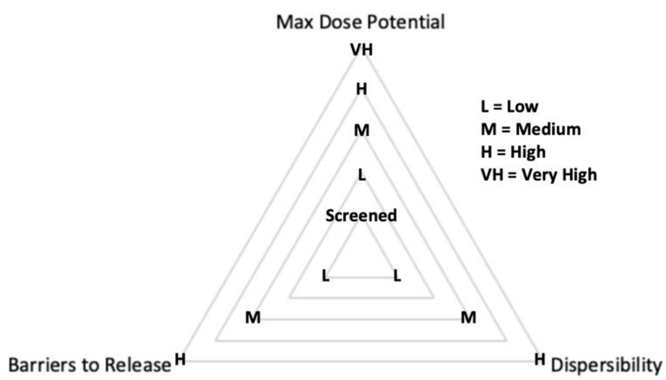

Figure 2.3: Radar plot ranking key.

The consequence assessment values for all radionuclide sources in the facility would be summarized in a “heat map” consequence assessment matrix. Table 2.1 shows the consequence matrix for a generic sodium fast reactor [1]. The consequence assessment matrix allows a comparative view of the radionuclide sources, their consequence potential, dispersibility, and barriers to release to risk-inform the facility’s safety-and-security design.

Table 2.1. Summary of SFR risk consequence rankings for various sources [1].

Source	Maximum Dose Potential Ranking	Dispersibility Ranking	Barrier Ranking
Reactor core	Very high	Low	Low
Cesium trap	Medium	Medium	Low
Sodium cold trap	Medium	Medium	Low
Noble gas decay tanks	Low	High	High
Used subassembly wash station	High	Medium	Low
Used fuel storage pool (Na)	Very high	Low	Low
Used fuel storage pool (H_2O)	Very high	Low	Medium

2.1.1. Maximum Dose Potential

The security risk methodology is adaptable to different regulatory structures. For this assessment, the U.S. ARC-100 design falls under the purview of the U.S. Nuclear Regulatory Commission (NRC), but the performance of the reactor systems in response to security events may have broad international applicability. The NRC has released draft rulemaking language requiring advanced and small modular reactors that the physical protection program "…must be designed to prevent a significant release of radionuclides from any source" consistent with the dose reference values in 10 CFR 50.34 and 10 CFR 52.79 [3]. The values in 10 CFR 50.34(a)(1)(ii)(D)(1) and (2) are 25 rem total effective dose equivalent (TEDE) for 2 hours after the event at the exclusion area boundary and 25 rem TEDE for 24 hours at the boundary of the low-population zone. The methodology is adaptable to varying radiological consequence thresholds which may apply internationally based on a State's regulatory requirements.

For the ARC consequence assessment, the dose impact qualification ratings are captured in Table 2.2. These ratings were used to qualify the doses and provide a risk-informed picture of potential radionuclide sources. Medium equates to 10 to 200 rem. This rating would be the threshold for potential offsite dose consequences and would start at 40% of the 24 rem value to provide a conservative threshold and avoid cliff-edge effects. A low rating would equate to a source that may not enter the regulated security space but would inform ARC on possible low-dose offsite consequences or sources that may enter regulated space if combined or collocated with other sources. Ratings of high and very high would risk-inform the ARC design as what radiological sources present the greatest security consequence potentials.

Table 2.2. Maximum dose impact ranking structure.

Ranking	Maximum Potential Dose Impact	Approximate TEDE Evaluation Level
Very High	Possible wide area early health effects	Very large doses (large radionuclide inventories), such as those associated with full core inventories or multiple used fuel assemblies (or equivalent)
High	Possible early health effects	200 rem < x < Very High rank
Medium	Possible late health effects	10 < x < 200 rem
Low	Possible exceedance of EPA PAG	1 < x < 10 rem
Screen	Below screening limit (EPA PAG)	x < 1 rem

2.1.2. Dispersibility

The dispersibility rating of radionuclide source rates the risk of dispersal of the radionuclide source to the environment. Sources with rating of low would likely be solid form and be chemically bonded, such that significant energy (e.g., explosives, chemical reactions, or heat) would be needed to disperse the radionuclides. Medium-risk-rated sources would be easier to disperse, require less energy or longer timeframes to release, and may include liquid sources. High risk of dispersibility ranking would be sources that would require very little or no energy for dispersal, such as gaseous radionuclide sources. Table 2.3 captures these ratings.

Table 2.3. Dispersibility factor ranking structure.

Ranking	Dispersibility Characteristics
High	Very limited or no energy needed for dispersal
Medium	Energy needed to initiate dispersal or small amount of continuous energy
Low	Significant energy needed for dispersal

2.1.3. Barrier for Dispersion

The ratings for barriers to dispersion are intended to qualify the engineered physical barriers that would prevent, retain, or mitigate a release of radionuclides. The qualifications are intended to credit both typical robust containments with leak rates as well as multiple layer functional containments seen in advanced reactor designs. Credit for a barrier is contingent on that barrier meeting the functional safety goal of retention, and barriers that mitigate would be given less credit in this assessment. Those radioactive sources that have a high qualification for barrier risk would be those sources that have no inherent barriers to release or have a single applied barrier (i.e., a vessel wall). A medium barrier qualification would be those sources that have a single inherent barrier (i.e., TRISO) or multiple applied barriers (e.g., vessel wall and shield barrier). Radioactive sources with multiple inherent and applied barriers would be qualified to have a low barrier risk value. These definitions are listed in Table 2.4. These barriers may also be security barriers, but no consideration is given for physical security barriers in this methodology.

Table 2.4. Barrier to radionuclide release ranking structure.

Ranking	Dispersibility Characteristics
High	No inherent barriers or single applied barrier
Medium	Single inherent barrier or multiple applied barriers
Low	Multiple inherent barriers or mix of inherent/applied barriers

2.2. SECURITY RISK ASSESSMENT

For each radionuclide source that is screened into the assessment methodology, design security risk methodology identifies structures, systems and components (SSCs) that meet the FSFs (i.e., reactivity control, heat removal, radionuclide retention) in addition to control of chemical hazards (e.g., to prevent the insertion of oxygen into the sodium boundary), and support systems and qualifies their relative vulnerability to adversary action. SSCs that respond to security events are not required to adhere to strict safety classification.

Initially, SSCs for each source are categorized according to FSFs and then further categorized into three SSeBD defense lines (DLs). The SSeBD DLs are adapted from the five levels of defense in depth (DID) for safety purposes outlined by the International Atomic Energy Agency (IAEA) safety reports series (SRS) 46 [4]. IAEA's DID gradation was intended to meet safety objectives and was adapted for the security risk assessment to credit safety features for security objectives. The use of SSeBD DLs allows the mapping of the functional safety of the design to the initial plant behavior and response before detailed design information is available (e.g., control and safety system logic, probabilistic risk assessment).

The generic SSeBD DL1 includes SSCs that meet the FSFs during normal and transient operations. DL2 comprises of SSCs that respond to accidents (both within the design basis and beyond the design basis). DL3 consists of SSCs that provide mitigative actions in response to accidents. The adaptation is listed in Table 2.5.

Table 2.5. Adaptation of SSC defense-in-depth level to security defense lines.

Defense-in-Depth and Defense Lines	
IAEA SRS-46 DID Levels [4]	**SSeBD Defense Line**
Level 1: Prevention of abnormal operation and failures Level 2: Control of abnormal operation and detection of failures	DL1: Normal facility operation (to include all modes of operation)
Level 3: Control of accidents within the design basis	DL2: Control of fundamental safety functions in response to an adversary-initiated event
Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	DL3: Mitigation of loss of fundamental safety functions (mitigation to reduce or delay offsite release)
Level 5: Mitigation of radiological consequences of significant releases of radioactive materials offsite emergency response)	Not used: Offsite emergency response to mitigate consequences to the public is not credited for performance-based U.S. commercial reactor safety or security regulation but is considered in the DID stature of the plant

2.2.1. SSC Importance of Protection

Once the SSeBD DL is determined for each SSC that supports a radionuclide source, the importance of protection qualification value can be determined. The importance of protection value represents the relative risk the loss or compromise of that system to an adversary would have on the safety of that radionuclide source. The SSC importance of protection is compiled from four values: *Impact of Safety Function*, *Reliance on Support Systems*, *Defense in Depth Risk*, and *Compromise Risk* [1]. These values can by tabulated in a design risk matrix. Figure 2.5 shows the link between these four values and the resulting *Total SSC Importance of Protection*.

2.2.1.1. Impact on Safety Function

The primary factor in determining the SSC importance of protection is the *Impact on Safety Function* value. The impact on safety function represents the degree of reliance on that SSC. Table 2.6 shows the ranking structure for the impact on safety function. Generally, SSeBD DL2 systems (those that the plant relies on in response to an event to fulfill the safety function) would be ranked high, and SSeBD DL1 systems (i.e., those normal operation active systems that are generally not credited with response to events) would receive a low ranking. SSeBD DL3 systems generally vary in contribution to the fulfillment of the fundamental safety functions.

[1] Terminologies that are categories are printed in italics throughout the report for emphasis.

Table 2.6. *Impact on Safety Function* ranking structure.

Ranking	Safety Function System or SSC Characteristics
High	Primary safety function system or SSC, ultimately relied upon to fulfill a safety function
Medium	SSC contributes to the fulfillment of a safety function for some time period or significance, contributes to safety function fulfillment as one of a few systems
Low	SSC may fulfill the safety function, but not under adverse conditions, contributes to safety function fulfillment as one of many systems

2.2.1.2. Reliance on Support Systems

The impact on safety function can be modulated by both the reliance on support systems and DID. For an SSC, increasing reliance on support systems increases the risk of that SSC and thus would would result in an increased level of importance of protection. Table 2.7 shows the ranking structure for reliance on support systems.

Table 2.7. *Reliance on Support Systems* ranking structure.

Ranking	Safety Function System or SSC Characteristics
High	Safety function system or SSC relies on three or more support systems
Medium	Safety function system or SSC relies on two support systems
Low	Safety function system or SSC relies on one support system
None	Safety function system or SSC is standalone, inherent, passive.

2.2.1.3. Defense-In-Depth Risk

The SSC *Impact on Safety Function* value can also be decreased by a lower DID risk ranking, indicating multiple redundancies for that SSC or diverse methods for the FSF. DID risk relates to the functional redundancies and diversities and the increased numbers of locations that an adversary may need to access to prevent the safety function. Considerations for common headers and instrumentation paths should be made to accurately capture the redundancies in the SSC. The ranking structure for DID is captured in Table 2.8.

Table 2.8. *Defense-in-Depth Risk* ranking structure.

Ranking	Safety Function System or SSC Characteristics
High	Safety function system or SSC has no DID
Medium	Safety function system or SSC has two or three redundant or diverse trains or has another fully redundant diverse system
Low	Safety function system or SSC has multiple redundant or diverse systems/trains (i.e., four)

2.2.1.4. Compromise Risk

Compromise risk has a similar importance to determining the *Importance of Protection* ranking value. For this methodology, the concept of "compromise" is defined as the use of a facility SSC or material by an adversary against the intended safety function of that SSC or material for the facility. Though traditionally captured within the concept of "sabotage," this is captured separately in this methodology. For this methodology, the compromise risk qualifies the potential for the SSC to be used by an adversary and thus factors in equally to the determination of SSC *Importance of Protection*. The characteristics of system or SSC compromise risk consequences are captured in Table 2.9.

Table 2.9. *Compromise Risk* ranking structure.

Compromise Risk Ranking Structure	
Ranking	**Safety Function System or SSC Compromise Consequence Characteristics**
High	Safety function system or SSC has severe negative outcomes
Medium	Safety function system or SSC has medium negative outcomes
Low	Safety function system or SSC has negligible negative outcomes
None	Safety function system or SSC has no negative outcomes

2.2.2. SSC Vulnerability to Attack Vectors

The safety function systems and SSC assessed for importance of protection are then evaluated for their vulnerability to three different adversary attack vectors. The methodology is flexible and can adapt to different design basis threats. The ARC assessment used the adversary characteristics outlined in the *Lone Pine Nuclear Power Plant Hypothetical Facility Data Handbook* [2]. The adversary characteristics resulted in three attack vectors: a direct attack on a system or SSC, indirect attack on a system or SSC, or a cyber-physical attack for the delivery of malicious cyber hardware. These attack vulnerabilities are based primarily on access to the location within the facility, based solely on the anticipated facility layout required to support engineered safety features and operational needs. No security barriers are credited in the assessment to maintain a security program agnostic method to evaluate the roles of safety systems and SSCs in security events. Figure 2.4 below shows the primary determining factor in the attack vector value by location within a facility. Other considerations may include time to sabotage the equipment or the difficulty of sabotage with adversary equipment.

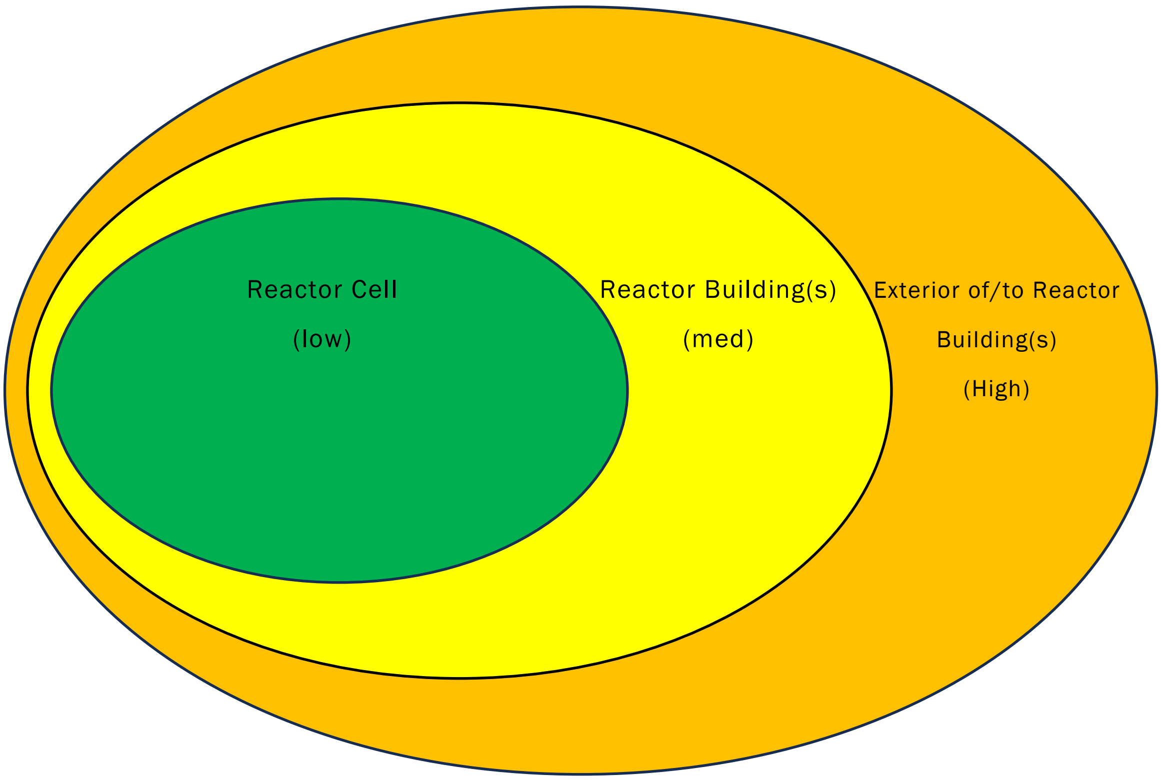

Figure 2.4. Attack vector accessibility levels.

2.2.2.1. Direct Attack Vulnerability

Direct attacks are assessed as attacks that happen directly to a system or SSC (adversary hands on the equipment). Given the available sabotage and compromise methods, adversary direct access would lead to loss of that equipment. The ranking structure for a direct attack is largely based on relative access by an adversary. The direct attack vulnerability rankings are captured in Table 2.10 below.

Table 2.10. *Direct Attack Vulnerability* ranking structure.

Direct Attack Vulnerability Ranking Structure	
Ranking	**Safety Function System or SSC Compromise Consequence Characteristics**
High	Safety function system or SSC can be defeated quickly by hand-carried equipment or hand manipulation and is very accessible (exterior of nuclear island building[s])
Medium	Safety function system or SSC can be defeated by hand-carried equipment with time required for the task and has medium accessibility (interior to nuclear island with personnel access, to include containment structures with doors, and would not include areas that need heavy equipment for access)
Low	Safety function system or SSC is resistant to hand-carried equipment, takes extensive time to defeat, is not very accessible (contained within a confinement cell that requires time and heavy equipment to access)
None	Safety function system or SSC is beyond adversary capability or time to defeat is beyond the timeframe established for a security event

2.2.2.2. Indirect Attack Vulnerability

Indirect attacks are assessed as attacks that happen to a system or SSC from a remote location. This may include the manipulation or prevention of function, or a compromise. Locations such as the main control room, remote shutdown stations, motor control centers, or use of other systems (e.g., remote overhead crane) may be locations where an indirect attack may occur. The ranking structure for an indirect attack is largely based on relative access by an adversary. The indirect attack vulnerability rankings are captured in Table 2.11 below.

Table 2.11. *Indirect Attack Vulnerability* ranking structure.

Indirect Attack Vulnerability Ranking Structure	
Ranking	**Safety Function System or SSC Compromise Consequence Characteristics**
High	Safety function system or SSC can be defeated or compromised by other plant systems or from several plant locations that have high accessibility (exterior of nuclear island building[s])
Medium	Safety function system or SSC can be manipulated or compromised from few plant locations with medium accessibility (interior to nuclear island with personnel access, to include containment structures with doors, and would not include areas that need heavy equipment for access)
Low	Safety function system or SSC can be manipulated or compromised from the main control room or a single location with medium accessibility
None	Safety function system or SSC cannot be manipulated or compromised remotely.

2.2.2.3. Cyberattack Vulnerability

Cyberattacks are assessed as attacks that happen to a system or SSC from a critical digital asset (CDA) (i.e., plant computer, control system, digital information device) that the adversary physically accesses. This may include manipulation or prevention of functions, spoofing data, or compromise. Locations such as the main control room, remote shutdown stations, plant computer centers, or other digital systems (e.g., network locations) may be locations where a cyberattack may occur. The cyberattack examined here is limited to the cyber-physical type and does not examine network or over-the-air attack types. The ranking structure for a cyberattack is largely based on the degree of CDA control of the system or SSC and relative access by an adversary. The indirect attack vulnerability rankings are captured in Table 2.12 below.

Table 2.12. *Cyberattack Vulnerability* ranking structure.

Cyberattack Vulnerability Ranking Structure	
Ranking	**Safety Function System or SSC Compromise Consequence Characteristics**
High	Safety function system or SSC is directly controlled by a CDA that is accessible
Medium	Safety function system or SSC relies on CDA information that is accessible
Low	Safety function system or SSC has minimal connections or requirements on a CDA or the CDA is very inaccessible
None	Safety function system or SSC has no CDA connections or requirements, or access is beyond accessibility

2.2.3. Total SSC Importance of Protection and Vulnerability Determination

The determination of the *Total SSC Importance of Protection* and *Total SSC Vulnerability* qualification values result from the ratings above. *Total SSC Importance of Protection* is determined from *Impact on Safety Function*, *Reliance on Support Systems*, *DID Risk*, and *Compromise Risk*, as seen in Figure 2.5.

Safety Function	System	Impact on Safety Function (I)	Reliance on Support Systems (S)	Defense in Depth Risk (D)	Compromise Risk (C)	Direct Attack Vulnerability (Da)	Indirect Attack Vulnerability (Ia)	Cyber Attack Vulnerability (Ca)	Total SSC Importance	Total SSC Vulnerability
		H,M,L	H,M,L,N	H,M,L	H,M,L,N	H,M,L,N	H,M,L,N	H,M,L,N		
Grouping Weighting		Low - Very High				None - Very High			Low - Very High	None - Very High
Heat removal	Primary loop helium circulators	Low	High	Med	Low	Low	Med	High	Low	Med
	Shutdown cooling	Low	High	Med	Low	Med	Med	High	Low	High
	Passive decay heat removal	High	None	Med	None	High	Low	Low	High	High
Reactivity Control	Negative temperature coefficient	High	None	Med	Low	Low	None	None	High	Low
	Control rods	Med	High	Med	Low	Low	Med	High	Med	High
	Defueling pebbles	Low	Med	Med	Med	Low	Med	High	Low	High

Figure 2.5. Design Risk Matrix illustrating the Total SSC Importance of Protection.

The *Total SSC Vulnerability* is determined from the direct, indirect, and cyberattack vulnerabilities, as shown in Figure 2.6

Safety Function	System	Impact on Safety Function (I)	Reliance on Support Systems (S)	Defense in Depth Risk (D)	Compromise Risk (C)	Direct Attack Vulnerability (Da)	Indirect Attack Vulnerability (Ia)	Cyber Attack Vulnerability (Ca)	Total SSC Importance	Total SSC Vulnerability
		H,M,L	H,M,L,N	H,M,L	H,M,L,N	H,M,L,N	H,M,L,N	H,M,L,N		
Grouping Weighting		Low - Very High				None - Very High			Low - Very High	None - Very High
Heat removal	Primary loop helium circulators	Low	High	Med	Low	Low	Med	High	Low	Med
	Shutdown cooling	Low	High	Med	Low	Med	Med	High	Low	High
	Passive decay heat removal	High	None	Med	None	High	Low	Low	High	High
Reactivity Control	Negative temperature coefficient	High	None	Med	Low	Low	None	None	High	Low
	Control rods	Med	High	Med	Low	Low	Med	High	Med	High
	Defueling pebbles	Low	Med	Med	Med	Low	Med	High	Low	High

Figure 2.6. Design Risk Matrix illustrating the Total SSC Vulnerability

The total values are arrived at through a set of logic paths, as seen in Figure 2.7. The SSC importance of protection is primarily determined by the *Impact on Safety Function*, modulated by *Reliance on Support Systems* and *DID Risk*, and the *Compromise Risk*. The *SSC Importance of Protection* is equal to the higher value of Compromise Risk or the modulated *Impact on Safety Function*.

The *Total SSC Vulnerability* is equally weighted between direct, indirect, and cyberattack and represents the highest value. Two "high" values will result in a "very high" determination for the *Total SSC Vulnerability*.

Safety Function	SSC	Impact on Safety Function	Reliance on Support Systems	Defense-in-Depth Risk	Compromise Risk	Direct SSC Attack Vul.	Indirect SSC Attack Vul.	Cyberattack Vul.	SSC Imp.	SSC Vul.
Heat Removal	A	Low	High	Low	Low	Low	Low	Low	Low	Low
	B	Med	Low	Low	Low	Med	Low	Low	Low	Med
	C	Med	Low	Low	Med	High	Low	Low	Med	High
Reactivity Control	D	Med	Med	Med	Med	Low	Med	High	Med	High
	E	Med	High	Med	Med	High	High	Med	Med	Very High
	F	Med	High	High	Med	High	Med	High	High	Very High
	G	High	None	Low	None	Med	High	High	Med	Very High
Radionuclide Retention	H	High	None	Med	Low	Low	Low	Low	High	Low
	I	Low	Low	Low	High	Med	Low	Low	High	Med
	J	High	High	Low	Low	Low	Low	Low	Very High	Low
	K	High	Low	High	Low	Med	Low	Low	Very High	Med
	L	High	Low	Low	High	Low	Low	Low	Very High	Low

Figure 2.7. Design Risk Logic for SSC Importance and Vulnerability

SSC Importance of Protection:

- SSCs A, C, D, E, H, I show that the resulting SSC importance of protection correlates to the qualification in the *Impact on Safety Function* or *Compromise Risk* columns (H and I specifically show that whichever has the higher qualification gives the result for the *SSC Importance of Protection*).
- The qualification values associated with the *Reliance on Support Systems* and *DID Risk* columns can affect the resulting value from the *Impact on Safety Function* to the *SSC Importance of Protection*. Examples in Figure 2.7 are:
    - Reductions for importance of protection
        - SSC B shows that a medium value for the *Impact on Safety Function* can be modulated to a low value if there are low values for both *Reliance on Support Systems* and *DID Risk*. The intent is to place less emphasis on SSCs with low reliance on supporting systems and multiple redundant trains.
        - SSC G shows that a high value for the *Impact on Safety Function* can be modulated to a medium value if there are none and low values for reliance on support systems and *DID Risk*. The intent is to place less emphasis on SSCs that would otherwise be qualified as high, if they have no reliance on support systems, and multiple redundant trains.
    - Increases for Importance of Protection
        - SSC F shows that if both *Reliance on Support Systems* and *DID Risk* values are high, then the medium value associated with *Impact on Safety Function* is elevated to a high for the *SSC Importance of Protection*.
        - SSC J, K, and L show that if *Impact on Safety Function* is qualified as high and if *Reliance on Support Systems*, *DID Risk*, or *Compromise Risk* values are also high, then the *SSC Importance of Protection* is very high.

Total SSC Vulnerability:

- The Total SSC vulnerability evenly weights *Direct SSC Attacks*, *Indirect SSC Attacks*, and *Cyber/Physical Attacks* (as show in SSCs A-D, and H-L).
- Any two high vulnerabilities result in a very high SSC vulnerability rating (as show in SSCs E, F, and G).

CHAPTER 3

3. IMPLEMENTATION ON ARC-100 REACTOR DESIGN

The SSeBD assessment on ARC-100 design is done by using a generic SFR assessment as the baseline template and readjusting the SSCs' importance and vulnerability based on the design differences between the two reactor models. The assessment at this present stage is done for the reactor core, used fuel pool, and subassembly wash station. This report is intended to be publicly releasable, thus sensitive results from the methodology pertaining to the ARC design were omitted. Those details were captured within a separate proprietary document for ARC internal use to inform the design and operations of their facility.

3.1. REACTOR CORE

The ARC-100 reactor is a 286 megawatts thermal Generation IV advanced small modular reactor utilizing the pool-type SFR technology. With this pool-type design, the primary coolant, reactor core, primary pumps, reactor components, and intermediate heat exchangers are mostly contained within the main reactor vessel [10]. The pool-type reactor also has a larger mass of primary sodium compared to the loop type, therefore providing greater heat capacity (larger thermal inertia) and allowing a longer grace period during temperature excursions. The ARC-100 core consists of fuel-containing driver subassemblies, successively surrounded by steel reflector assemblies and shield assemblies. Fuel pins within the driver assemblies each contain a generous gas plenum to capture fission gases. The core is divided into inner, middle, and outer core zones to flatten the radial power distribution.

3.1.1. Risk Consequence Assessment

3.1.1.1. Maximum Dose Potential

ARC-100 uses a U-10%Zr (uranium with 10wt% zirconium) sodium-bonded binary metallic fuel with an average uranium enrichment of 13.1 wt% U-235 [10]. The maximum enrichment is less than 20%. There are 99 fuel assemblies each having 217 fuel pins (total = 21,483 pins) placed inside the reactor core within the reactor vessel that generates power for 20 years [10]. After the 20 years cycle, irradiated fuel assemblies are transferred to the spent fuel storage tubes within the reactor vessel [5][12].

ARC-100's core design is shown in Figure 3.1. Because the reactor core contains the full inventory of fuel assemblies needed for the reactor operation, its maximum dose potential is very high following the definition given in Table 2.2.

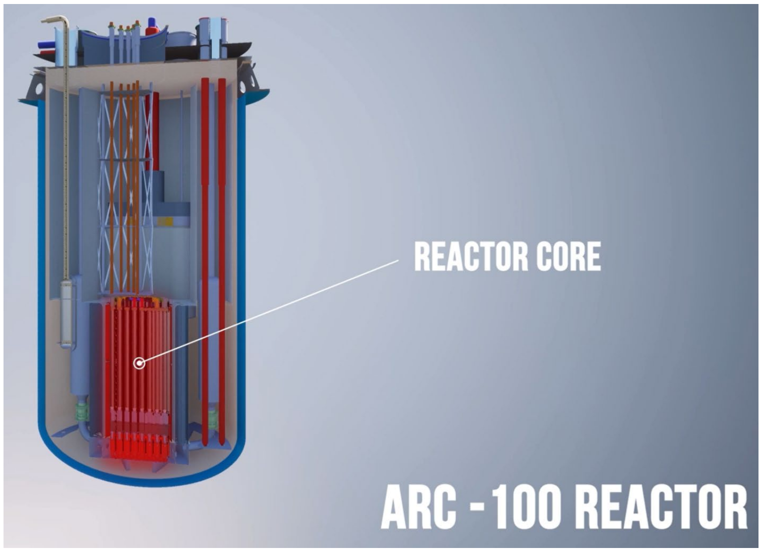

Figure 3.1. ARC-100 reactor core [5].

3.1.1.2. Dispersibility

Dispersibility of radioactive materials in ARC-100 reactor core is directly tied to the physical and chemical properties of the fuel design. As mentioned in the previous section, ARC-100 fuel is a metallic fuel design. The general schematics of this fuel pin design are shown in Figure 3.2. This design provides larger safety margins in normal operating modes and in postulated accidents compared to the oxide fuel design. This margin increase is made possible by the high thermal conductivity and high gap conductance that provide a longer grace period for operator actions [6].

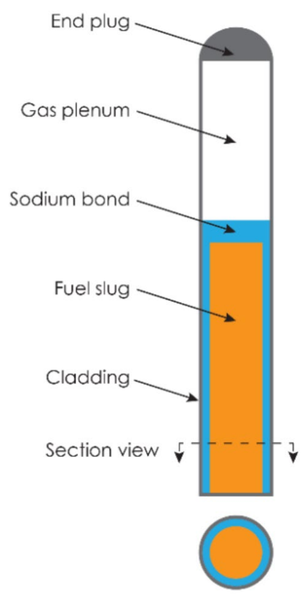

Figure 3.2. Schematic of a metal fuel pin, representative of ARC-100 design [7].

ARC-100 fuel adapts design improvements of previous metallic fuels tested in the EBR-II and the Fast Flux Test Facility (FFTF). It is worthy to note that EBR-II was the most successful test reactor operation, testing virtually every fast reactor fuel type for 30 years [8] and providing a wealth of information on metallic fuel characteristics. The following are notes on the evolution of metallic fuel designs tested in EBR-II with regards to their safety performance:

EBR-II FUEL DESIGN EVOLUTION:

Quoted from the Fast Reactor Working Group (FRWG) White Paper 18-01 [7] (emphasis added):

"Cladding breach is penetration of the cladding, which serves as the boundary between the fuel and the coolant and is considered the first fission product barrier. In early metal fuel designs (Mark I,-IA) used at EBR-II, cladding breach was caused by FCMI from fuel swelling at burnups of 1-3 at. %. In the subsequent Mark-II design, the **smear density was lowered to 75% to accommodate swelling, effectively eliminating failures due to FCMI**. Following this critical change, very few elements experienced cladding breach and much higher burnups were routinely achieved."

"As EBR-II transitioned from Mark-II fuel, evidence of the substantial improvements was seen in the outstanding performance of the Mark-III/-IIIA/-IV fuel. **Out of the 16,811 U-Zr and 660 U-Pu-Zr fuel elements that were irradiated at EBR-II, only 22 experienced cladding breach**. Defective welds were the cause of breach in 16 of the 22 fuel elements, **an issue that was eradicated early in the program**. Three cladding breaches occurred in the plenum region due to unknown causes. After these breaches, metal fuel designs were **modified to incorporate a larger fission gas plenum, with a plenum to fuel volume ratio of 1.4 becoming the reference** for EBR-II experiments and driver fuel. Lastly, three fuel elements breached in the fuel column region due to creep failure. One of these fuel column failures occurred in fuel that reached very high burnup (16.4 at. %). The other two occurred at 9.5 at. % burnup in elements that were intentionally operated at higher-than-normal temperatures (660 ^{0}C for HT9 cladding). These 22 breaches led to appropriate **fuel design changes and improvements in fabrication.** The small number of failures, and the constant push to improve the fuel designs in response, have effectively made **cladding breach a concern only under particularly challenging temperature regimes or at very high burnups**."

The reference also reported a good compatibility of the metallic fuel with sodium, which means that the fuel does not react rapidly with sodium coolant accelerating the fuel slug's dispersion:

EBR-II BREACH TEST CONCLUSION:

Quoted from the FRWG White Paper 18-01 [7] (emphasis added):

"The resulting behavior from the breached rods showed that **metal fuel is chemically compatible with sodium coolant**, since there were **no fuel-coolant reaction products, nor substantial washing out of fuel into the coolant**. Breaches were not substantially widened, because the breach released any pressure from fission gas. Bond sodium, fission gas, and cesium were released to the coolant, but overall, it was determined that a sodium fast reactor could operate benignly with breached fuel. This meant that the breach of a single metal fuel element would not necessarily require shutdown, and the reactor could continue to operate until a convenient time, or even the end of the cycle, prior to replacing the breached element."

Table 3.1 lists the evolution of metallic fuel design parameters beginning from EBR-II to ARC-100 that are relevant to ARC-100 fuel. These fuels all have a solid physical form that is chemically compatible with the sodium coolant. They share common traits when compared to oxide fuel designs, i.e., higher thermal conductivity, higher gap conductance, lower heat capacity, flatter radial thermal distribution, lower swelling risk, lower fuel failures from fuel cladding chemical interaction and fuel cladding mechanical interaction (FCMI) [6]. Compared to the EBR-II and FFTF fuel models, ARC-100 fuel has a lower enrichment, lower burnup limit, and thicker cladding, which suggests a better safety performance.

Table 3.1. Comparison of ARC-100 fuel properties with other sodium fast reactor fuel designs.

Sodium fast reactor fuel design comparison [7][9] [2]					
Fuel design	**Fuel alloy (wt%)**	**Cladding**	**U-235 (wt%)**	**Smear density (%)**	**Maximum burnup (at%)**
EBR-II Mark-IA	U-5Fs	SS304L	64	85	2.6
EBR-II Mark-II	U-5Fs	SS316	52	75	8
EBR-II Mark-IIC	U-10Zr	SS316	47	75	8.9
EBR-II Mark-IICS	U-10Zr	SS316	47	75	6.4
EBR-II Mark-III	U-10Zr	CW D9	83	75	10
EBR-II Mark-IIIA	U-10Zr	CW SS316	83	75	10
EBR-II Mark-IV	U-10Zr	HT9	78	75	N/A
FFTF	U-10Zr	HT9	Various	75	14
ARC-100	U-10Zr	HT9	< 20	75	14

The fuel characteristics described above provide a high safety margin, which in combination with the relatively low core energy of 286 MWth, makes it more difficult for the fuel slug to be aerosolized during postulated accidents and/or sabotage events due to the energy required to disperse the solid fuel. For that reason, the reactor core's dispersibility ranking is low as per the criteria given in Table 2.3.

3.1.1.3. Barrier for Dispersion

ARC's metallic fuel is encased within a metallic cladding as shown in Figure 3.2. Sodium bond is added to improve fuel pin's heat transfer especially during the early life of reactor, which also serves as a barrier to radionuclide's dispersion. A total of 217 of these fuel pins are then assembled into an enclosed fuel assembly having coolant inlet and outlet ports as shown in Figure 3.3.

[2] Fs: Fissium, SS: Stainless Steel, CW: Cold-worked, wt%: weight percent, at%: atomic percent.

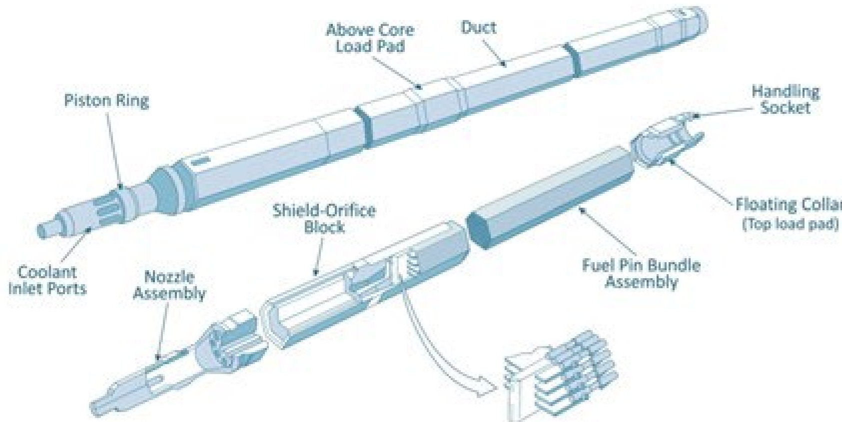

Figure 3.3. Schematic of ARC-100 fuel assembly design [10].

Fuel assemblies in the core are surrounded by shield assemblies and steel reflector assemblies within the reactor vessel. The reactor vessel is based on the pool-type SFRs where a pool of liquid sodium is contained within the reactor vessel and top plate. The liquid sodium is blanketed with argon gas cover maintained at slightly above atmospheric pressure. The reactor vessel, the reactor top plate, and mounted components, such as the rod drive mechanisms, intermediate heat exchangers, and the direct reactor auxiliary cooling system (DRACS) heat exchangers, comprise the primary system boundary [10]. This primary coolant boundary serves as the coolant loop for the primary heat transport system. The reactor vessel is also enclosed within the guard vessel which serves as a backup leak jacket. These vessels are located below grade as shown in Figure 3.4.

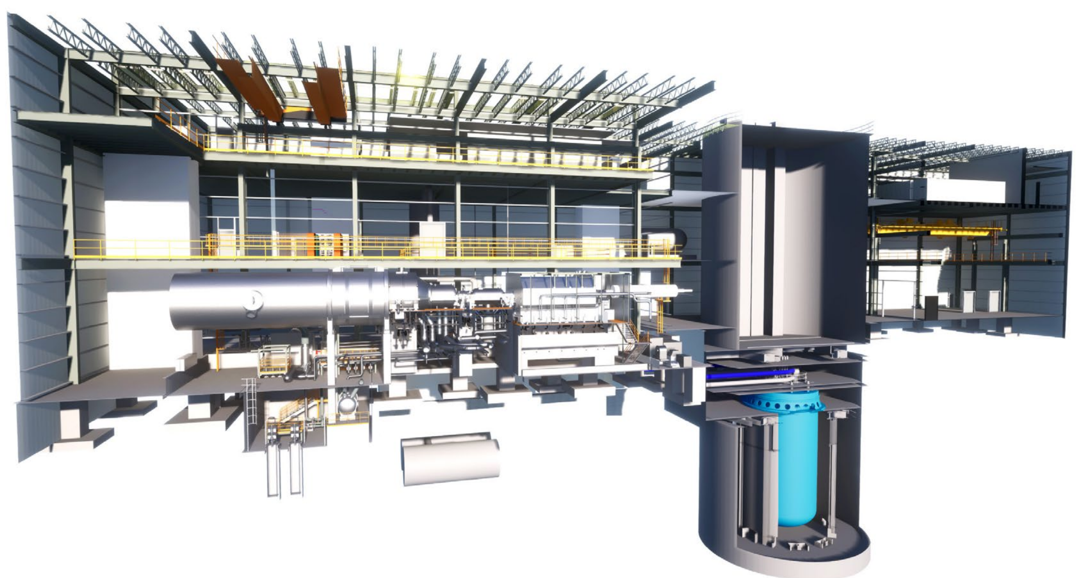

Figure 3.4. ARC-100 reactor building and confinement system [10].

With the description above, it can be concluded that ARC-100 reactor core has multiple inherent radionuclide barriers (i.e., fuel matrix, sodium bond, cladding, sodium coolant, the primary sodium boundary, the guard vessel, and the confinement system). As such, the barrier ranking is low as defined by the criteria in Table 2.4.

It is important to note that ARC's reactor building is a confinement system rather than a leak-tight containment system. The system includes a cylindrical concrete structure with the reactor vessel located below ground level and an operating deck above the reactor vessel. The structure includes containment doors, isolation valves in process lines, and dampers in the ventilation ducts that penetrate the containment envelope. The key notable feature in this confinement system is that it allows a limited amount of continuous air leak up to 1% of volume per day from anticipated operational occurrence, design basis events, and beyond design basis events [11]. The 1% vol/day limit is due to leaks from heating, ventilation, and air conditioning (HVAC) ductwork, doors, etc.

In summary, the radiological consequence assessment of ARC-100 reactor core is similar to the generic SFR (i.e., a very high maximum dose potential, a low dispersibility, and a low barrier to dispersion ranking). These ranks are visualized in a radar plot shown in Figure 3.5.

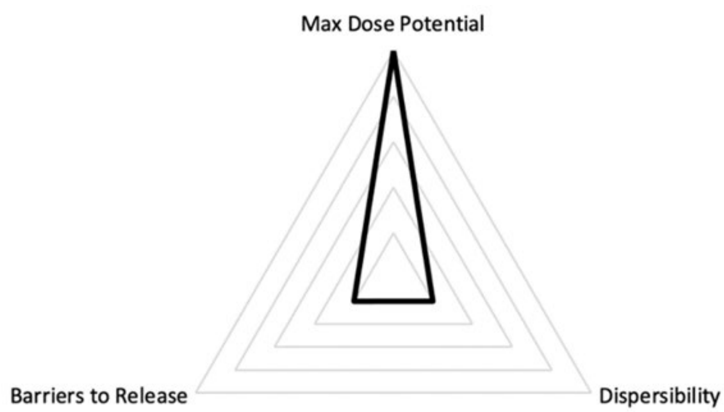

Figure 3.5. Radar plot for ARC-100 core radiological consequence assessment

3.1.2. Security Assessment

As shown in Figure 2.1, the security assessment process starts by identifying SSCs that meet certain FSFs. These FSFs are heat removal, reactivity control, radionuclide retention, chemical hazards prevention, and support functions [1].

For ARC-100 core region, SSCs responsible for performing the heat removal FSF include the entire active heat transport system as well as the passive DRACS and RVACS. Reactivity control SSCs include inherent reactivity feedback, control rods, and safety rods. Radionuclide retention is performed by fuel/cladding structure, sodium coolant, primary coolant boundary, top plate, guard vessel, and the confinement (HVAC) system. The chemical hazards cover the introduction of oxygen into the sodium loop. Support systems include power, instrumentation and control (I&C), and plant cooling systems.

As for the SSCs' DLs, ARC has adopted IAEA SRS 46 DID classification [4]. Therefore, this safety DID ranking was translated to the appropriate security DL ranking following Table 2.5. The security design risk was assessed for the ARC-100 design. The detailed results and conclusions are explained in a separate non-public report to ARC to inform their facility design and operations with respect to SSeBD and SeBD. Discussions and findings are provided in that report for each SSC analysis, covering each aspect in Section 2.2. i.e., DL ranking, impact on safety function ranking, reliance on support system ranking, DID risk ranking, compromise risk ranking, direct attack vulnerability ranking, indirect attack vulnerability ranking, cyberattack vulnerability ranking, and the resulting importance of protection and vulnerability rankings. Substantial insights were found for the safe and secure operation of the ARC reactor core. Meanwhile, this public report captures only some of these aspects, primarily the defense line ranking of all systems analyzed to date, and contributions of systems to the safe operation of the facility.

The security assessment ranking for each SSC related to ARC-100 core is discussed below:

1. Entire active heat transport system as a heat removal SSC.
    a. DL ranking is 1 because it serves to maintain normal power operation, in other words they work to prevent and control abnormal operation. Therefore, they belong in the safety DID level 1 and 2 according to IAEA SRS-46 [4], and consequently in the security DL ranking 1 following Table 2.5.
    b. The importance of protection ranking is low.
2. DRACS as a heat removal SSC.
    a. DL ranking is 2 because it functions to control accidents below severity level postulated within design basis. Therefore, it is categorized as DID level 3 [4] and consequently DL ranking 2.
    b. Importance of protection ranking is high.
3. RVACS as a heat removal SSC.
    a. DL ranking is 2 for the same reason as DRACS' DL.
    b. Importance of protection ranking is high.
4. Inherent reactivity feedback as a reactivity control SSC.
    a. DL ranking is 1 because it functions to prevent abnormal operation. Therefore, it is categorized as DID level 1 [4], and DL ranking 1.
    b. Importance of protection ranking is medium.
5. Control rods as a reactivity control SSC.
    a. DL ranking is 1 because it functions to control abnormal operation, therefore it is categorized in DID level 2 [4].
    b. Importance of protection ranking is medium.
6. Safety rods as a reactivity control SSC.
    a. DL ranking is 1 for the same reason as control rods' DL ranking.
    b. Importance of protection ranking is medium.

7. Fuel/cladding as a radionuclide retention SSC.
    a. DL ranking is 1 because it is necessary to maintain normal power operation. In other words, it prevents abnormal operation from happening. Therefore, it is categorized in DID level 1 [4].
    b. Importance of protection ranking is low.
8. Coolant as a radionuclide retention SSC.
    a. DL ranking is 1 for the same reason as fuel/cladding's DL ranking.
    b. Importance of protection ranking is high.
9. Primary coolant boundary as a radionuclide retention SSC.
    a. DL ranking is 1 for the same reason as fuel/cladding's DL ranking.
    b. Importance of protection ranking is medium.
10. Guard vessel as a radionuclide retention SSC.
    a. DL ranking decreases from 2 to 3 relative to the generic SFR design [1], because as can be expected, it does not prevent abnormal operation or control design basis accidents. Rather, it functions to mitigate the consequences of severe accidents affecting the reactor vessel's integrity. Therefore, it is categorized in the DID level 4 [4] and consequently in the DL ranking 3 following Table 2.5.
    b. Importance of protection ranking is low.
11. Confinement (HVAC) as a radionuclide retention SSC.
    a. DL ranking is 3 because it functions to mitigate the consequences of severe accidents. Therefore, it is categorized as a DID level 4 [4].
    b. Importance of protection ranking is low.
12. Power as a support system SSC.
    a. DL ranking is 1 because power serves to maintain normal reactor operation and prevent abnormal operation and failures; therefore, power is classified as a DID level 1 SSC [4] and consequently as a DL1 SSC.
    b. Importance of protection ranking is low.
13. I&C as a support system SSC.
    a. DL ranking is 1 for the same reason as power's DL ranking.
    b. Importance of protection ranking is high.
14. Plant cooling (not safety related) as a support system SSC.
    a. DL ranking is 1 for the same reason as power's DL ranking.
    b. Importance of protection ranking is low.

With those considerations, the security assessment for ARC-100 core can be summarized in a simplified format in Table 3.2 below. As the table shows, several SSCs have higher importance rankings than others, including DRACS, sodium coolant, and I&C. Protection efforts should be prioritized for these SSCs. The specific insights determined from the methodology were captured within the proprietary report. ARC has taken the insights under advisement and, as a result of this work, has conducted analyses to support the performance of the core under adverse circumstances and amended the facility design.

Table 3.2. ARC-100 reactor core security assessment.

ARC-100 Reactor Core Security Assessment			
FSF	**SSC**	**DL**	**SSC Importance**
Heat removal	Entire active heat transport system	1	Low
	DRACS	2	High
	RVACS	2	Medium
Reactivity control	Inherent reactivity feedback	1	Low
	Control rods	1	Medium
	Safety rods	1	Medium
Radionuclide retention	Fuel / cladding	1	Low
	Coolant	1	High
	Primary coolant boundary	1	Medium
	Guard vessel	3	Low
	Confinement (HVAC)	3	Low
Chemical hazards	Oxygen	N/A	Low
Support systems	Power	1	Low
	I&C	1,2	High
	Plant cooling	1	Low

3.2. USED FUEL POOL

The ARC-100 includes spent fuel storage locations in the reactor vessel with sufficient capacity to hold an entire core load of driver fuel assemblies [12]. After 20 years of operation, the irradiated fuel assemblies are transferred from the reactor core to the in-vessel fuel storage tube locations using the in-vessel transfer machine (IVTM). The used fuel assemblies will then reside in the storage rack locations to allow for thermal and radioactive decay. Spent fuel assemblies are moved from their storage rack locations in the reactor vessel after their thermal load has decayed significantly. They are extracted with the use of the fuel unloading machine (FUM). The assemblies are then transferred into the onsite dry storage facility [12].

3.2.1. Risk Consequence Assessment

The maximum dose potential ranking for used fuel pool is the same as the ranking for reactor core because they are in the same location—similarly, for the dispersibility ranking. Because the used fuel retains its physical and chemical configuration in the pool (i.e., fuel is within the fuel pins configured in fuel assemblies), the barrier to release ranking is likewise the same with the fuel in reactor core. Therefore, the maximum dose potential ranking is very high, the barriers to release ranking is low, and the dispersibility is low as shown in Figure 3.5.

3.2.2. Security Assessment

FSFs for the used fuel pool are the same as for the core region (i.e., heat removal, reactivity control, radionuclide retention, chemical hazards, and support systems). The following are the SSC rankings for SSCs that perform those FSFs:

1. Entire active heat transfer system, which is the same SSC performing the same heat removal FSF discussed in Section 3.1.2. having a low safety importance.
2. Passive cooling, representing DRACS and RVACS discussed in Section 3.1.2. having a high safety importance.
3. Storage racks (tubes) as a reactivity control SSC. There is no significant change in the design and function of these storage racks compared to the generic SFR. It is a simple and straightforward passive in-vessel structure designed to physically secure the used fuel assemblies in place, thereby preventing criticality and flow blockages. The storage rack's safety importance ranking is high.
4. Administrative controls as a reactivity control SSC. ARC-100 does not have specific administrative control on used fuel assembly positioning. Any used assembly can be placed in any available storage rack slots without any risk of local criticality or temperature hotspots. However, the successful positioning of these assemblies depends on the IVTM. Therefore, IVTM is considered as the administrative control SSC in this regard.
    a. DL ranking is 1 because IVTM functions to prevent abnormal operation and failures (e.g., dropping used fuel assembly). Therefore, it belongs to the DID level 1 and correspondingly to the DL1 category.
    b. Importance of protection ranking is low.
5. SSCs for radionuclide retention (i.e., fuel/cladding, coolant, vessel, guard vessel, and confinement [HVAC]) are the same with SSCs for the reactor core; their ranking is discussed in Section 3.1.2.
6. Likewise, SSCs for chemical hazards and support systems are the same as SSCs for the core region as discussed in Section 3.1.2.

With the aforementioned considerations, the security assessment for ARC-100 used fuel pool is summarized in Table 3.3. The table suggests that passive cooling, storage racks, and I&C should be prioritized for design improvements and/or additional protection measures due to their relatively higher importance than other SSCs.

Table 3.3. ARC-100 used fuel pool security assessment.

ARC-100 Used Fuel Pool Security Assessment			
FSF	**SSC**	**Defense Line**	**SSC Importance**
Heat removal	Entire active heat transport system	1	Low
	Passive cooling	2	High
Reactivity control	Storage tubes	1	High
	Administrative controls	1	Low
Radionuclide retention	Fuel/cladding	1	Low
	Coolant	1	High
	Primary coolant boundary	1	Medium
	Guard vessel	3	Low
	Confinement (HVAC)	3	Low
Chemical hazards	Oxygen	N/A	Low
Support systems	Power	1	Low
	I&C	1,2	High
	Plant cooling	1	Low

3.3. SUBASSEMBLY WASH STATION

The wash station is a facility used to wash used fuel assemblies of any remaining sodium before they are transported to the dry storage facility from the previous in-vessel used fuel pool [12]. This wash station is located inside the reactor building. It is designed to wash one used fuel assembly at a time.

3.3.1. Risk Consequence Assessment

There is only one used fuel assembly during each washing process in the wash station [12]. This is the same design as the generic SFR wash station. Therefore, the maximum dose potential ranking should be the same (i.e., high). The used fuel form is also the same with the generic SFR (i.e., solid metallic fuel or in aerosol form if released). Therefore, the dispersibility ranking is likewise the same (i.e., medium). A difference is that used fuel in ARC's wash station is not encased within a transport cask until the washing process is complete [12]. Nonetheless, there are still multiple inherent barriers preventing radionuclide release, namely fuel matrix, cladding, and the leak-tight wash station room. Therefore, the barrier to dispersion ranking is low. Figure 3.6 summarizes the consequence assessment for both ARC-100 and the generic SFR's wash station facilities.

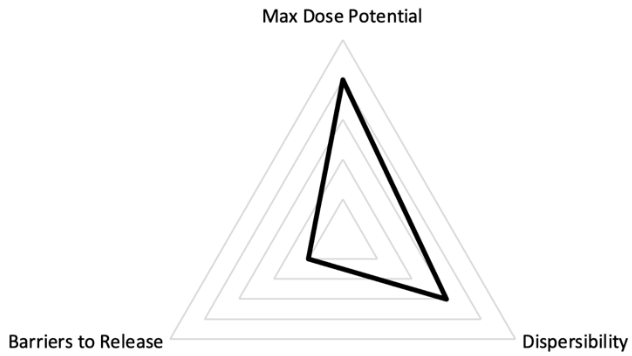

Figure 3.6. Radar plot for the used fuel wash station consequence assessment.

3.3.2. Security Assessment

Considerations for SSC security assessment on ARC-100 wash station are as follows:

1. Active and passive cask cooling systems. These systems are not used in ARC-100 wash station because fuel assemblies have cooled down significantly in the used fuel pool. Therefore, there is no thermal hazard, and consequently, dedicated cooling SSCs are not needed.
2. The reactivity hazard of used fuel is nullified by the design of the wash station.
3. Fuel/cladding as a radionuclide retention SSC.
    a. DL ranking is 1 because the fuel cladding serves to prevent abnormal operation (i.e., radionuclide release). Therefore, it belongs to the Level 1 DID SSC and consequently the first DL.
    b. Importance of protection ranking is medium.
4. Cask as a radionuclide retention SSC is not used in ARC-100 wash station. It will be used after the fuel is washed to transfer it to the dry storage facility [12].
5. Sealed compartment as a radionuclide retention SSC.
    a. DL ranking is 2 because it functions to control accidents that releases radionuclides from the fuel assembly. Therefore, it belongs in the level 3 DID SSC and consequently in the DL2.
    b. Importance of protection ranking is medium.
6. Argon inert gas system as a chemical hazard prevention SSC.
    a. DL ranking is 1 because its function is to prevent abnormal operation (sodium oxidation), so it belongs in the level 1 DID SSC and consequently in DL1.
    b. Importance of protection ranking is medium.
7. FUM as a support system SSC.
    a. DL ranking is 1 because it prevents abnormal operation such as fuel assembly drop and damage; therefore, it belongs in the level 1 DID SSC and consequently in DL1.
    b. Importance of protection ranking is medium.

8. Power as a support system SSC.
    a. DL ranking is 1 because it is required for the normal operation of washing used fuel assemblies.
    b. Importance of protection ranking is low.
9. I&C as a support system SSC.
    a. DL ranking is 1 for the same reason as power's DL ranking.
    b. Importance of protection ranking is low.

With those considerations, the wash station security assessment is summarized in Table 3.4. The systems with the highest safety importance should be prioritized for protection. ARC received the insights associated with the fuel wash station in a proprietary report, and as a result made design and operational changes to increase the safety and security of the system.

Table 3.4. ARC-100 wash station security assessment.

ARC-100 Wash Station Security Assessment			
FSF	**SSC**	**Defense Line**	**SSC Importance**
Radionuclide retention	Fuel/cladding	1	Medium
	Sealed compartment	2	Low
Chemical hazards	Argon inert gas system	1	Medium
Support systems	Power	1	Low
	I&C	1	Low
	FUM	1	High

CHAPTER 4

4. CONCLUSIONS AND FUTURE WORKS

The SeBD and SSeBD study on three systems of ARC-100 SFR was done on the reactor core, used fuel pool, and used fuel assembly wash station. The security assessment results show changes in SSCs safety importance and vulnerabilities relative to the generic SFR SSCs. However, the consequence assessment results are the same as generic SFR. Several SSCs have higher importance rankings than others, including DRACS, RVACS, I&C, used fuel storage tubes, sodium coolant, and FUM. It is recommended that protection efforts are prioritized for these SSCs. ARC has conducted safety analyses and design and operational changes (SSeBD) with regards to the reactor core and subassembly wash station as a result of this work.

Possible sabotage scenarios were discussed during the study and captured in a non-public report. These postulated scenarios reviewed adversary actions against safety systems. ARC is considering design modifications to address some of these sabotage scenarios and incorporate SeBD for planned deployments. This work will continue in the Fiscal Year 2025 for the remaining ARC-100 systems, including cesium trap, sodium cold trap, noble gas decay tanks, and used fuel dry storage facility, to provide SSeBD and SeBD insights and recommendations on non-core systems.

CHAPTER 5

5. REFERENCES

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