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PR&PP Evaluation:
ESFR Full System Case Study
Final Report

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Prepared by:

Proliferation Resistance and Physical Protection
Evaluation Methodology Working Group

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LIST OF ACRONYMS

ANL	Argonne National Laboratory
ANL-W	Argonne National Laboratory-West (now part of Idaho National Laboratory)
ASD	Adversary Sequence Diagram
C	Consequences
CR	Conversion ratio
C/S	Containment and surveillance
DE	Detection Resource Efficiency
DOE	U.S. Department of Energy
DP	Detection Probability
DU	Depleted uranium
DV	Design Variation
EASI	Estimate of Adversary Sequence Interruption
ESFR	Example Sodium Fast Reactor
FCF	Fuel cycle facility
GIF	Generation IV International Forum
HEPA	High-efficiency particulate air
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KMP	Key Measurement Point
LEU	Low-enriched uranium
LWR	Light-water reactor
MBA	Material balance area
MT	Fissile Material Type
MW_e	MegaWatt electric
MW_{th}	MegaWatt thermal
NDA	Nondestructive assessment
NWD	Nuclear weapon device
NES	Nuclear Energy System
NNSA	National Nuclear Security Administration
NPT	Nuclear Nonproliferation Treaty
PAS	Probability of Adversary Success
PC	Proliferation Cost
PIDAS	Perimeter intrusion detection and assessment system
PP	Physical Protection
PPR	Physical Protection Resources
PR	Proliferation Resistance
PR&PP	Proliferation Resistance and Physical Protection
PT	Proliferation Time
PUREX	Plutonium-uranium extraction
s	Second(s)
SFR	Sodium-cooled fast reactor
SQ	Significant quantity
TD	Technical Difficulty
TRU	Transuranic
WG	Weapon Grade

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EXECUTIVE SUMMARY

The Generation IV International Forum (GIF) emphasizes proliferation resistance and physical protection (PR&PP) as a main goal for future nuclear energy systems. The PR&PP Working Group developed a methodology to evaluate these systems. The evaluation framework focuses on the range of threats that future systems may face and evaluates their response using a set of measures, corresponding metrics, and proposed techniques to evaluate the metrics. While developing this methodology, the group gained an international consensus on concepts, an evaluation framework, and a common vocabulary. The GIF approved the current version of the PR&PP Evaluation Methodology, Revision 5, dated November 30, 2006, for unrestricted distribution. The methodology is supplemented by an addendum report with additional information.

The PR&PP Working Group developed the methodology with the aid of a series of studies based on an Example Sodium Fast Reactor (ESFR). The ESFR is a hypothetical nuclear energy system consisting of four sodium-cooled fast reactors of medium size co-located with a dry fuel storage facility and a pyrochemical spent-fuel reprocessing facility. These studies showed that the methodology can be applied to practical cases. However, review of this initial work indicated areas for further development, such as the use of expert elicitation as a routine component of a PR&PP analysis. Further progress on the PR&PP methodology required a more comprehensive evaluation of a complete reactor/fuel cycle to gain practical experience in applying the process, discern the needs for further methodology development and presentation of results, and confirm the usefulness and usability of the evaluation methodology. In particular, the PR&PP Working Group was requested by GIF to demonstrate that designers can obtain practical guidance and compare design options by applying the methodology. Another request was to demonstrate the capability to apply the PR&PP framework at different levels of detail, corresponding to different efforts and resources. For these reasons, the PR&PP Working Group undertook a 2-year case study. This report describes the study and lessons learned at the conclusion of the 2 years.

The major objectives of the case study were established during a meeting of the PR&PP Working Group held in Berkeley, California, from February 28 to March 1, 2007. The objectives were updated during subsequent planning teleconferences. The specific objectives of this case study are as follows:

1. Exercise the GIF PR&PP methodology for a complete Generation IV reactor/fuel cycle system
2. Demonstrate, by comparing different design options, that the methodology can generate meaningful results for designers and decision makers in particular
3. Provide examples of PR&PP evaluations for future users of the methodology.

Because comparing design options is a key goal of the methodology, the group took particular care in selecting the reactor/fuel cycle system for the case study. Because the ESFR with an associated fuel cycle facility (FCF) has already been well characterized, the working group selected it as the reference case study design. Whereas the case study focuses on facility-level PR&PP questions, it may also support, with further analysis, observations about PR&PP at the country global system architecture level.

To facilitate the analysis, the case study threat space was divided into four major categories:

1. Concealed diversion of material
2. Concealed misuse of the facility
3. Breakout and overt diversion or misuse
4. Theft of weapons-usable material or sabotage of facility system elements.

For the first three threat categories, the actor is the host state. For the fourth threat category, the actor is a sub-national group. Within the PR&PP methodology, a clear distinction is always made between host state (PR) threats and non-host state (PP) threats. For both the PR and the PP threat categories, actor objectives and capabilities were also defined.

Four working subgroups were created to study the respective threat categories, using qualitative assessment to identify targets and evaluate pathways that would ensue from the threats. In general terms, the methodology framework requires identifying security challenges to a given nuclear fuel cycle, examines the system's responses to those challenges, and delineates outcomes. It should be noted that the analyses that could be performed within the available time and resources were not comprehensive or definitive; and part of the motivation for letting different subgroups work independently at each threat scenario was, in fact, to see how different users might approach the implementation of the methodology. Not surprising, the approaches used by the different threat subgroups were non-uniform, reflecting their choices and perspectives. This is a valid outcome of this aspect of the case study, and it highlights the need for greater standardization of the methodology and its use.

The baseline design of the ESFR nuclear energy system operates in a net actinide burning mode and requires an external source of actinides for make-up. The ESFR consists of the following main system elements:

- Light-water reactor (LWR) spent-fuel storage
- A co-located Fuel Cycle Facility
- ESFR spent-fuel and fresh-fuel storage cell
- Fuel services building (containing single fuel assembly staging/washing area and transfer tunnels for each reactor)
- Four identical sodium-cooled fast reactors (SFRs) with in-vessel storage baskets
- Waste storage
- LWR spent-fuel cask receiving and parking area
- Excess uranium storage
- Uranium container parking area.

The case study considered the safeguards context used to evaluate host-state threats as well as the PP system for non-host-state threats.

With input from ESFR designers, the PR&PP Working Group generated a list of interesting design options for potential consideration in the case study. These include the following:

- Remote vs. onsite reprocessing of the LWR make-up feed

- Remote vs. onsite reprocessing of ESFR spent fuel
- Breeder vs. self-sustaining vs. burner conversion ratio (CR)
- Blend vs. not blend low-burn-up fuel material
- Start-up phase options (to generate first fuel load)
- Various physical arrangement options
- Various passive access control options

The first year of the case study focused on evaluating the baseline ESFR design, which consists of four reactors 800-MW_{th} with a transuranic (TRU) CR=0.64. For the second year of the case study, the group investigated whether and how effectively the PR&PP evaluation methodology could detect the impact on PR and PP when the CR is varied. To this aim a set of design variations was defined with different TRU conversion ratios (0.73, 0.22, 1.00, 1.12).

The case study exercise illustrated a practical approach for applying the PR&PP methodology in a traceable way, leading to accountable and dependable results for evaluating PR pathways at a qualitative level and PP pathways at qualitative and quantitative levels.

Basic lessons learned from the case study included the following:

- Each PR&PP evaluation should start with a qualitative analysis allowing scoping of the assumed threats and identification of targets, system elements, etc.
- Detailed guidance for qualitative analyses should be included in the methodology.
- Access to proper technical expertise on the system design as well as on safeguards and physical protection measures is essential for a PR&PP evaluation
- The use of expert elicitation techniques can ensure accountability and traceability of the results and consistency in the analysis.
- Qualitative analysis offers valuable results, even at the preliminary design level.
- Greater standardization of the methodology and its use is needed.

Completeness in identifying potential diversion pathways is a key evaluation goal. Targets and potential pathways can be systematically identified for each specific threat, and plausible scenarios can be systematically found to describe the potential proliferant host state's strategies to divert target material. A set of diversion pathway segments can be developed, and the PR measures, i.e. the high level PR qualifiers defined by the PR&PP methodology for each pathway, (Technical Difficulty, Proliferation Time, Proliferation Cost, Material Type, Detection Probability and Detection Resources Efficiency) can be estimated.

The diversion threat pathways analysis can also provide a variety of useful information to stakeholders, including regulatory authorities, government officials, and system designers. This information includes how attractive the material is to potential proliferators for use in a weapons program, how difficult it would be to physically access and remove the material, and whether the facility can be designed and operated in such a manner that all plausible diversion pathways are covered by a combination of intrinsic features and extrinsic measures.

The misuse threat pathways analysis requires consideration of potentially complex combinations of processes to produce weapons-usable material (i.e., it is not a single action on a single piece of equipment but rather an integrated exploitation of various assets and system elements). Given a proliferation strategy, some measures are likely to dominate the others, and within a measure some segments will dominate the overall estimate over the whole pathway.

The breakout threat pathways analysis found that breakout is a *modifying strategy* within the diversion and misuse threats and can take various forms that depend on intent and aggressiveness, and ultimately the proliferation time assumed by a proliferant state. Furthermore, PR measures can be assessed differently within the breakout threat, depending on the breakout strategy chosen. Note that some additional factors related to global response and foreign policy were identified as being relevant to the characterization of the breakout threat, but those factors are not included in the PR&PP methodology.

A substantial base of analytic tools already exists for theft and sabotage pathway analysis. The case study verified that these tools can be used within the PR&PP methodology framework.

The theft and sabotage threats pathways analysis found that multiple targets and pathways exist. The most attractive theft target materials appeared to be located in a few target areas. Specifically, for the ESFR, the most attractive theft target areas with the most attractive target materials were found to be the LWR spent-fuel cask parking area, LWR spent-fuel storage, the fuel services building staging/washing area, the FCF air hot cell, and the FCF inert hot cell.

The case study generated a number of additional insights. In particular, subgroups noted that during the evaluation process the analyst must frequently introduce assumptions about details of the system design, for example the delay time that a door or portal might generate for a PP adversary. As the study progressed, the working groups realized that, when these assumptions are documented, they can provide the basis for establishing functional requirements and design bases documentation for a system at the conceptual design stage. By documenting these assumptions as design bases information, the detailed design of the facility can be assured of producing a design that is consistent with the PR&PP performance predicted in the initial conceptual design evaluation (or, if the assumptions cannot be realized in detailed design, the original PR&PP evaluations must be modified appropriately).

The PR&PP methodology therefore has the potential to be a powerful tool that can be applied at the conceptual design stage for nuclear energy systems, to generate the design bases for detailed system design. Future work will include efforts to further exercise this approach and demonstrate its utility in guiding the design of Generation IV nuclear energy systems.

1. INTRODUCTION

Generation IV nuclear energy systems (NESs) highlight the goal of proliferation resistance and physical protection (PR&PP) [1.1]. The PR&PP Working Group developed an evaluation methodology applicable to the PR&PP robustness evaluation of Generation IV nuclear energy systems. The evaluation framework includes a set of measures, (i.e. the high level PR qualifiers defined the by PR&PP methodology for each pathway: Technical Difficulty, Proliferation Time, Proliferation Cost, Material Type, Detection Probability and Detection resources Efficiency) illustrative corresponding metrics, and proposed ways to evaluate the metrics. While developing this methodology, the group gained an international consensus on concepts, the framework, and a common vocabulary. The current release of the Generation IV International Forum (GIF) PR&PP Evaluation Methodology is Revision 5, dated November 30, 2006. It is a consensus document, approved by the GIF for unrestricted distribution [1.2, 1.3].

The PR&PP Working Group developed the methodology with the aid of a series of studies. An initial development study (2004) was followed by a demonstration study (2005-06) using the Example Sodium Fast Reactor (ESFR). The ESFR is a hypothetical NES consisting of four sodium-cooled fast reactors (SFRs) of medium size (800 MW_{th}, ~300 MW_e) co-located with a dry fuel storage facility and a pyrochemical spent-fuel reprocessing facility [1.4]. The ESFR is a pool reactor of the L2 type according to the classification scheme developed during the Generation IV Roadmap project [1.1].

The development study was a coarse pathway analysis of PR and PP for very specific threats. It considered the entire ESFR NES without any details of an assumed safeguards approach. For the demonstration study, the PR&PP Working Group decided to revise the ESFR system definition to incorporate a safeguards system description. Furthermore, the group decided to redefine the limits of the system to more narrowly focus on the PR aspects of the methodology applied to only a portion, or "slice," of one of the ESFR system elements: the co-located pyroprocessing fuel cycle facility (FCF). By focusing the study in this way, the group demonstrated the use of quantitative methods [1.5, - 1.7].

These previous studies showed that the methodology can be applied to practical cases. However, review of this initial work indicated areas for further development, such as the use of expert elicitation as a routine component of a PR&PP analysis. Further progress on the PR&PP methodology required a more comprehensive evaluation of a complete reactor/fuel cycle system to gain practical experience in applying the process, discern the need for further methodology development and presentation of results, and confirm the usefulness and usability of the evaluation methodology. In particular, the PR&PP Working Group was requested by GIF to demonstrate that designers can obtain practical guidance by applying the methodology. Another request was to demonstrate the capability to apply the PR&PP evaluation framework at different levels of detail, corresponding to different efforts and resources. For these reasons, the PR&PP Working Group undertook a 2-year case study. The current report describes the case study and lessons learned at the conclusion of two years of work.

1.1 Objectives

The major objectives of the case study were established during a meeting of the PR&PP Working Group held in Berkeley, California, from February 28 to March 1, 2007. The objectives were updated during subsequent planning teleconferences. The specific objectives of the case study are as follows:

1. Exercise the GIF PR&PP methodology for a complete Generation IV reactor/fuel cycle system
2. Demonstrate, by comparing different design options, that the methodology can generate meaningful results for designers and decision makers in particular
3. Provide examples of PR&PP evaluations for future users of the methodology:
    a. Facilitate the transition to other studies (as planned by Japan and France)
    b. Facilitate other ongoing collaborative efforts (e.g., the International Atomic Energy Agency program on Innovative Nuclear Reactors and Fuel Cycles, INPRO).

Because comparing design options is a key goal of the case study, the group exercised particular care in selecting the reactor/fuel cycle system for the case study. Because the ESFR with an associated FCF has already been well characterized, the working group selected it as the reference case study design.

1.2 Scope

The scope of the case study included a baseline system design and alternative design variations for comparison (Chapter 2), consideration of a safeguards approach (Chapter 3) and PP approach (Chapter 4), and a specific threat space (Chapter 5). With input from designers, the group generated a list of interesting design options for consideration:

- Remote vs. onsite reprocessing of the light-water reactor (LWR) make-up feed
- Remote vs. onsite reprocessing of ESFR spent fuel
- Breeder vs. self-sustaining vs. burner conversion ratio (CR)
- Blend vs. not blend low-burnup fuel material
- Startup phase options (to generate first fuel load)
- Various physical arrangement options
- Various passive access control options.

Year 1 of the case study focused on the baseline ESFR design, which consisted of four 800-MW_{th} sodium-cooled fast reactors operating in a net actinide burning mode with a transuranic (TRU) conversion ratio (CR) of 0.64. For the second year of the case study, the group investigated whether and how well the PR&PP evaluation methodology could detect the impact of varying the TRU CR. To this aim a set of design variations of the baseline design was defined with different conversion ratios (0.73, 0.22, 1.00, 1.12).

1.3 Approach for Evaluation.

To facilitate the analysis, the case study threat space was divided into four major categories:

1. Concealed diversion of material

2. Concealed misuse of the facility
3. Breakout and overt diversion or misuse
4. Theft of weapons-usable material or sabotage of facility system elements.

Four working subgroups were created to study the system response for the respective threat categories, using qualitative assessment to identify targets and evaluate pathways that would ensue from the threats. Each subgroup had meetings and teleconferences to aid in the process of performing their respective evaluations, thus exercising expert judgment.

The subgroups followed the framework laid out in the PR&PP methodology, as shown in Figure 1.1 [1.2]. In general terms, the methodology framework requires identifying security challenges to a given nuclear fuel cycle, examines the system's responses to those challenges, and delineates outcomes. It should be noted that the analyses that could be performed within the available time and resources were not comprehensive or definitive, and part of the motivation for letting different subgroups work independently at each threat scenario was, in fact, to see how different users might approach the implementation of the methodology. Not surprising, the approaches used by the different threat subgroups were non-uniform, reflecting their choices and perspectives.

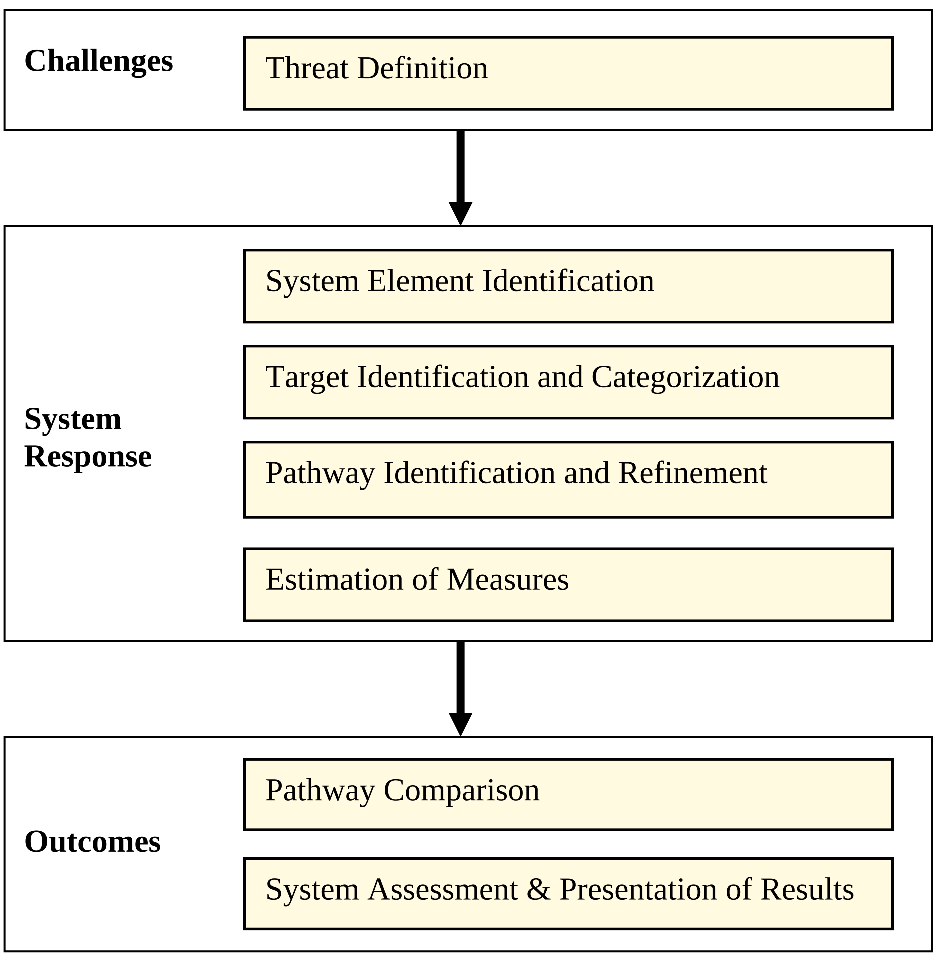

Figure 1.1: Framework of the PR&PP Methodology [1.2]

The evaluation methodology accounts for the system's intrinsic and extrinsic protective features. The former includes the inherent properties or physical design parameters of the system; the latter covers institutional aspects, such as international safeguards and external barriers.

Separate measures for comparing the robustness of proliferation resistance (PR) and physical protection (PP) features relevant, respectively, to the host state and non-state threats were developed under the PR&PP approach.

For PR, the measures are

- *Proliferation Technical Difficulty* (TD) – The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation.[1]
- *Proliferation Cost* (PC) – The economic and staffing investment required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities.
- *Proliferation Time* (PT) – The minimum time required to overcome the multiple barriers to proliferation (i.e., the total time planned by the Host State for the project).
- *Fissile Material Type* (MT) – A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives.
- *Detection Probability* (DP) – The cumulative probability of detecting a proliferation segment or pathway.
- *Detection Resource Efficiency* (DE) – The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the NES.

For PP, the measures are

- *Probability of Adversary Success* (PAS) – The probability that an adversary will successfully complete the actions described by a pathway and generates a consequence.
- *Consequences* (C) – The effects resulting from the successful completion of the adversary's action described by a pathway.
- *Physical Protection Resources* (PPR) – the staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

By considering these measures, system designers can identify design options that will improve system PR&PP performance.

[1] "Barriers" refers to intrinsic barriers (e.g., technical difficulty) and extrinsic barriers (e.g., safeguards) but does not include difficulties in weaponization.

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2. EXAMPLE SODIUM FAST REACTOR DESCRIPTION

A conceptual design of a Generation IV system with sufficient information about all the elements of the fuel cycle, as well as deployment considerations, has not yet been developed. Even for the Generation IV reactor technology that is considered more mature (sodium-cooled reactors), an off-the-shelf concept for testing the implementation of the methodology does not exist.

Therefore, the working group developed a hypothetical Generation IV ESFR system that includes the power plant, fuel cycle facilities, and a deployment scenario. For the power plant layout and concept, the group used one of the ideas submitted to the Generation IV Roadmap (AFR-300) [2.1]. The group selected a dry (i.e., non-aqueous) recycling technology (pyroprocessing[2]) for the fuel cycle facility (FCF) of the system. The case study assumes a plausible deployment involving co-location of the FCF and four reactor units.

The following sections provide an overview of the ESFR NES.[3] Appendix A contains more detailed information. The reactor and fuel recycle technologies, respectively, are discussed in references [2.2, 2.3]. The *boundaries* of the system coincide with the boundaries of the ESFR site. Facilities, material, and processes within the site boundary are *internal* to the ESFR system; all others are *external*.

2.1 System Elements Identification

The term ***system elements*** is defined as a collection of facilities[4] inside the identified *nuclear energy system* where diversion/acquisition and/or processing could take place. The ESFR contains the following system elements:

1. LWR spent-fuel storage
2. A co-located Fuel Cycle Facility
3. ESFR spent-fuel and fresh-fuel storage cell
4. Fuel services building (containing single fuel assembly staging/washing area and transfer tunnels for each reactor)
5. Four identical SFRs (each having an in-vessel storage basket)
6. Waste storage
7. LWR spent-fuel cask receiving and parking area
8. Excess uranium storage
9. Uranium container parking area.

[2] Pyroprocessing has been under development at both Argonne National Laboratory (ANL) and Idaho National Laboratory (INL); historically flow sheet development and lab scale tests were done at ANL-East (now ANL), while scale-up and engineering scale demonstrations were done at ANL-West (now part of INL).

[3] This ESFR description includes some material contributed by engineers from ANL and ANL-W, who are not part of the PR&PP group: C. Grandy, T. Fanning, M. Goff, and R. Kulak.

[4] According to International Atomic Energy Agency (IAEA) Additional Protocol, *facility* means "*(i) A reactor, a critical facility, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or (ii) Any location where nuclear material in amounts greater than one effective kilogram is customarily used*" [2.4]. The implicit facility definition given above in the text is compatible with the IAEA definition.

These are the facilities (locations) inside the ESFR system containing nuclear material or processes that could be attractive for proliferation or theft and/or sabotage. Current documentation for the nuclear facility on which the ESFR is modeled does not explicitly include the LWR spent-fuel cask receiving and parking area, the LWR spent-fuel storage and a waste storage facility. For completeness, these are included as internal ESFR system elements.

Figure 2.1 shows the ESFR nuclear system, including all the system elements listed above.

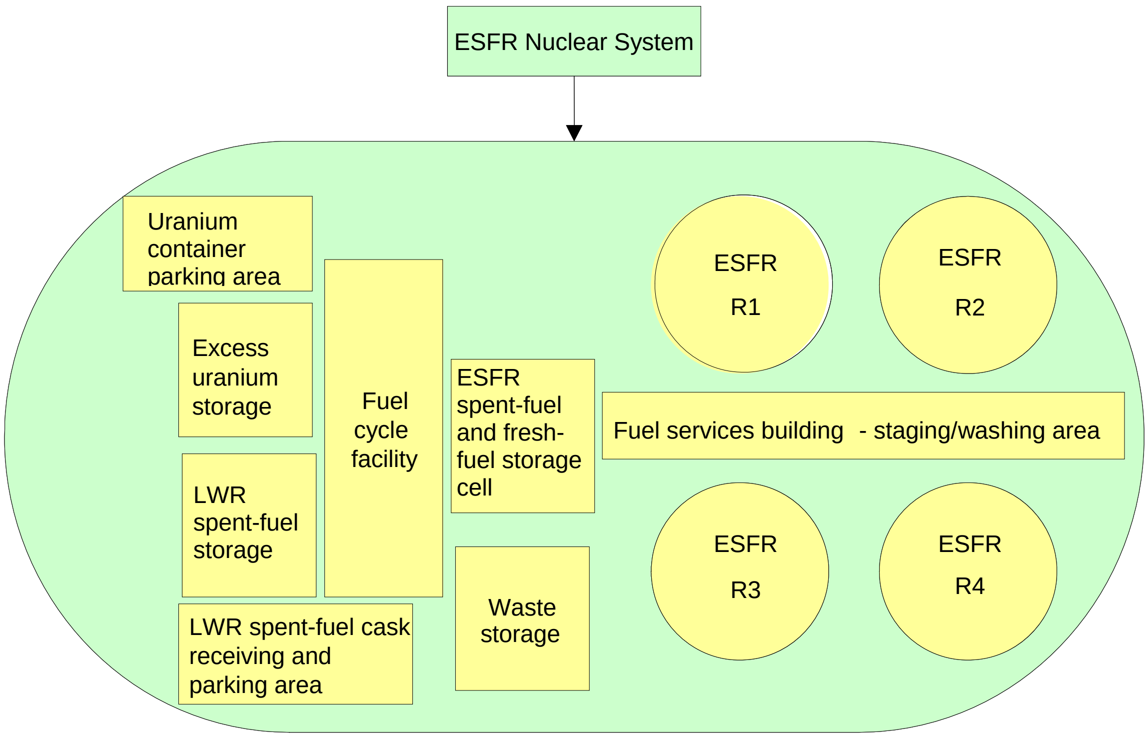

Figure 2.1: Diagram of ESFR Nuclear System Elements

2.2 Baseline Site Description

The operation characteristics of the pyroprocessing technology make it amenable to small throughputs, providing the opportunity for co-location of a fuel cycle facility with the power plants, as assumed in the ESFR design for the case study. The ESFR site consists of four sodium-cooled fast reactor power plants (nominally, 300 MW_e each) and a single FCF.

The site also includes a fuel services building that contains a spent-fuel staging area used for washing spent-fuel assemblies and transferring them to the FCF. Fresh (recycled) fuel is also transferred from the FCF to the reactors via the fuel services building. At the front of the FCF, a spent-fuel and fresh-fuel storage area is provided to allow for enough storage space to maintain steady operations of the facility and transfers to and from the reactors.

Figure 2.2 shows an artist's view of the site layout. Potentially relevant details about security-related buildings, gates, fences, etc. have not been developed, and the PR&PP group made assumptions. Placement of auxiliary buildings has not been developed either. Figure 2.3 shows a possible overall site plan for the ESFR nuclear energy system. Note, however, that Figures 2.2 and 2.3 do not contain all the system elements identified previously.

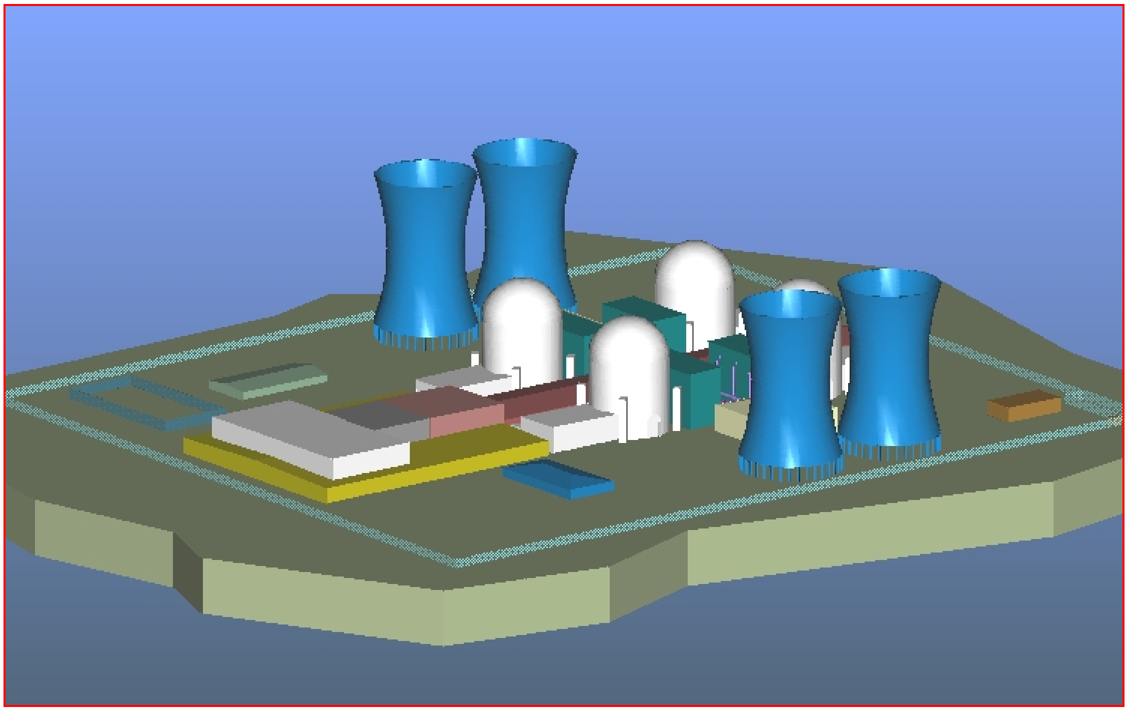

Figure 2.2: Site View for the Example Sodium-Cooled Fast Reactor

For the baseline of the ESFR system, the working group assumed that the reactors would operate in a net actinide burning mode, which is the assumption made in the Generation IV program for initial deployment of fast spectrum reactors with an actinide management mission. Therefore, the reactors would not operate in a self-sufficient mode and would require an external source of actinides for make up. Several options existed for the external source of actinides. Because the recycled fuel is assumed to be fabricated in the onsite FCF, an external source needs to be provided to that facility. The assumption made for the baseline ESFR system is that the external source is provided in the form of LWR spent-fuel assemblies. This assumption avoids the need to consider an external FCF to reprocess the LWR spent fuel. The LWR oxide fuel will be processed in the onsite FCF, which requires a front end step to reduce the oxide fuel to metal before processing in the electrorefiner.

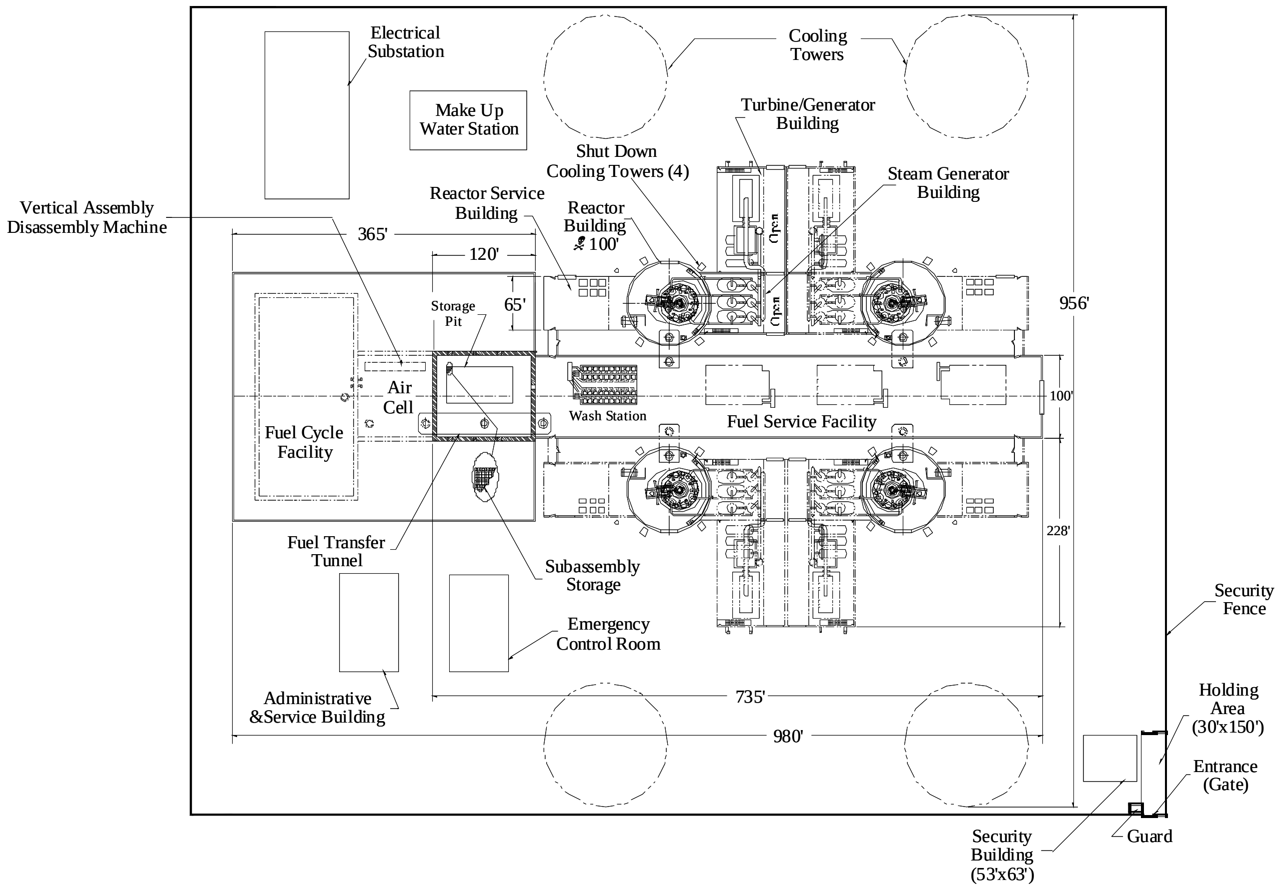

Figure 2.3: Possible Overall Site Plan

2.3 Design Variations

The baseline ESFR system examined in Year 1 of the case study consisted of four 800-MW_{th} SFRs operating in a net actinide burning mode with a TRU CR of 0.64. Researchers at ANL conducted design sensitivity studies of a 1000-MW_{th} ESFR to achieve low and high CRs [2.5]. The PR&PP Working Group used the data from those studies for its case study design variations. Therefore, the design variations considered the following four cases:

- Design Variation 0 (DV0): TRU CR = 0.73
- Design Variation 1 (DV1): TRU CR = 0.22
- Design Variation 2 (DV2): TRU CR = 1.00
- Design Variation 3 (DV3): TRU CR = 1.12

DV0 is a net actinide burner comparable to the baseline ESFR system (TRU CR = 0.64) but with a larger core. DV1 examines a deep actinide burner core case. DV2 is a case of a break-even core without any fertile blanket assemblies, whereas DV3 is a breeder core case with both radial and internal fertile blanket assemblies. Further information for each of the design variations is provided in the figures and tables in Appendix A.

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3. Overview of the Example Sodium Fast Reactor Safeguards Approach

For a state under a comprehensive safeguards agreement [3.1][5], the ESFR safeguards approach could be addressed on the basis of existing safeguards criteria [3.2]. Generic safeguards criteria exist indeed for the different types of facilities and the ESFR can be seen, as a first approximation, as a collection of different types of facilities. The safeguards approach considered in this case study uses some of the existing safeguards criteria as a starting point.[6] When pathway analysis is performed for specific diversion and misuse targets, assumptions about the types of safeguards measurements and their detection capabilities are recorded, and this information can then be used to provide functional requirements for detailed design.

For the ESFR NES, material protection, control and accountability would be administered within material balance areas (MBAs). The following MBAs were defined for the ESFR system (see Figure 3.1):

- XE01 to XE04 would contain ESFRs 1 to 4 and therefore would include Reactor 1 to 4 core and related in-vessel storage baskets.
- XE05 would contain the ESFR area inside the fuel services building, including the washing station and the related area.
- XE06 would contain the cell with the pits used for storing both ESFR fresh-fuel assemblies and ESFR spent-fuel assemblies.
- XE07 would contain the ESFR FCF. This MBA will eventually be divided into smaller MBAs for future studies, but because this part of the site was widely investigated during the previous demonstration study, in the case study the fuel cycle facility was treated as a black box with a single MBA.
- XE08 would contain the excess uranium storage, where the excess uranium recovered from the FCF would be kept until removal.
- XE09 would contain the LWR spent-fuel storage. This is assumed to be a pool.
- XE10 would contain the LWR spent-fuel containers/casks parking area outside the LWR spent-fuel storage pool.

Note that no MBA has been associated to waste storage as the waste is assumed not to be under safeguards; consequently the waste storage is not indicated in Figure 3.1. Figure 3.1 presents in addition the Key Measurement Points (KMP), subdivided into inventory measurement points (in red) and transfer measurement points (in yellow). The type of measurement and detector is also indicated.

At each MBA, nuclear material accountancy, containment and surveillance (C&S), and design information verification would be carried out. In the ESFR NES, most nuclear material would be remotely handled in areas that would be difficult to access (e.g., either inside the reactor immerged in liquid sodium or inside a building with an inert atmosphere etc.). Radioactivity levels of ESFR (re-fabricated) fresh-fuel assemblies would likewise be sufficiently high to require remote handling and transport in shielded casks. For almost all of the inventory areas using remote handling, hands-on access for verification would not be possible, and the monitoring system must be designed to allow

[5] Although Generation IV NESs are supposed to be deployed in countries where integrated safeguards are in force, the current case study considered a traditional safeguards approach.
[6] This discussion does not include the safeguards approach for the ESFR FCF. A preliminary safeguards approach for the FCF can be found in [3.3, 3.4].

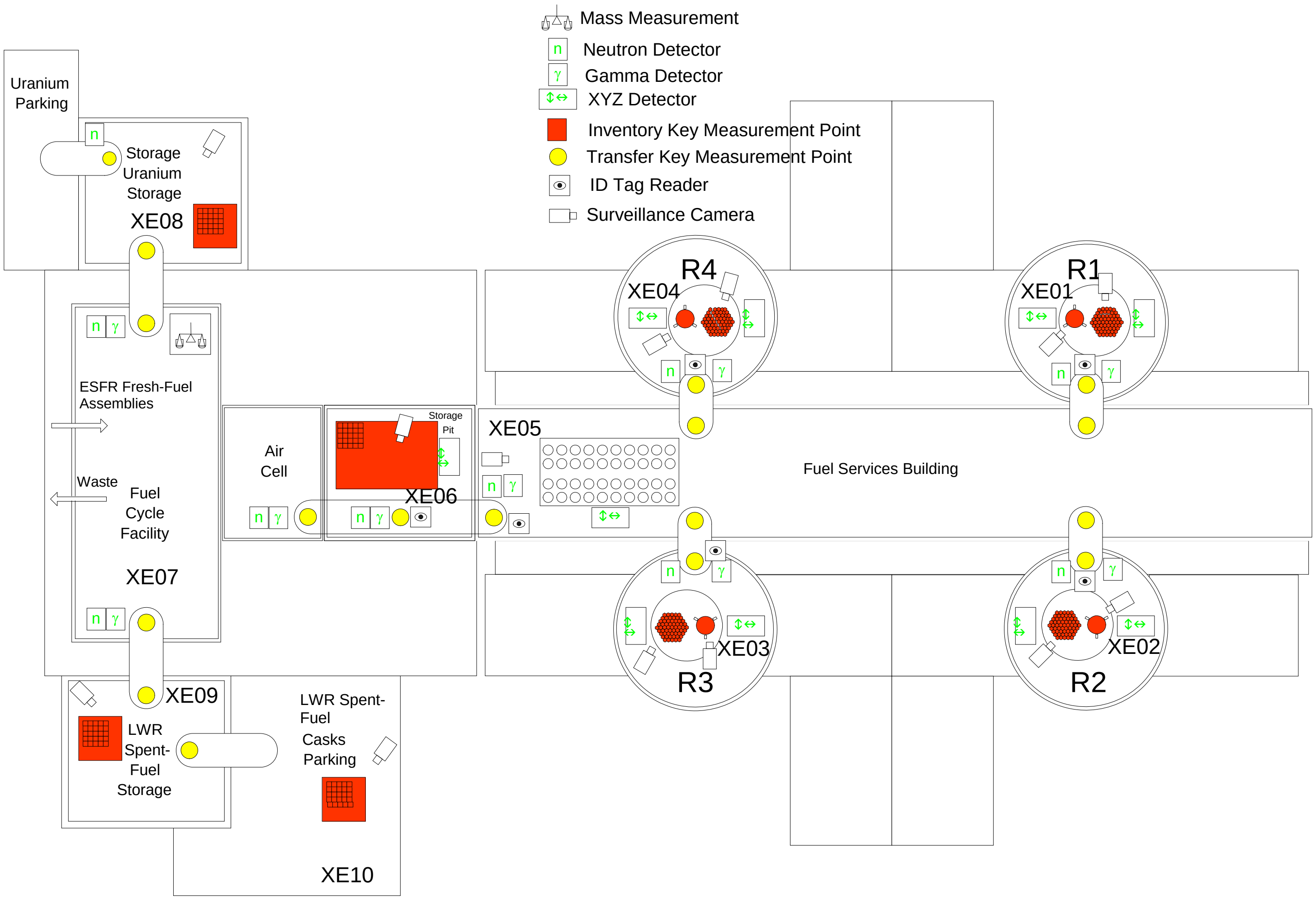

Figure 3.1: Overview of ESFR Safeguards Approach.

the type and amount of material in these areas to be determined from the monitored/recorded material flows under all system operating modes.

Based on current safeguards practice for sodium fast reactors, the following inventory verification activities were assumed:

- For *normal accessibility areas*, a single C/S system is required:
  - For LWR spent fuel assemblies[7]:
    - Evaluation of the C/S system
    - Item counting
  - For ESFR fresh-fuel assemblies[8]:
    - Evaluation of the C/S system
    - Item counting
    - Verification via serial number identification
    - Nondestructive assessment (NDA) with 10% detection probability for gross defects (See Reference [3.2] for the definition of gross defect)
  - For ESFR spent-fuel assemblies:
    - Evaluation of the C/S system
    - Item counting of transfer casks

- For *low accessibility areas*, a dual C/S system with two different and independent monitoring systems is required, and the foreseen activity is the evaluation of the dual C/S system. Inventory is calculated by the difference between items entered in the area and items exited from the area.
- For material and equipment *entering and leaving low accessibility areas*, measures have to be taken to confirm the operator's declaration regarding the transfers. A variety of methods are available to detect and monitor such transfers, providing the capability for redundancy and diversity in detection. Materials in transit are verified with high detection probability for gross defects. This verification includes measurements capable of distinguishing dummy, fresh-, and spent-fuel elements. Equipment transfers for maintenance are inspected to verify the absence of undeclared materials. For off-normal and accident conditions, it is valuable to have a method to de-energize and passively "lock-down" transfer equipment to help preserve continuity of knowledge.

These actions should be effective for all normal operating modes, as well as for off-normal transients that have a reasonable probability of occurring. Identification of off-normal transients should be consistent with the transients that are identified and analyzed in the facility safety analysis.

[7] LWR spent fuel assemblies are the only assemblies that are kept in normal accessibility areas, all other fuel assemblies are kept in difficult to access areas.

[8] ESFR fresh and spent fuel assemblies are not supposed to be stored in normal accessibility areas. The only possible storage for these kinds of items is the washing/staging machine: although no storage of items is foreseen in the machine during routine operations, the piece of equipment is designed to offer a limited number of places in cases where problems of transfer of the nuclear material inside the ESFR re-fabricated and spent fuel storage pit are encountered.

Concerning inspection activities and frequencies, the working group made the following assumptions:

- For *Interim Inventory Verification*, an inspection every 3 months is expected, and activities include book audit, C/S systems verification, and item counting[9].
- For *Physical Inventory Verification*, an inspection per year is expected, with the activities described in the above paragraphs.
- For *Design Information Verification,* one inspection per year is expected to check for undeclared design variations.

Appendix B provides additional information on the ESFR safeguards approach.

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[9] Typically, in an integrated safeguards approach, some of the inspections for Interim Inventory Verification would be unannounced and random.

4. OVERVIEW OF THE EXAMPLE SODIUM FAST REACTOR PHYSICAL PROTECTION APPROACH

Theft of nuclear materials or information involves actions by non-host-state actors, who may be sophisticated thieves, terrorists, or agents of rogue states. Information related to technologically challenging systems, such as electrochemical processing and even some aqueous extraction processes, is sensitive, and access to this information requires control to prevent theft. Nuclear facilities also have PP systems that restrict access to and prevent theft of nuclear materials and sabotage of equipment. The barriers to theft of nuclear materials, information, and equipment include both intrinsic characteristics of the materials themselves (mass, bulk, and radiation levels), encoding (information encryption), and equipment (fragility), intrinsic characteristics of the locations where the materials/information/equipment are stored and handled (vaults, hot cells, transfer casks, equipment rooms, and other controlled locations), and extrinsic measures associated with the design of the PP system, which can detect, delay, and neutralize adversaries and control the effects of insider actions (alarms, motion sensors, armed security forces, access control systems, locks, and seals).

Three primary strategies reduce the risk of nuclear material theft or sabotage that would release radioactive materials:

1. Achieve a globally uniform level of PP (via both intrinsic features and extrinsic measures) for the plant site that is commensurate with local threats and the intrinsic material barriers that impede the theft of materials and the intrinsic equipment characteristics that impede sabotage.
2. Optimize design to increase the intrinsic material barriers that impede theft/sabotage and to improve PP system technology to achieve equivalent protection levels at a reduced cost.
3. Change the global system architecture to reduce long-term risks by using mechanisms, such as spent-fuel return, that prevent very long-term storage of nuclear materials in dispersed locations where resources for applying appropriate PP may not be available in the future.

The ESFR PP approach described in this chapter addresses only the first two primary strategies. Appendix C provides additional information on the ESFR physical protection approach.

4.1 Physical Protection Approach for Theft Targets

The ESFR case study focused on theft targets. This section describes specific design features that were assumed in the PP analysis. Sabotage targets were also studied in an earlier phase of the analysis; results are described in Appendix D.4.

4.1.1 Spent-Fuel Cask Parking

While the LWR spent-fuel cask parking area would be the most accessible to an adversary, it also would contain the least attractive material. However, since radiological sabotage would also be a threat, the cask parking area must be protected.

Detection may include numerous types of sensors and visual observation. The parking area (or alternatively the entire ESFR facility, depending on the detailed physical arrangement) would be surrounded by a PIDAS, which is a fencing and detection system with access controls to ensure only authorized personnel can enter or exit. This system would also include an element of three-dimensional space; that is, detection and potentially barricades must go vertically above grade and below, if such would be accessible to the adversary. Heavier steel fencing would enclose the most vehicle-accessible areas. Concrete or steel barricades that can be raised would be placed on roads at access points. Additionally, the casks themselves, when fully closed and secured, would provide barriers to nuclear material access.

4.1.2 Spent-Fuel Storage and Fuel Services Building Staging/Washing Areas

The ESFR spent-fuel storage and staging/washing areas would contain the next most attractive material targets. Here assemblies would be removed from the casks could be more accessible to an adversary.

These areas would be within a PIDAS. Additionally, detection could be placed on access doors and equipment ports into the storage and staging area. Cameras and sensors would be provided to observe the internal volumes. Assembly lifting devices (cranes) are designed to be locked out or disabled when not in use. Vault-type doors would be installed on vehicle and equipment access openings large enough for removal of the assemblies. The facility walls and roof would be hardened. Pitched versus flat roofs would be used, or rooftop barriers would be placed to prevent aircraft access.

4.1.3 Fuel Cycle Facility

The FCF would be a large hot-cell facility that reprocesses the spent fuel and fabricates fresh fuel. Included are both an air hot cell and an inert hot cell. Metal product ingots and fresh fuel elements would provide the most attractive theft targets, because fission products would have been largely removed.

The FCF would include multiple PP features:

- Loading equipment (cranes, hoists) would be designed to be disabled or locked out during non-facility use.
- The manipulator equipment would be installed with hard-to-remove fasteners. They may be able to be manufactured in a paired configuration, such that the opening size in the cell wall would be too small to be useful for theft. The manipulators could be locked out when not in use and access controlled when in use.
- Equipment access ports would be minimized in size where possible; however, at least one must be of sufficient size to accommodate the in-cell equipment. That large equipment access port would be either closed with a crane-movable hatch or equipped with a vault-type door.
- Detection sensors would be placed on all large ports.
- Oil filled windows are used; they are less resistant to penetration than the cell wall and would have to be hardened to increase delay time.

- Walls, floors, and ceilings of hot cells are normally thick, reinforced concrete for shielding purposes. Additional reinforcement and smaller reinforcement spacing would be added during construction to strengthen the walls, floor, and ceiling to increase their vault-type effectiveness.
- Detection sensors would be placed within the areas around the cells, within the cells, and even within the walls.
- Portions of ventilation and high-efficiency particulate air (HEPA) filtration systems that are not enclosed within concrete would be hardened. Ventilation openings would be reduced in size or have barriers placed to prevent access. Detectors would be added to the access barriers.

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5. THREATS CONSIDERED

Because the definition of threats is a fundamental and central element of the PR&PP methodology, the working group selected the representative threats analyzed in this case study (Chapter 6) to cover a relatively large fraction of the total PR&PP threat space for the ESFR. This chapter reviews the PR&PP threat space and discusses the basis for selecting the representative threat definitions.

Threats can be categorized by type of actor, the actor's capabilities, the actor's objective, and the actor's strategy [5.1]. A detailed threat space definition must specify and consider each of these dimensions.

It is useful to subdivide the PR&PP threat space based on the general approaches and tools used to defend against a specific threat. For example, the expert community has reached broad consensus that the threats of theft and sabotage, which are managed by PP measures, should be treated separately from the threats of diversion and misuse where the actor is the host state that has physical control of a facility and materials. Both the adversary and the defender are dramatically different in these two cases – host state versus a sub-national entity – and so are their capabilities, strategies, and actions. Consequently, this case study includes both representative PP threats and PR threats.

For PR threats, some of the important tools used to defend against host state proliferation are institutional measures, which include (1) the capability of the IAEA to apply safeguards to declared facilities and materials; (2) the export control regime, which can detect and control the transfers of dual-use equipment that might be used in clandestine production facilities; and (3) the international regime of bilateral and multilateral security assurances and other measures, which create incentives for nations to remain within the framework of the Nuclear Nonproliferation Treaty (NPT). These three tools provide a basis for generating three high-level categories for the PR threat space:

1. Concealed acquisition of material from a declared facility
2. Concealed production of material in a clandestine facility
3. Breakout and overt misuse of declared materials and facilities.

For this case study, three representative PR threats, drawn from the first and third categories, are considered in Sections 6.1, 6.2, and 6.3 of this report. For these three categories, the assumed objective of the host state is to obtain at least one significant quantity (SQ) of plutonium to assemble at least one nuclear weapon. The host state's assumed capabilities are those of a typical developed industrial nation. Three different host-state strategies are assumed and studied separately in Sections 6.1 (concealed diversion of material), 6.2 (concealed misuse of the facility), and 6.3 (breakout and overt diversion from and misuse of the facility). Table 5.1 summarizes the host state's assumed threat description.

Table 5.1: Assumed Host State Capabilities and Objectives

Characteristic	Description
Capabilities	
Technical skills	Advanced, with strong know-how in all relevant scientific and technological fields
Resources	Sufficiently high to pose no limitations
Uranium and Thorium Resources	Not present
Industrial capabilities	Advanced industrial state
Nuclear capabilities	Electricity production via the operation of advanced sodium-cooled fast reactors, with next generation back-end solution
Objectives	
No. of nuclear weapon devices (NWD)	1
Technical Performance (yield and reliability[10]) of NWD	Any yield; >50% reliability
Ability to stockpile	Sufficient for short-term stocking (around 10 years)
Deliverability	Compatible with modern multi-role fighter jets
Production rate	Not applicable. Only one device is planned

The definition of a PP threat has two components: a description of the actor (which includes type, objectives, and capabilities); and a description of the actor's strategy. The threat space is defined by considering an appropriate range of combinations of actors and strategies. For PP threats, the simplest and broadest subdivision involves distinguishing theft, where the adversary's objective is to remove material or information, from sabotage (or terrorism), where the adversary's objective is to generate damage or a radiological release.

In this study, the representative threats of theft of material (Section 6.4) and sabotage of nuclear facility system elements (Appendix D.4) were considered. We define the following specific threat for theft:

Actor Type: Military trained assault force
Actor Capabilities:

- ***Knowledge*** – knowledge of plant layout and PP basic design, sufficient knowledge of plant processes to understand targets of opportunity
- ***Skills*** – ability to design assault equipment to penetrate barriers, training in using assault weapons,
- ***Weapons and tools*** – assault weapons, specialized explosive ordinance, armored vehicles
- ***Numbers of actors*** – 12 outsiders and 1 insider
- ***Dedication*** – Military Objective oriented

[10] Attaining the desired yield is assumed to be a stronger function of adversary capabilities than of material properties. Reliability is related to the probability of pre-initiation, which is driven by the spontaneous fission rate of the fissile material.

Objective: Theft of items from the ESFR facility in sufficient quantity to obtain 1 SQ of nuclear weapon material.
Strategy: Surprise assault on ESFR facility directed at material storage areas.

Because a primary goal of the case study is to illustrate how the PR&PP methodology can be of value to the facility designer, the work focuses on facility-specific design implications and examines how different design options may affect the relevant pathways, outcomes, and associated measures.

The following sections discuss each of the high-level threat categories in greater detail.

5.1 Concealed Acquisition of Material from a Declared Facility

The case study considers two concealed acquisition threats. Concealed acquisition from a declared facility involves either the diversion of material from (Section 6.1) or the undeclared production of material (Section 6.2) in a facility that has been declared to the IAEA and is under that agency's safeguards. Nuclear material that might be successfully diverted or produced through undeclared activities is generally assumed to be processed in a clandestine facility to produce metal for fabrication of nuclear explosives. Where the processing would involve only chemical separation and reduction to metal, the host state is commonly assumed to be capable of constructing a small, clandestine, low-throughput chemical separations facility. Detection of such a small facility could be challenging, although for states that are party to the Additional Protocol of the NPT [5.2], there are additional means available to IAEA to detect undeclared activities

Conversely, for materials that would require enrichment (e.g., low-enriched uranium [LEU]), a state capable of constructing a small, clandestine, low-throughput enrichment facility would be able to choose to enrich undeclared natural uranium, as an alternative to risking detection of diversion of LEU.

Under the NPT, in a non-nuclear weapons state, the primary strategy to minimize the risk of concealed acquisition of material from declared facilities is to apply effective IAEA safeguards monitoring. The objective of IAEA safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities and deterrence of such diversion by the risk of early detection. The implementation of effective safeguards monitoring, using a combination of design information verification, nuclear material accounting, and C/S, is effected primarily by the facility type and the facility design. The research and development to improve the effectiveness and efficiency of materials accounting and C/S play an important role in improving the detection capabilities of safeguards. Further, designing buildings to facilitate materials accounting, control, and C/S also brings benefits in the areas of PP, safety, and reliability.

5.2 Concealed Production of Material in a Clandestine Facility

Concealed production of nuclear materials in clandestine facilities involves either enrichment of uranium in a clandestine facility or irradiation of uranium in a clandestine reactor followed by separation of plutonium in a clandestine reprocessing facility. This threat was not studied in this ESFR case study. These proliferation pathways do not involve direct misuse of declared nuclear energy infrastructure; however, the acquisition of equipment and skills for a clandestine facility may be aided by the existence of a declared program. Conversely, the probability of detection of the clandestine facilities is increased if the state has signed and brought into force an Additional Protocol to its Comprehensive Safeguards Agreement (which is required in connection with the NPT) and, moreover, if the state operates its nuclear energy infrastructure in a transparent manner that is consistent with economic production of nuclear energy and is proactive in meeting its obligations under the Additional Protocol.

5.3 Breakout and Overt Misuse of Declared Materials and Facilities

Breakout involves overt actions to remove materials from declared facilities or misuse declared facilities. The breakout threat was analyzed in this case study (Section 6.3). Because breakout includes the termination of IAEA safeguards, these actions would not be detected by safeguards. In principal, any non-nuclear weapons state possessing civil nuclear energy infrastructure has the theoretical capability to break out. In general, a state that chooses to break out would be expected to place a high premium on rapid acquisition of a nuclear explosive device, and therefore the materials and facilities that are most sensitive from the perspective of breakout are those that would allow the most rapid acquisition with the lowest probability of technical failure.

5.4 Theft of Nuclear Materials or Information

Theft of nuclear materials or information involves actions by non-host-state actors, who may be criminal or terrorist groups, or agents of rogue states, and who may have assistance from insiders. A second potential target for theft is information related to technologically challenging systems, such as enrichment centrifuges. These types of information are sensitive, and access to them must be limited through access control. This case study includes analysis of the threat of material theft (Section 6.4). Nuclear facilities also have PP systems that restrict access to and prevent theft of nuclear materials. Both intrinsic features and extrinsic measures are required to protect the material, because, without any extrinsic PP measures, all materials become vulnerable to theft by terrorist groups. The design of PP systems for material protection, control, and accounting has significant overlap with the design for effective implementation of international safeguards, safety, and reliability.

5.5 Radiological Sabotage of Nuclear Facilities or Transport

Radiological sabotage involves actions by one or more terrorists who may have assistance from insiders. This case study briefly summarizes previous analysis [5.3] of the threat of radiological sabotage (Section 6.4). The design of facilities and transport systems to resist radiological sabotage is closely related to safety designs. Nuclear facilities have PP systems that restrict access to target-sets of equipment that, if disabled, could result in radiological releases.

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6. Representative Pathway Identification and Analysis

This case study identifies and analyzes four sets of representative pathways, selected to cover a relatively large fraction of the total PR&PP threat space for the ESFR:

- Concealed diversion of material
- Concealed misuse of the facility
- Breakout and overt diversion of material and misuse of the facility
- Theft of nuclear material and sabotage of nuclear system elements.

Each section below summarizes the results of target identification and the threat strategies considered, discusses the analysis of selected pathways among those that were considered, and offers insights for further study. Appendix D provides detailed results for each threat area.

6.1 Diversion

While the diversion analysis is primarily qualitative and high level, it attempts to be complete in the breadth of coverage. As more detail is developed in the ESFR design and operating characteristics, in target properties, and in safeguards, new or modified pathway segments may be identified.

6.1.1 Diversion Target Identification

Diversion target identification for the ESFR begins by dividing the ESFR into system elements for analysis, as shown in Figure 2.1. Certain elements of a complete NES are beyond the scope of this case study. Specifically, uranium mining and separation facilities and sources of LWR fuel needed to feed the “inside the fence” portion of the ESFR are not analyzed in this study. In addition, the recovered uranium is also considered out of scope. Figure 3.1 shows the proposed safeguards MBAs and key measurement points (KMPs) for the ESFR.

A system element review looks for targets in each of the MBAs. The target analysis in this case study considers the different types of nuclear material in each system element, its location, and its configuration. Although several targets for diversion were identified in the four reactors (e.g., the reactor in-vessel storage basket is accessible while the reactor is operating), in the fuel services building, and in the ESFR fresh-fuel and spent-fuel storage cell, no credible pathways for concealed diversion of the SFR fuel subassemblies[11] have been identified. All nuclear material is contained in the subassemblies and for a concealed diversion must be moved through the FCF and then out through the excess uranium system element, the LWR spent fuel system element, or waste. No credible physical pathways for diversion of subassemblies are found to exist, since it is assumed that diversion of whole subassemblies would be easily detected by the existing safeguards system. This key assumption is important to the safeguards system performance and, therefore, leads to a functional requirement for the design bases for detailed design. The target analysis identified seven distinct targets, as listed in Table 6.1.

[11] Historically, sodium-cooled fast reactor fuel assemblies have been referred to as “subassemblies.”

Table 6.1: Diversion Target Description

Target ID	Target Description	Target Material Character
T1	Cask of LWR fuel assemblies	Irradiated U-235 and TRU (oxide)
T2	LWR fuel assembly(s)	Irradiated U-235 and TRU (oxide)
T3	TRU metal from electro-refiner process	TRU metal (80% plutonium)
T4	Waste containing TRU metal from electro-refiner cleanout process	TRU metal (80% plutonium)
T5	ESFR fresh-fuel subassembly	U-TRU fuel alloyed with zirconium
T6	ESFR spent-fuel subassembly	Irradiated U-TRU fuel alloyed with zirconium
T7	Recycled Uranium metal	Recycled uranium

6.1.2 Diversion Pathways Analysis

The diversion analysis proceeds along the following steps:

- Examine every potential target
- Characterize the target material
- Identify the possible physical mechanisms that could be used to remove the material
- Identify the physical and design barriers to removal
- Identify the safeguards instruments and approaches that detect each physical mechanism that could be used to remove the material
- Hypothesize ways to defeat the safeguards
- Lay out qualitative pathways for removal of each target
- Perform a coarse qualitative estimation of the measures for each diversion pathway.

The first result of this process is a list of diversion pathway segments as shown in Table 6.2. As described in the PR&PP methodology, proliferation of nuclear weapons has three stages:

Acquisition➔Processing➔Fabrication

Only the first stage, acquisition, is mapped in the first step of the analysis. The focus in this section is on how the target can be moved from its normal position.

Table 6.2: Initial Diversion Pathways Analysis

Target ID	Target Description	Diversion Points	Potential Strategies	Proliferator Actions (Enablers)	Pathway ID	Pathway Description
T1	Cask of LWR fuel assemblies.	XE-10-1	3 - Abrupt diversion	Use heavy truck and trailer to move cask. Fool or disable the camera. Compromise the inventory measurement records.	T1-XE-10-1	Cask of LWR spent fuel assemblies is in the LWR cask parking lot. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.
		XE-09-1 XE-10-1	3 - abrupt diversion	Send back a loaded cask instead of a empty cask. Use heavy truck and trailer to move cask. Fool or disable the camera. Compromise the inventory measurement records.	T1-XE-09-1	A full cask of LWR spent fuel is sent back instead of an empty one. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
T2	LWR Fuel assembly(s).	XE-09-1 XE-10-1	1. Protracted diversion	Fuel assembly(s) inserted in cask. Use heavy truck and trailer to move cask. Compromise the inventory measurement records	T2-XE-09-1a	Empty Cask of LWR Spent Fuel Facility is partially reloaded and sent back. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
		XE-10-1	1. Protracted diversion	Fuel assembly(s) left in cask. Use heavy truck and trailer to move cask. Compromise the inventory measurement records.	T2-XE-10-2	Cask of LWR Spent Fuel Facility is not unloaded completely. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
	LWR Fuel assembly(s).	XE-09-1	1. Protracted diversion	Use special container to conceal and move fuel assembly. Fool or disable the camera. Compromise the inventory measurement records.	T2-XE-09-1b	Fuel assembly intended for XE-07 is placed in the proliferators own transport container and is removed from XE09. Camera is compromised. Proliferator takes container and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.

Target ID	Target Description	Diversion Points	Potential Strategies	Proliferator Actions (Enablers)	Pathway ID	Pathway Description
T3	TRU metal from electro-refiner process.	XE-07-01	1. Protracted diversion (abrupt?)	Put TRU metal in metal waste container. Fool or disable the neutron and gamma detectors (if they exist) Fool Cameras, material recorders	T3-XE-07-1	Proliferator put TRU material in waste container and transports out through waste portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records.
		XE-07-02	1. Protracted diversion (abrupt?)	Put TRU metal in Fuel Assembly Hardware Container Fool or disable the neutron and gamma detectors (if they exist), Fool cameras, material records.	T3-XE-07-02	Proliferator put TRU material in new fuel assembly hardware container and transports out through assembly hardware portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records (audit etc.)
		XE-07-03 XE-08-01	1. Protracted diversion (abrupt?)	Put TRU metal in Recovered Uranium Container. Move Metal to XE08 MBA for later removal from MBA. Fool or disable the neutron and gamma detectors (if they exist), Fool cameras, material records.	T3-XE-07-03	Proliferator put TRU material in Recovered U container and transports out through Recycled U portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras in transition between XE-07/08. Material will be removed from MBA-8 later. Compromise material records (audit etc.) Compromise neutron detectors in final move.
T4	Waste containing TRU metal from electro-refiner process.	XE-07-01	1. Protracted diversion (abrupt?) 4. Protracted misuse and diversion combined	Proliferator receives waste container, does not send to established and controlled waste storage location.	T4-XE-07-1	Proliferator collects normal TRU via waste container and sends to concealed facility. Misuse potential: Electro-refiner could be modified to increase TRU content of waste (misuse scenario).
T5	ESFR Fresh fuel sub-assembly	Not credible for concealed diversion				
T6	ESFR Spent fuel sub-assembly	Not credible for concealed diversion				
T7	Recycled Uranium	XE-80-01	Protracted Diversion	Proliferator transports recycled Uranium to concealed enrichment facility for processing	T7-XE-08-1	Proliferator constructs concealed enrichment facility, transports recycled U to facility for enrichment Misuse potential: proliferator could manipulate electro-refiner to produce "cleaner" uranium than specified.

The final step in the current analysis is to estimate the PR measures (defined in Section 1.2) for the pathway, as shown in Table 6.3 for two representative diversion pathways.

Table 6.3: Measures Estimation for Representative Diversion Pathways

	T3-XE-07-02			T3-XE-07-03		
	Proliferator puts TRU material in a new fuel assembly hardware container and transports it out through the assembly hardware portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records (audit etc.)			**Proliferator puts TRU material in Recovered U container and transports out through Recycled U portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras in the transition between XE-07/08. Material will be removed from XE-8 later. Compromise material records (audit etc.) Compromise neutron detectors in final move.**		
	Value	**Acquisition Basis**	**Processing Basis**	**Value**	**Acquisition Basis**	**Processing Basis**
Proliferation Technical Difficulty	Low	TRU metal in new fuel assembly container.	Most processing is done, only need hot cell with chemical processing capability to finish	Low	TRU metal in recovered U container.	Most processing done, need only hot cell with chemical processing capability
Proliferation Cost	Very low	Little or no special equipment required, but some kind of neutron shielding may be used	Much smaller facility is needed for processing TRU	Very low	Little or no special equipment required, but some kind of neutron shielding may be used	Much smaller facility is needed for processing TRU
Proliferation Time	Medium	Dependent on the amount of TRU taken and how often put into fuel assembly containers	May not need much time to construct a clandestine chemical reprocessing facility	Medium	Dependent on the amount and of TRU taken and how often put into recovered U containers	May not need much time to construct as a reprocessing facility
Detection Probability	Medium	TRU in fuel assembly container may be able to be moved undetected	Detection probability of processing facility not considered	High	TRU in recovered U container may be able to be moved undetected, but will have to go through two MBAs	Detection probability of processing facility not considered
Fissile Material Type	Medium	TRU already processed and cleaned up	weapons usable but not optimum	Medium	TRU already processed and cleaned up	weapons usable but not optimum
Detection Resource Efficiency	High	This is part of a multi-reactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multi-reactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

The results identify the target type, the system element where the diversion begins (note that the diversion may involve more than one area), and the unique pathway number.

6.1.3 Evaluation of Design Variations for Diversion

To evaluate the effect of variation in reactor design and operation, the working group established a set of fast reactor design variations, as discussed in Section 2.3 and displayed in detail in Table A.3 of Appendix A. The variations involved, among other things, changes to

- Irradiation cycle duration
- Number of assemblies (core/blanket)
- Number of batches (core/internal/radial)
- Residence time, days (core/internal/radial)
- Pins per assembly (core/internal/radial)
- Structural pins per assembly
- Average TRU enrichment, %
- Fissile/TRU conversion ratio.

The coarse pathways identified in Table 6.2 were reviewed to determine what, if any, effect on diversion these variations would have. Although misuse scenarios could be affected in a variety of ways, no major change in diversion pathways could be identified, except for possible moderate changes in the isotopic composition of the TRU that would be diverted[12]. In particular, the breeder configuration contains weapons-grade plutonium in the radial blankets; however, because the blankets are assumed to be reprocessed with driver fuel, no weapons-grade plutonium diversion targets exist in the FCF from the electrorefiner onwards. Concerning the disassembly and chopping system, a possible way of diverting WG plutonium targets has been analyzed in the misuse section (Section 6.2), and will not be addressed here.

6.1.4 Insights from Diversion Analysis for Further Study

Because the analysis was conducted at a coarse, qualitative level, more detailed analysis could identify specific pathway segments that offer a greater chance to avoid detection or new physical mechanisms for removal.

Measures should be determined for each pathway segment (i.e., acquisition and processing) and not rolled up to achieve one specific set of values. Note that aggregation of a measure along a pathway can obscure important insights into specific vulnerabilities that may affect overall proliferation strategies. For instance, the differences in proliferation cost, technical difficulty, and time in the acquisition phases for the different pathways is often over-shadowed by the related values in the processing phase.

Additional design, placement, and operational data on safeguards would be useful to permit thorough analysis and evaluation of measures and reduce the number of assumptions. For example, more detailed information on maintenance and repair practices would be valuable because these practices may affect access to the target material.

[12] As already stated before, no credible pathways for a concealed diversion of a full subassembly have been identified.

6.2 Misuse

The misuse threat was analyzed under three different scenarios involving the baseline design and two design variations (DV0 and DV1) of the ESFR NES. Misuse may correspond to several feasible pathways, hence a representative one was selected for detailed analysis. The methodology proved capable of identifying system performance differences resulting from design variations and identified areas where improved safeguards arrangements are likely to improve overall PR.

6.2.1 Misuse Target Identification

Misusing an NES to achieve weapons-usable fissile material is a complex process, typically not involving a single action on a single piece of equipment but an integrated exploitation of various assets of the system. The ESFR NES co-locates much of the fuel cycle on a single site; therefore possible proliferation targets range from fabrication of irradiation targets to irradiation in the reactor cores to fissile material recovery. Figure 6.1 illustrates the major ESFR system elements (shown in blue) and the associated misuse targets (shown in green).

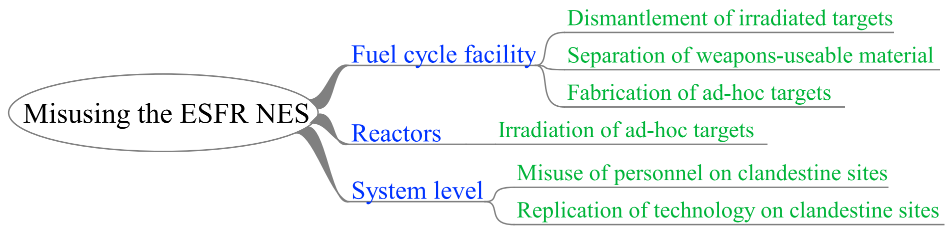

Figure 6.1: Relevant System Elements (in blue) and Related Possible Misuse Targets (in green)

Of all the possible system elements and targets in the ESFR, the qualitative screening[13] used in this case study concluded that the analysis of covert irradiation of ad-hoc targets[14] in the reactor cores best reflects the objectives of the case study and the characteristics of the ESFR NES.

6.2.2 Misuse Pathways Analysis

This analysis focuses on the concealed production of plutonium, and the high level pathway considered is the concealed irradiation of uranium targets in the ESFR reactor cores (*Acquisition Stage*) followed by plutonium recovery in a clandestine reprocessing facility (*Processing Stage*). This pathway requires that the proliferator 1) acquires

[13] Two suitable approaches for identifying and screening relevant targets within a system might rely on a tailoring of Hazard and Operability (HAZOP) techniques or make use of structured expert judgment techniques.

[14] "Ad hoc targets" refers to fertile material that is covertly introduced into the reactor core for the purpose of producing undeclared fissile material, e.g., substituting normal fuel pins with U-238 fuel pins, or entire core subassemblies with "blanket" subassemblies containing only U-238, in order to produce undeclared Pu-239 after irradiation.

uranium feed, 2) fabricates uranium pins, 3) assembles final targets, 4) irradiates targets in the reactor/s, 5) disassembles targets, and 6) separates plutonium. Each of these activities may be further split into more elementary activities and carried out in different ways. These six main activities are sufficient to capture the main proliferator decisions. The first layer of Figure 6.2 illustrates these six activities along with the many alternatives for implementing them, represented by the second and third layers in green and in red, respectively[15].

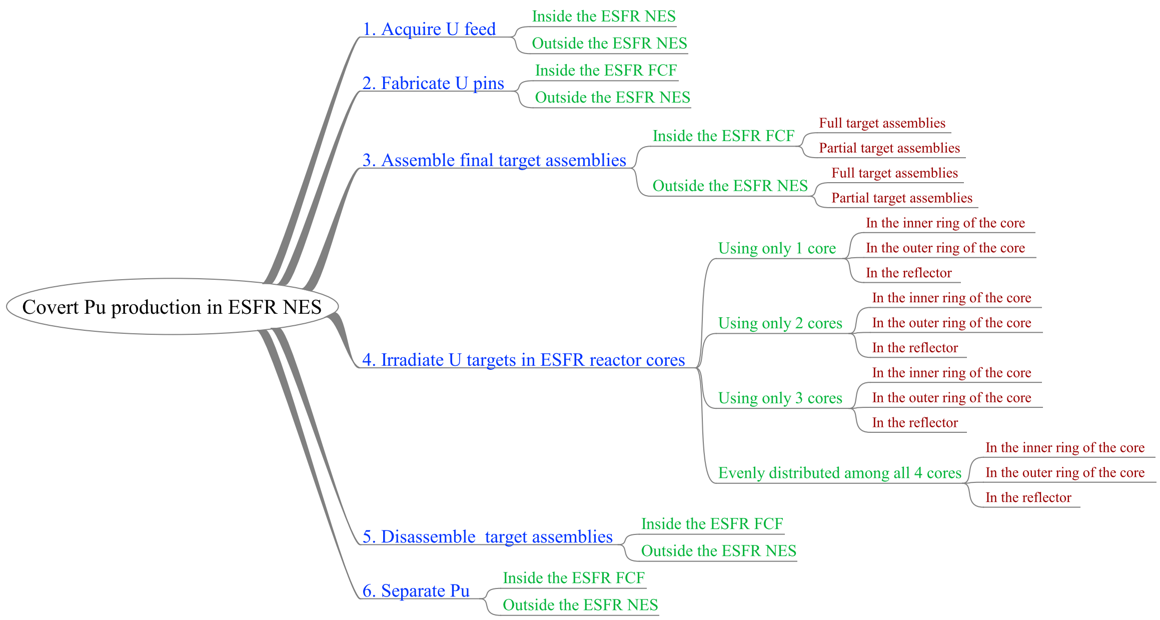

Figure 6.2: Covert Plutonium Production in Pathway Identification

There are 5184 different pathways that would result from all the various combinations of these alternatives. This is too large a number of pathways for a detailed analysis even of qualitative type. At least in principle, all these pathways could be mechanistically generated and then ranked, using some criterion, in order to identify a reduced number of them for a subsequent analysis. A possible ranking criterion can be the probability of non-detection of the pathways, as the overall non-detection probability of each pathway can be computed, and is simply the product of the non-detection probabilities of the different segments, given that these probabilities can all be reasonably estimated.

Alternatively the potential pathways can be qualitatively screened with some considerations on the possible alternatives, represented by the second and third layers of figure 6.2. The subgroup analyzing the misuse threat adopted this qualitative screening option and then selected one representative pathway that appears both

[15] A representation by an event tree, actually a decision tree since all splits would represent choices to be made by the proliferator rather than events, would have shown the links among choices and their possible dependencies. A representation with a logic tree (a Success tree in this case, as the top event would be the success of covertly producing Pu in the ESFR NES) can be derived from Figure 6.2 simply by linking with AND operators all the activities in the first layer and by linking with OR operators the possible alternatives for implementing them, represented by the second and third layers in green and in red, respectively. Mutual exclusivity of different choices and options could be taken into account.

feasible (from the proliferator's perspective) and sufficiently challenging (from the PR&PP methodology perspective). Several assumptions were made to select this pathway:

a) All transfers/movements inside the facility would follow standard procedures and schedules to minimize perturbation of normal operations and minimize the likelihood of detection, fixing irradiation time at 12 months.
b) The proliferator would use existing openings (e.g., maintenance accesses) to introduce nuclear material into the ESFR site and remove material after irradiation.
c) The uranium pins would be fabricated outside the ESFR site to minimize activities performed in a safeguarded area and minimize the likelihood of detection.
d) Material would be irradiated the outer ring of the core to match overall core flux and avoid causing safety problems or arousing suspicion.
e) Based on data provided by ANL, between 1400 and 3100 uranium target pins would need to be irradiated to get one SQ of weapons-grade plutonium in a 12-month irradiation period. Conservatively taking the lower value of 1400 pins, these pins were assumed to be distributed among 10 assemblies made up of standard and target pins to minimize the detection capability of the radiation monitors and avoid disturbances in the design neutron flux.
f) The target assemblies would be evenly distributed among the four reactors to minimize the number of suspicious movements within the same core and keep operation of all the reactors similar.

As a result, the representative pathway becomes:

1. Host state acquires outside natural uranium (or depleted uranium [DU] if available).
2. Host state prepares target uranium pins outside the ESFR site.
3. (Host state introduces target pins into the ESFR site and then into the FCF).
4. Host state assembles ESFR final target fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins using the FCF.
5. (Host state transfers target assemblies from the FCF to in-vessel storage baskets).
6. (Host state loads target assemblies into the outer ring of the four reactors during refueling).
7. Host state irradiates target assemblies for 12 months in the outer ring of the core.
8. (Host state unloads target assemblies from reactor cores into in-vessel storage baskets during subsequent refueling and leaves them there for cooling).
9. (Host state transfers target assemblies out of in-vessel storage baskets to FCF).
10. Host state disassembles target assemblies and recovers target pins at the FCF then transfers target pins out of the ESFR FCF to a clandestine facility.
11. Host state separates plutonium at the clandestine facility.

Segments, 1, 2, 4, 7, 10, and 11 correspond to the first layer of Figure 6.2. Segments in parenthesis correspond to routine activities of the ESFR (transfers, etc.).

The subgroup analyzing this pathway adopted a qualitative but systematic and traceable approach to estimate the PR measures of the representative pathway:

- Develop questions supporting the measures estimation for each of the pathway segments
- Estimate the PR measures for each segment according to the metrics proposed in the methodology[16]
- Obtain PR qualifiers for each segment (either qualitatively or by entering the measures estimates in the corresponding bins proposed in the methodology)
- Aggregate the estimates for each measure over the whole pathway using judgment, rather than a mechanistic aggregation of the segment estimates.

Table 6.4 reports most of the questions the subgroup developed. Replies to the questions are not included for space reasons and are reported in the Section D.2.5 of Appendix D. Table 6.5 presents the PR qualifiers for all the pathway segments for the baseline option[17]. Questions related to MT ("What is the MT at the end of a processing step?") and DE ("How much does it cost to cover the segment?") were omitted from Table 6.4 because they do not change through the segments. Moreover, according to Revision 5 of the methodology report, MT should be estimated at the pathway level.

This illustrative ESFR qualitative analysis of the baseline design highlighted that 1 SQ of weapons-grade plutonium might be covertly produced in the standard irradiation period of 12 months; however such an attempt would involve challenges difficult to overcome. TD is mainly driven by the difficulty to defeat safeguards, especially in the FCF (segments 4 and 10), and PT is dominated by the choice of following the standard operations schedule. Both measures are strongly influenced by the choice of a covert strategy, invoking all reasonable efforts to minimize detection by the international community. Should the proliferator decide to abrogate from the NPT, PT would be greatly reduced, and TD would likely be influenced, because concealment accounts for a substantial share of the pathway difficulty. Because of the considered safeguards approach, DP is dominated by the large uncertainty in the DP FCF segment estimates, in particular in segments 4 and 10. Safeguards coverage of these segments is achieved only by means of surveillance cameras: the source of uncertainty lies in the difficulty of assessing the effectiveness of the necessary concealment actions (e.g., in-front-of-the-lens tampering). The considered safeguards approach foresees a measurement of the n-gamma signature of each assembly just after the assembling stage in the fabrication area; such a "fingerprint" will then be used as reference for checking the assemblies at the other foreseen n-gamma measuring stations. If cameras in the fuel fabrication area are defeated, the fingerprint would be taken on the already modified assembly, and the other foreseen n-gamma measurements would not be able to recognize that the assembly is not genuine. In addition, no "cross-checking" between the fingerprints of different assemblies would be performed, excluding the possibility of noticing any deviation of a single n-gamma signature from the average of the others. This fact accounts for the very low detection probability assigned to segments 5, 6, and 9.

[16] One way to estimate the measures would be to set up a panel of experts, seek their judgments, and document their rationale.

[17] Part of the analysis of the baseline ESFR design for the misuse threats has been published in: G.G.M. Cojazzi, G. Renda, J-S. Choi, Applying the GIF PR&PP Methodology for a qualitative analysis of a misuse scenario in a notional Gen IV Example Sodium Fast Reactor, *INMM-49th Annual Meeting*, July 13-17, 2008, Nashville, Tennessee, USA. Table 6.5. differs slightly from the corresponding table there reported. In table 6.5 the PR qualifiers were derived in a normative way from the bins of Ref. [6.2].

This analysis reveals that the postulated safeguards approach could be improved in terms of coverage and robustness with inexpensive modifications such as *inter alia* more control on FCF maintenance accesses (segment 3), adding a radiation monitor in the assembly fabrication area (segment 4), and foreseeing comparison of fingerprints of different assemblies (segments 5, 6, and 9).

Table 6.4: Questions Supporting the Measures Estimation for the Misuse Pathway Segments

Seg	TD	PT	PC	DP
1	a) How difficult is it to find the necessary uranium without being detected? b) How difficult is it to ship?	a) How long does it take to organize procurement? b) How long does it take to import all necessary material?	a) How much does the material cost? b) How much does shipment cost?	a) Is the Additional Protocol (AP) in place? b) Can the AP be effectively enforced? c) Can the AP measures detect the segment? d) Would export control and trade analysis help? e) How likely are those measures to detect the illicit action?
2	How difficult is it to: a) Build a clandestine facility b) Train the people and run it c) Deliver the expected output at a sufficient quality?	How long does it take to: a) Build the clandestine facility? b) Train the needed personnel? c) Produce all the pins?	How much does it cost to set up the needed infrastructure?	Same as segment 1
3	a) How difficult is it to introduce the pins via the maintenance routes? b) How difficult is it to conceal the action?	How long does it take to transfer in the necessary pins?	How much does it cost to transfer the necessary pins?	a) Which safeguards measures are in place for this segment? b) How likely are those measures to detect the illicit action?
4	a) How difficult is it to assemble the dummy assemblies? b) How difficult is it to conceal the action?	a) How long does it take to assemble the dummy assemblies? b) How long does it take to conceal the action?	How much does it cost to: a) Assemble the dummy assemblies? b) Conceal the action?	a) Which safeguards measures are in place for this segment? b) How likely are those measures to detect the dummy assemblies?
5	How difficult is it to transfer dummy assemblies	How long does it take?	How much does it cost?	Same as segment 4
6	How difficult is it to insert “out-of-spec” assemblies?	How long does it take? How long does it take compared to normal operation?	How much does it cost to overcome technical difficulties?	Same as segment 4
7	How difficult is it to irradiate the dummy assemblies without compromising safety and operability?	How long does it take?	a)How much does it cost to overcome technical difficulties? b) How much does it cost in terms of variation of electricity production?	Same as segment 4
8	a) How difficult is it to withdraw “out-of-spec” spent assemblies ?	How long does it take? How long does it take compared to normal operation?	How much does it cost to overcome technical difficulties?	Same as segment 4

Seg	TD	PT	PC	DP
	b) How difficult is it to conceal the action?			
9	How difficult is it to transfer?	How long does it take?	How much does it cost?	Same as segment 4
10	How difficult is it to: a) Tamper with the camera b) Recover the dummy pins c) Substitute them with the “original” ones d) Transfer dummy pins out of the ESFR FCF through maintenance channels e) Transfer dummy pins to a clandestine facility	How long does it take to perform the actions described for TD?	How much does it cost?	a) Which safeguards measures cover the segment? b) How likely are those measures to detect diversion or tampering?
11	Same as segment 2	How long does it take to: a) Build the clandestine facility? b) Train the needed personnel? c) Process all the pins?	How much does it cost to set up the needed infrastructure?	Same as segment 1

Table 6.5: Proliferation Resistance Qualifiers Related to the Baseline Design and Design Variation 0

Segment	TD	PT	PC	MT	DP	DE
1 Host state acquires natural uranium (or DU if available)	Very low to low	Very low to medium	Very low	NA	Very low	Low
2 Host state prepares dummy uranium pins outside the ESFR site	Very low to low	Low	Very low	NA	Very low	Low
3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Very low	Very low to low	Very low	NA	Very low	Very high
4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuel pins	Medium	Very low	Very low	NA	Low to high	Very high
5 Host state transfers dummy assemblies from the FCF to in-vessel storage baskets	Very low	Low	Very low	NA	Very low	Medium
6 Host state loads dummy assemblies into outer ring of reactor core (during refueling)	Very low	Very low	Very low	NA	Very low	Very high
7 Host state irradiates dummy assemblies for 12 months	Very low	Low	Very low	NA	Very low	Very high
8 Host state unloads dummy assemblies from reactor core into in-vessel storage basket (during subsequent refueling) and leaves them there for cooling	Very low to medium	Medium	Very low	NA	Low to medium	High to very high
9 Host state transfers dummy assemblies out of in-vessel storage basket to the FCF	Very low	Medium	Very low	NA	Very low	Medium
10 Host state recovers dummy pins at the FCF and transfers them to a clandestine facility	Medium	Very low	Very low	NA	Low to high	High to very high
11 Host state recovers plutonium at the clandestine facility	Low	Very low to medium	Very low	Low (WG Pu)*	Very low to low	Low
Overall Aggregated Value	Medium	Medium	Very low	Low (WG Pu)*	Low to high	Low to high

*WG Pu=weapons grade plutonium.

6.2.3 Evaluation of Design Variations

Two design variations were considered for misuse.

DESIGN VARIATION 0. The first design variation is similar to the baseline design: a burner configuration (TRU conversion ratio of 0.73 instead of 0.64) that uses a TRU feed made of LWR spent-fuel elements. The core configuration differs in the number of assemblies (180 versus 102, with the same number of pins per assembly), their composition (22.1% versus 24.9% of average TRU enrichment still arranged in two core zones), and their overall residence time (1300 versus 930 days). The cycle length is the same (12 months). Preliminary ANL calculations show that to produce 1 SQ in 12 months of undeclared plutonium from U-238 target assemblies, between 6 and 14 full target assemblies would be needed, depending on the assumptions.

Because the baseline design and this design variation are so similar, the pathway analysis for the baseline design is also applicable, and it is worthwhile to investigate how the core design's variations influence the estimates of the measures on the selected scenario. Assumptions made for the baseline design still hold, with the exception of the different number of target assemblies needed for producing 1 SQ of plutonium (twelve instead of ten, with 50% modified target uranium pins). Because of the different core geometry and refueling strategy, the DP measure is expected to be mostly influenced by this design variation. The estimation of the detailed pathway for the baseline design provides an opportunity to test the ability of the PR&PP methodology to discriminate between very similar design options and how it could support designers' choices within the same context.

The analysis of this pathway used the same procedure as the baseline design analysis and resulted in similar replies to the supporting questions of Table 6.4. Although small differences could be pinpointed by the replies to the questions, the final PR qualifiers for all segments were identical to those of the baseline design. For this reason Table 6.5 applies to both the baseline and DV0 analyses. In this case, the fact that even very small differences can be highlighted via a qualitative analysis shows the level of detail the approach could reach. The fact that the final PR qualifiers are identical should not be seen as the result of not enough discriminating power caused by the binning process, but the confirmation that the differences highlighted are not important enough to alter the overall PR judgments of the segments.

DESIGN VARIATION 1. This variation is a deep burner configuration, with a TRU conversion ratio of 0.22. This difference implies a substantial variation in the overall fuel cycle strategy, leading to a shorter cycle length (6.6 months instead of 12 months) and a different fuel composition (in particular, the average enrichment in TRU is 58.5%, arranged in two zones, instead of approximately 22% for DV0). A larger number of LWR spent-fuel elements per year are needed as input feed. The number of assemblies within the core is the same as that for DV0 (but the number of pins per assembly is larger: 324 versus 271), and the overall residence time is longer (1445 days). The configuration uses eight batches instead of three (baseline) or four (DV0). This difference leads to more fuel-handling operations within the core before final discharge.

This case shows that the methodology can be used to assess how major core configuration changes affect PR and can support strategic fuel cycle decisions at policy-making levels.

As with the previous case, the pathway selected for the baseline study is applicable to this variation with only minor differences in the original assumptions. For example, the difference in radiation cycle length.

Based on preliminary ANL calculations, between 22 and 48 equivalent full target assemblies are estimated to be irradiated to produce 1 SQ of plutonium in a single 6.6-month irradiation cycle. Assuming the lower bound and that only half the fuel pins in the assembly are target pins, the host state would need to irradiate 44 modified target assemblies to acquire 1 SQ of plutonium in one 6.6-month cycle.

When DV1 was assessed using the same procedure as for the baseline and DV0 analyses, similar replies were produced to the supporting questions for most segments, with the exception of the replies to the PT questions for segment 7. Table 6.6 lists the final PR qualifiers for all segments[18]. The results highlight how, even for DV1, the overall PR qualifiers are identical to those of the baseline design. Although one could

[18] Part of the analysis of the ESFR design variations for the misuse threats has been published in: G. G. M. Cojazzi, J. Hassberger, G. Renda, Applying the PR&PP Methodology for a qualitative assessment of a misuse scenario in a notional Generation IV Example Sodium Fast Reactor. Assessing design variations, *Proceedings of Global 2009*, Paris, France, September 6-11, 2009. Table 6.6. differs slightly from the corresponding table there reported. In table 6.6 the PR qualifiers were derived in a normative way from the bins of Ref. [6.2].

expect a higher DP estimate (because of the larger number of assemblies requiring irradiation), this did not occur for two reasons: a) the high uncertainty in the two most critical segments (4 and 10) dominates the outcome and b) the assumed safeguards approach is not able to identify the existence of dummy assemblies in segments 5, 6, and 9. This fact should trigger specific requirements for the plant safeguards design..

Table 6.6: Proliferation Resistance Qualifiers Related to Design Variation 1

Segment	TD	PT	PC	MT	DP	DE
1 Host state acquires natural uranium (or DU if available)	Very low to low	Very low to medium	Very low	NA	Very low	Low
2 Host state prepares dummy uranium pins outside the ESFR site	Very low to low	Low	Very low	NA	Very low	Low
3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Very low	Very low to low	Very low	NA	Very low	Very high
4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuel pins	Medium	Very low	Very low	NA	Low to high	Very high
5 Host state transfers dummy assemblies from the FCF to in-vessel storage baskets	Very low	Low	Very low	NA	Very low	Medium
6 Host state loads dummy assemblies into outer ring of reactor core (during refueling)	Very low	Very low	Very low	NA	Very low	Very high
7 Host state irradiates dummy assemblies for 6.6 months	Very low	Low	Very low	NA	Very low	Very high
8 Host state unloads dummy assemblies from reactor core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Very low to medium	Medium	Very low	NA	Low to medium	High to very high
9 Host state transfers dummy assemblies from in-vessel storage baskets to the FCF	Very low	Medium	Very low	NA	Very low	Medium
10 Host state recovers dummy pins at the FCF and transfers them to a clandestine facility	Medium	Very low	Very low	NA	Low to high	High to very high
11 Host state recovers plutonium at the clandestine facility	Low	Very low to medium	Very low	Low (WG Pu)*	Very low to low	Low
Overall Aggregated Value	Medium	Medium	Very low	Low (WG Pu)*	Low to high	Low to high

*WG Pu=weapons-grade plutonium.

The fact that the PR qualifier related to the PT measure of segment 7 ("host state irradiates dummy assemblies for 6.6 months) is identical to that of both the baseline design and of DV0 suggests that, in this particular case, the bin proposed by the rev.5 methodology is not sufficiently discriminating. Indeed the reduction from 12 to 6.6 month of the irradiation time should trigger some difference in the PR qualifier of the segment. The DV0 and DV1 results demonstrate that a qualitative application of the methodology to a misuse scenario allows identifying small differences in the rationale and measure estimates. Even though these differences were discernable, the binning process resulted in equal results for all segments, and overall PR estimates of the two variations were the same as for the baseline design. Consequently, the notional aggregation process carried out over the segments judged the PR qualifiers for the whole pathways to be the same for DV0 and DV1.

6.2.4 Insights from Misuse Analysis for Further Study

This analysis demonstrates that the PR&PP Evaluation Methodology is useful and robust. It also shows that a qualitative approach can produce traceable, accountable, and dependable results. The analysis of a misuse strategy shows how proliferation pathways are likely to involve more than one target, complicating both target and pathway identification. This analysis also shows that some aspects of the methodology need further investigation. In particular, practical application of some measures and metrics (especially MT and DE) necessitate refinement of the methodology, and some of the example metrics (especially those of PC and DE) need some additional investigation. Moreover, the binning presented in the rev.5 report of the methodology should be considered as illustrative and tailored specifically on each study. Although this might create some additional problems when comparison of results between different studies is attempted, the normative application of the binning proposed in the methodology report could not be suited for every possible PR analysis.

For the cases considered here, some measures appear to dominate within some segments and may dominate the overall estimate. The implications of this observation need further investigation.

The following additional work should be undertaken for this ESFR example:

- Perform additional expert analyses of DV0 and DV1. These analyses would allow further testing of the procedure, validation and comparison of the experts' rationales, testing of the existing suggested metrics and scales, and comparison of measure estimates (and the resulting PR qualifiers) carried out by different analysts
- Analyze DV2.
- Analyze DV3.

The PR&PP group has discussed the possibility of combining TD and DP as an overall index of proliferation success. The detailed pathways here available could provide the basis to investigate this topic in a controlled environment.

6.3 Breakout

The third PR threat strategy considered in the case study is breakout and the diversion of material and/or misuse of the ESFR to produce fissile material. Note that the breakout threat was formerly referred to as "abrogation" in PR&PP literature; it was decided that "breakout" is a less restrictive term for this scenario, as a state may or may not include formal abrogation in its strategy.

As a strategy, breakout does not exist unto itself but as a 'strategy modifier': ultimately every successful proliferant state necessarily breaks out if/when it decides to use or announce possession of a nuclear weapon. The nature of the breakout determines much of the nature of the threat (both the time available to the proliferant state – before and after breakout, and ultimately the complexity of weapon made possible).

Because misuse and diversion are treated explicitly in Sections 6.1 and 6.2, including target and pathway identification, the interesting aspect of breakout will be the scenario that minimizes the time from breakout to weapons readiness, which is effectively a subset of the PT measure (i.e., answering the question, "What is the fastest a proliferant state can prepare a weapon using ESFR technology, once international controls are moot?”). The goal of analyzing the breakout scenario is therefore to complement the concealed misuse/diversion scenarios by exploring the minimum post-breakout time to weapons readiness.

6.3.1 Breakout Target Identification

Because the breakout scenario is assumed to include a minimum time from breakout to weapons readiness, a number of potential targets were chosen as candidates from among the following:

- Diversion targets:
  - Stockpiled ESFR fresh fuel – plutonium separation in ESFR facility
  - Stockpiled ESFR fresh fuel –plutonium separation in a clandestinely developed plutonium-uranium extraction (PUREX) facility
  - Stockpiled LWR spent fuel – plutonium separation in ESFR facility
  - Stockpiled LWR spent fuel – plutonium separation in a clandestinely developed PUREX facility

- Misuse targets:
  - Undeclared irradiation of targets and separation in ESFR fuel facility
  - Low-burnup irradiation of ESFR fuel and separation in ESFR fuel facility
  - Low-burnup irradiation of DU targets (for an ESFR breeder) and separation in ESFR fuel facility
  - Irradiation of various materials in the ESFR and separation in a clandestinely developed PUREX facility
  - Misuse of ESFR fuel cycle facility to extract high-plutonium-purity TRU.

The targets chosen for further analysis were as follows:

1. Diversion of stockpiled ESFR fresh fuel – plutonium separation from spent LEU in a clandestinely developed PUREX facility (utilizing either the full pin length or just the lower-burnup ends of the pins)

2. Misuse of facility to irradiate fertile material in-core

3. Misuse of facility to irradiate fertile material in storage baskets

4. Misuse of facility to extract high-plutonium-purity TRU in the FCF.

Note that the breakout strategy chosen by a proliferant state will affect both the time available and potential complexity of proliferation activities, as outlined below and illustrated (qualitatively only) in Figure 6.3:

- Immediate, absolute breakout (proliferant state decides to break out and immediately acts on decision): minimum time, minimum complexity of proliferation activities.
- Immediate, *ad hoc* breakout (proliferant state “effectively” breaks out through actions, without explicitly breaking out): medium time, medium complexity of proliferation activities. Delayed, optional breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and intention to break

out if/when detection occurs): medium time, medium complexity of proliferation activities.

- Delayed, intended breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and a predetermined schedule for breakout and overt activity – the "load the gun" scenario): maximum time, maximum complexity of proliferation activities.

The category of breakout chosen by a proliferant state is significantly affected by political factors (foreign relations agenda of state, probability [timing and extent] of external intervention after breakout, external dependence of proliferant state's supply chain, etc.). These factors, although of interest, must be excluded from the ESFR technology case study because of their complexity.

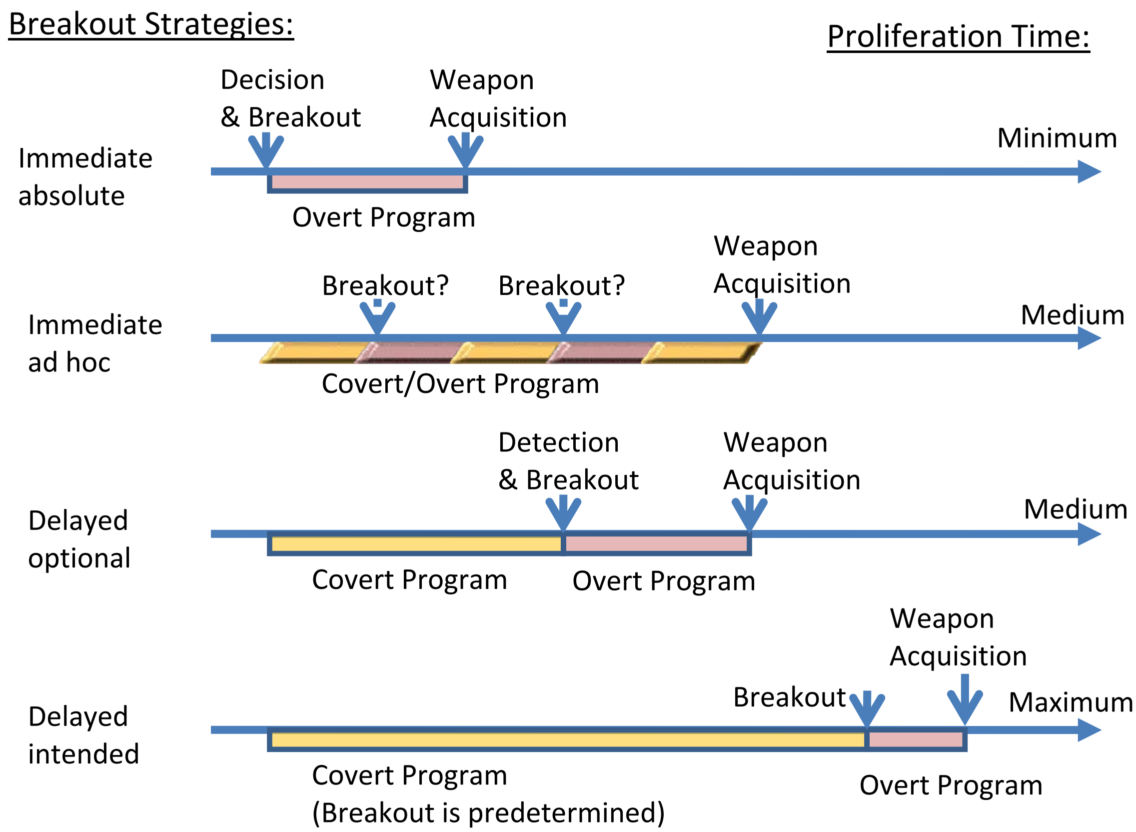

Figure 6.3: Qualitative Depiction of Breakout Strategies

6.3.2 Breakout Pathways Analysis

A qualitative pathways analysis was conducted for each candidate target to determine relative ranking of "target attractiveness" as determined by the PT measure, and specifically as it applies to the post-breakout period. Table 6.7 provides the preliminary results of this analysis.

Table 6.7: Dependence on Breakout Strategy of Target Attractiveness as Determined by the Proliferation Time Measure

Target [2]	**Breakout Strategy** [4] (decreasing Proliferation Time, and thus available complexity) →			
	Delayed intended[1]	**Delayed optional**[1]	**Immediate *ad hoc***[3]	**Immediate absolute**
Diversion: TRU from ESFR fresh fuel (full pin length)	Medium	Medium	High	High
Diversion: TRU from ESFR fresh fuel (top & bottom sections of pins)	High	High	High	High
Misuse: TRU from undeclared irradiation of targets in core	High	High	Medium	Very low
Misuse: TRU from undeclared irradiation of targets in storage baskets	High	High	Low	Very low
Misuse: misuse FCF to extract high-plutonium-purity TRU	High	Medium	Low	Very low
Design Variation: breeder, *Diversion* – inner blanket	High	Medium	Low	Very low

Notes:
1. If detected – select least-time path between continuing at maximum rate or taking TRU directly from TRU extraction.
2. Requires PUREX processing, assumed in a clandestine offsite location.
3. Plan is to continue, assuming "acceptable" international reaction.
4. Breakout pathways would take all SQs possible, usually more than 1.

6.3.3 Insights from Breakout Analysis for Further Study

Until the point of breakout is reached, safeguards, supplier-group controls, national intelligence agencies, and technical means will play a role in detecting the intent to break out. The DP and DE measures are important during this period but play no role after breakout.

Intuitively it is not clear which, if any, of the above breakout strategy leads to a minimum post-breakout time or if generalizations of this sort can be made. For example, "delayed, intended breakout" allows the maximum total time, but because the "gun is fully loaded" at the time of breakout it may lead to a minimum post-breakout time to weapon readiness. On the other hand, if the proliferant state's strategy includes overt weapons-grade material production following breakout, a simpler end-product intended by a less-premeditated breakout scenario may lead to a shorter post-breakout period and thus be more attractive. Among other things, the value of the MT measure is brought into question with such considerations, as strategies based on specific political gains (for example) may be satisfied with lower-grade weapons.

A key issue in assessing the breakout pathways is the definition of the proliferant state's strategy concerning detection and how the state's aversion to detection risk changes as it progresses to the end of the pathway. Such "dynamic strategy" considerations add another level of complexity to the analysis.

It will be informative to explore how/if pre-breakout measures can significantly affect the post-breakout time to weapon readiness (see Table 6.8), at least in the context of the ESFR case study. It will also be interesting to compare with alternate acquisition strategies, such as enrichment.

Finally, the close connection of the breakout strategy with the diversion and misuse threat strategies suggests that performing a parallel pathway analysis with one of those groups, but from the point of view of a breakout threat strategy, will potentially offer insight into how the change in threat strategy influences measures. This potential will be investigated using a specific baseline misuse pathway analysis.

Table 6.8: Factors Benefiting Breakout and Measures That Address These

Phase	Breakout Factor	PR&PP Measure
Pre-Breakout	Low probability of detection of diversion/misuse	• DP • DE
	Low scrutiny of collateral clandestine activities to reduce time for subsequent overt activities	• DP (Additional Protocol) • DE • PT • TD (need to start technical development in pre-breakout phase)
	Low scrutiny/interference of supply chain to acquire needed equipment and materials	• DP (Additional Protocol?) • TD (need to import equipment vs. domestic development) • PC
Post-Breakout	Available time/speed of development	• TD • PT • MT
	Available inventory and material type	• DP (addresses build-up of nuclear material inventory during pre-breakout stage) • MT
	Technology for weaponization	• TD • MT • DP (addresses build-up of necessary technology during pre-breakout phase)
	Knowledge for weaponization	• TD • MT • DP (addresses build-up of necessary expertise during pre-breakout phase)
	Physical barriers to external intervention	• Transparency of facilities * • Robustness of facilities *
	Political barriers to external intervention	• Foreign relations (will and ability to intervene) * • Response time and capability *

* These measures were not included in PR&PP methodology.

6.4 Theft of Fissile Material

The PP threat considered in the case study, described in Chapter 5, has as its objective, the single theft of fissile material from the ESFR in sufficient quantity to obtain 1 SQ of nuclear weapon material. For additional theft and sabotage scenario studies, see Appendix D.4.

6.4.1 Theft Target Identification

Certain areas of the ESFR could be the target for theft of nuclear materials (as modified from [6.1]). The ESFR layout is shown in Figure 2.3.

Within the plant boundary, the following system elements could incorporate accessible or removable targets for the theft of nuclear materials:

- LWR spent-fuel cask parking area
- LWR spent-fuel storage
- FCF
  - Air cell (hot cell)
  - Inert hot cell
- Fuel services building staging/washing area

Note that the reactors themselves were not included in this analysis, because fuel inside the cores is not accessible, without very time-consuming actions compared to that in other facility locations and is not transportable for any distance without a shielded vehicle. Rather, item storage areas were considered more attractive because of the mobility of the materials. For a more detailed explanation of the targets, please see Appendix D.4.

6.4.2 Theft Pathways Analysis

Once the targets are identified, pathways to those targets can be identified, as shown in Figure 6.4. The pathways are outlined in terms of an Adversary Sequence Diagram (ASD). For a complete review of all ASDs, see Appendix D.4. The ASD for theft of TRU/uranium product in a process cell was the example case analyzed. This analysis only addresses theft with removal of the target to the site boundary and does not address activities beyond the site boundary.

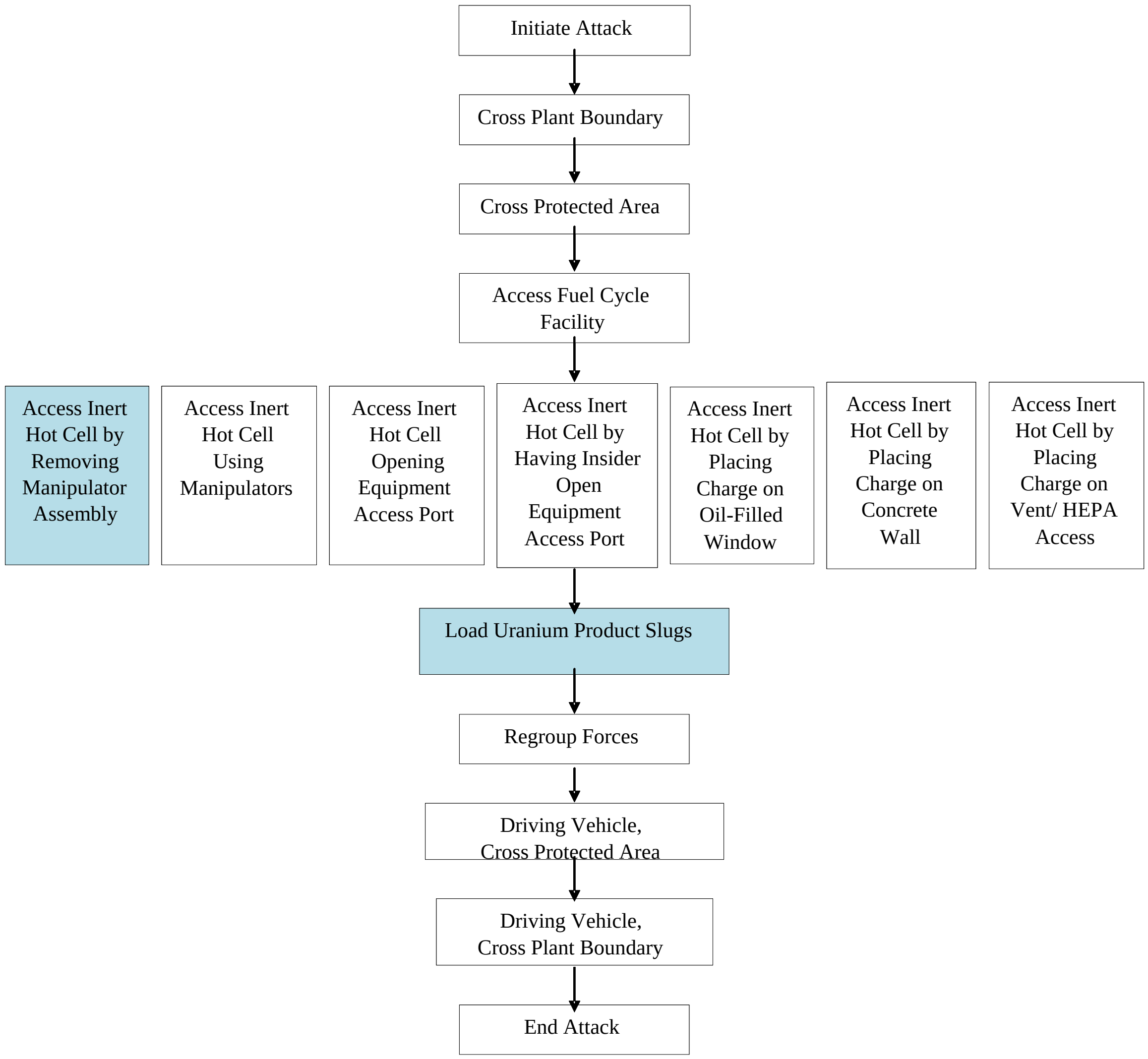

Figure 6.4: Adversary Sequence Diagram for Theft of TRU/Uranium Product (in process cell)

Using the PR&PP methodology, an ASD can be analyzed either quantitatively or qualitatively. For the purpose of demonstrating the methodology, the adversary pathway identified in Figure 6.4 was analyzed qualitatively. This particular pathway was selected because the uranium/TRU slugs represent the stage of the electrochemical process where the material is in a readily portable form (solid metallic slugs), and the TRU concentration is high compared to potentially down-blended fuel (i.e., this is a relatively attractive target for theft). Appendix D.4 contains a quantitative example.

To succeed, the adversary must cross the site and PIDAS boundaries, access the FCF, access the inert hot cell, collect uranium/TRU slugs, and the escape the site. The consequence of adversary success is the theft of 1 SQ or more of fissile material.

When analyzing plant designs in the conceptual phase, qualitative analysis is less complicated, because exact design of the plant is not yet completed. It is also advantageous to analyze PP needs before developing a PP design to identify areas of interest, potential pathways, and targets. When performing a qualitative analysis, the exact answers for each system are not always known. Therefore, a high, low, medium and no ranking system can be beneficial. To keep a consistent definition of these terms, ranges of acceptable values should be defined for each ranking. Table 6.9 contains the binning process used in this qualitative example.

Table 6.9: Qualitative Analysis of Each Step along the Theft Pathway

Task	PD[1]	Delay	Assessment Description
1-Initiate attack	Low	No	The militarily trained force is assumed to achieve both strategic and tactical surprise.
2-Cross plant boundary	Low	No	The outer boundary is typically a simple fence and or vehicle barrier. Note that they will be detected by various sensors at this point.
3-Cross protected area	Medium	Medium	The PIDAS boundary is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this but not without detection. At this point, defensive forces are moving in and engaging the adversary.
4-Access FCF	High	High	When the sensors alarm, the building will be locked down. The adversaries will have to force (probably via explosives) their way in. If the insider's task is to be inside the building, the insider can defeat the locks and open a door. This step must be performed while under fire. If the building is hardened, multiple breaching charges (while under fire) will be required.
5-Access inert hot cell by removing manipulator assembly	High	Medium	This step is very time intensive, and thus is unlikely to be completed.
6-Load uranium product slugs	Low	Low	The adversaries must be equipped with self-contained breathing equipment. Any adversary loading fuel slugs is not available to engage the defensive forces. The adversary is in a restrictive location, and the defensive forces are already aware. However, the adversaries inside the cell are expected to be alone.
7-Regroup forces	N/A[2]	No	Regrouping must occur under fire, through known access points (the opened door), and in a known location (within the PIDAS).
8-Driving vehicle, cross protected area	N/A	Low	Complete defensive force response (including heavier weapons and armored vehicles) will have arrived by this point. Vehicles will be placed under heavy fire to disable them as an avenue of escape. Dismounted adversaries have to cross the PIDAS while under fire.
9-Driving vehicle, cross plant boundary	N/A	Low	Because the defensive forces will be converging on the adversaries, is it assumed that successful escape from the PIDAS constitutes a breakout. Accordingly it is easier to then continue on through the plant boundary.
10-End attack	N/A	No	Only the adversary gets to decide when to quit.

Notes: 1. Probability of Detection of adversary by physical protection system
2. Probability of Detection is no longer applicable. Adversary location is known by defensive forces.

The next step in the qualitative analysis is to determine the response force times. The following values where used:

- Option A: 150 s
- Option B: 300 s
- Option C: 600 s

To model the results of the quantitative analysis the software Estimate of Adversary Sequence Interruption (EASI) v200 was used. Probability of guard communication, which refers to the probability of the alarm signal being communicated to the protective force, was assumed to be 1.0, and all standard deviations were estimated to be 10% of the mean values. The mean value for each range was used in the analysis. Analysis of the pathway shown in Table 6.9 is laid out in Figures 6.5, 6.6, and 6.7 for each of the response force times.

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		150	15		
6		**Theft of TRU/Uranium Product Slugs Pathway 5a**							
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	
17		9	Cross Plant Boundary	0.1	M	330	33	360	Critical Detection Point
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure 6.5: Probability of Interruption of Theft
When Response Force Time Is 150 s (Option A)

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		300	30		
6		**Theft of TRU/Uranium Product Slugs Pathway 5a**							
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	
17		9	Cross Plant Boundary	0.1	M	330	33	360	Critical Detection Point
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure 6.6: Probability of Interruption of Theft
When Response Force Time Is 300 s (Option B)

	A	B	C	D	E	F	G	H	I
1									
2–5			***Estimate of Adversary Sequence Interruption***	Probability of Guard Communication		Force Time (in Mean	Standard Deviation		
				1		600	60		
6			**Theft of TRU/Uranium Product Slugs Pathway 5a**						
7–8		Task	Description	P(Detection)	Location	Delays (in Seconds): Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	Critical Detection Point
17		9	Cross Plant Boundary	0.1	M	330	33	360	
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure 6.7: Probability of Interruption of Theft When Response Force Time Is 600 s (Option C)

For theft scenarios, adversary interruption by the protective force equates to adversary failure. A Probability of Interruption of 1.00 means that the adversary has been interrupted along the pathway by the protective force, and has, therefore, been defeated. The probability of adversary success is zero for all options.

6.4.3 <u>Insights from Theft Analysis for Further Studies</u>

Because the adversaries get to determine when and where to initiate an attack, they will most likely succeed in arriving at and crossing the plant boundary. The probability of detection is low. Pushing the plant boundary and or the detection boundary farther will provide more response time for the defensive forces and thus reduce the probability of future steps succeeding.

The adversary will then need to cross the PIDAS boundary. The probability of detection is greater there than when crossing the site boundary. In addition, the PIDAS boundary is generally more robust than the site boundary, and thus the delay for the adversary will be greater. In addition, the PIDAS boundary can be strengthened (i.e., by adding remotely operated weapons or equivalent) to reduce the probability of adversaries successfully getting across.

The FCF is assumed to be a non-hardened building surrounding the hot cells. Construction of the building as a hardened structure will reduce the probability of adversary success dramatically, as entrance by explosive breaching charges will be required. Hardening at this step provides the greatest benefit against an adversary attack as an adversary would be forced to stop and set charges, while still outside the facility and exposed to defensive fire. At this point detection is extremely likely, and the delay is quite long.

An insider has the greatest ability to increase the adversary's overall probability of success. If the insider can pre-open doors or hot cell access ports, or can overcome interlocks during an attack, the probability of success increases noticeably. Steps to reduce the potential influence of an insider (guard-controlled overrides, automatically closing doors, guards inside the facility) will have a great benefit compared to cost.

The next greatest weakness in accepting the hot cells as secure rooms is the presence of the windows and adversary access to the manipulators. These windows must be large enough to provide the operators with a view of the work area. Accordingly, they are typically large enough for a person to easily get through the opening if the window is removed. Ballistic glass, shutters, and covers will reduce the probability that an adversary can successfully use the windows to access the hot cells before being neutralized by defensive forces. The manipulators can allow the adversary to access material inside the hot cell, and, using proper procedures remove the material from the hot cells. Features that lock out manipulators from unauthorized access will neutralize the adversary's ability.

A typical defensive force response is to converge on the adversaries with overwhelming firepower (i.e., superior numbers with heavier weapons). Any barrier that slows the adversary reduces the adversary's probability of success. Additionally, even if the adversaries successfully access the hot cell and obtain uranium/TRU fuel slugs, they will have to fight through all remaining defensive forces to escape. To escape, they must go through known areas by known routes (i.e., the existing holes in the fences and barriers). This necessity provides a great advantage to the defensive forces.

Overall, the ESFR facility is deemed to have a low probability of adversary success for theft, because, although some steps are rated as highly or moderately successful, the adversary must accomplish all steps in a serial fashion to succeed. However, at many points, the probability can be reduced even more.

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7. LESSONS LEARNED FOR METHODOLOGY IMPROVEMENT

The application through case studies was helpful in developing the PR&PP methodology and in testing its ease of use and ability to provide useful information to designers and policy/decision makers. In fact, lessons were learned across all the various ESFR studies:

- Lessons from the initial 2004 development study primarily set the form of the methodology
- Lessons from the 2006 demonstration study dealt with the process of organizing and managing a PR&PP evaluation and to test different analytical techniques for pathway identification
- Lessons from the current case study improved and structured the evaluation process and provided insights for further advancing the methodology. For PR, the lessons have clarified the relationships among diversion, misuse, and breakout threats.

Basic lessons learned from the case study included the following:

- Each PR&PP evaluation should start with a qualitative analysis allowing scoping of the assumed threats and identification of targets, system elements, etc.
- Detailed guidance for qualitative analyses should be included in the methodology
- Access to proper technical expertise on the system design as well as on safeguards and physical protection measures is essential for a PR&PP evaluation
- The use of expert elicitation techniques can ensure accountability and traceability of the results and consistency in the analysis.
- Qualitative analysis offers valuable results, even at the preliminary design level.
- Greater standardization of the methodology and its use is needed.

In addition, subgroups noted that during the evaluation process the analyst must frequently introduce assumptions about details of the system design which are not yet available at early design stages. For example, the delay time that a door or portal might generate for a PP adversary. As the study progressed, the working group realized that when these assumptions are documented, they can provide the basis for establishing functional requirements and design bases documentation for a system at the conceptual design stage. By documenting these assumptions as design bases information, the detailed design of the facility can be assured of producing a design that is consistent with the PR&PP performance predicted in the initial conceptual design evaluation (or, if the assumptions cannot be realized in detailed design, the original PR&PP evaluations must be modified appropriately).

The following sections discuss specific lessons learned for pathways analysis, PR design, and PP design as well as areas for further study.

7.1 Lessons from Pathways Analysis

Completeness in identifying potential diversion pathways is a key evaluation goal. Targets and potential pathways can be systematically identified for each specific threat, and plausible scenarios can be systematically found to describe potential proliferant host state's strategies to divert target material. A set of diversion pathway segments can be developed, and the PR measures for each pathway can be estimated. The methodology can compare and distinguish how different design choices affect PR.

The pathways analysis for the diversion threat can also provide a variety of useful information to stakeholders, including regulatory authorities, government officials, and system designers. This information includes how attractive the material is to potential proliferators for use in a weapons program, how difficult it would be to physically access and remove the material, and whether the facility can be designed and operated in such a manner that all plausible acquisition pathways are covered by a combination of intrinsic features and extrinsic measures.

The misuse threat pathways analysis requires consideration of potentially complex combinations of processes to produce weapons-usable material (i.e., it is not a single action on a single piece of equipment but rather an integrated exploitation of various assets and system elements). Given a proliferation strategy, some measures are likely to dominate the others, and within a measure some segments will dominate the overall estimate over the whole pathway.

The breakout threat pathways analysis found that breakout is a modifying strategy within the diversion and misuse threats and can take various forms that depend on intent and aggressiveness, and ultimately on the proliferation time assumed by a proliferant state. Furthermore, estimations of the same PR measure applied to different breakout strategies can lead to varying results, as proliferator motivations and priorities vary. Note that some additional factors related to global response and foreign policy were identified as being relevant to the characterization of the breakout threat, but those factors are not included in the PR&PP methodology.

The theft and sabotage threats pathways analysis found that multiple target and pathways exist. The most attractive theft target materials appeared to be located in a few target areas. Specifically, for the ESFR, the most attractive theft target areas with the most attractive target materials were found to be the LWR spent-fuel cask parking area, LWR spent-fuel storage, the fuel services building staging/washing area, the FCF air hot cell, and the FCF inert hot cell.

As noted in the PR&PP methodology, a substantial base of analytic tools already exists for theft and sabotage pathway analysis (e.g., EASI). The case study verified that these types of tools can be used within the paradigm of the PR&PP methodology.

7.2 Proliferation Resistance Assessment Lessons

Structured qualitative analysis can produce traceable, accountable, and dependable results that provide useful information to system designers, even when detailed design information is largely missing (e.g., by introducing reasonable design assumptions that are documented and become functional requirements).

Traceability can be provided in the analysis outcomes via the explicit recording of the evidence on which the measures estimates and PR judgments were made. This recording can lead to a thorough review of the analysis results, building confidence for the dependability and accountability of the outcomes. Breakout strategies may be changing, as political stresses evolve.

Note, however, that every technical system (NES) is embedded in a soft system (state owning it and operator running it, inspectors checking it, etc.), which in its turn is placed within a given context (political situation, crisis versus non-crisis scenario, etc.). The overall PR of a NES comes from the interaction of these layers, and therefore PR is not just an intrinsic characteristic of an engineering asset.

In trying to assess a design outside its soft system and context (Generation IV systems don't even exist yet), the working group developed a notional threat space against which the system can be tested (i.e., the group created a soft system and a context against which the system could be assessed and eventually compared with other options). Of course any final judgment on the six measures will have to be referred to the scenario analyzed and might not be valid in another context. In this sense no true intrinsic measure can be analyzed and eventually judged without considering the scenario.

TD is an intrinsic measure in the sense that no matter which soft system and context, the would-be proliferator will have to make technical modifications to the system to reach goals. Depending on the scenario, these modifications might be less or more in both quantity (e.g., concealment or not) and effectiveness (e.g., technologically advanced country or not). DP, on the other hand, is considered to be an extrinsic measure because it is a barrier only in given contexts. For example, a system where no inspections are foreseen (or allowed) could not count on inspections as a deterrent.

7.3 Physical Protection Assessment Lessons

While containment of the adversary is adequate to prevent theft, a deterrence strategy that denies adversary access to targets is required to prevent sabotage. Given the proximity of theft and sabotage targets in the ESFR facility, the ESFR will likely require a deterrence strategy because the PP system will not be able to determine adversary intent (i.e., theft or sabotage) early enough. This determination will require a robust perimeter detection system and effective use of the passive barriers provided by hot cell radiation shielding structures and reactor passive safety systems.

7.4 Areas for Further Study

The case study indicated that the PR methodology could be improved by

- Applying the measures to a broader range of targets and pathways to gain additional experience with their practical application
- Some of the metrics were difficult to apply
- How to make the best use of the MT and DE measures is unclear. For example, perhaps MT should be included as part of the target description, and DE tends to be facility specific rather than pathway specific.
- Providing additional investigation on the precise form of the metrics, especially those of PC, DP, and DE.

The PP methodology could be improved by

- More closely examining the qualitative methods and the grouping of qualitative values for coarse pathway assessment
- Considering more systematically the response force deployment strategy (the size of the plant introduces placement complexity)
- Considering more systematically the potential role of active insiders; consideration of this element of the threat definition was minimal in the case study
- More closely examining how the number of theft and sabotage targets at a facility influences the response force's ability to predict the adversary's target selection and successfully interrupt the adversary.

The PR&PP methodology has the potential to be a powerful tool that can be applied at the conceptual design stage for NESs, to generate the design bases for detailed system design as well as specific and well motivated requirements and recommendations. Future case study work will include efforts to further exercise this approach and demonstrate its utility in guiding the design of Generation IV NESs.

APPENDICES

Appendix A: ESFR System Description

Appendix B: Safeguarding the ESFR Nuclear Energy System

Appendix C: ESFR Physical Protection System

Appendix D: Representative Pathway Descriptions and Analyses
D1 – Diversion
D2 – Misuse
D3 – Breakout
D4 – Theft and Sabotage

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Appendix A: ESFR System Description

A conceptual design of a Generation IV system with sufficient information about all the elements of the fuel cycle, as well as deployment considerations, has not been developed yet. Even in the Generation IV reactor technology that is considered more mature (sodium-cooled reactors), an off-the-shelf concept for testing the implementation of the methodology does not exist.

Therefore, the Example Sodium Fast Reactor (ESFR) system has been developed as a hypothetical Generation IV system that includes the power plant, fuel cycle facilities and a deployment scenario. For the power plant layout and concept, one of the concepts submitted to the Generation IV Roadmap (AFR-300) is used. The dry recycling technology (pyroprocessing) that has been under development primarily at the former ANL-W (now part of Idaho National Laboratory), is selected as the fuel cycle facility for the system. A plausible deployment involving co-location of the fuel cycle facility and four reactor units is assumed for the ESFR nuclear energy system. The reference ESFR nuclear energy system is described in this section.[1] More detailed descriptions about the reactor and the fuel recycle technologies can be found in references [A.1, A.2].

The *boundaries* of the system coincide with the boundaries of the ESFR site. Facilities, material, and processes within the site boundary are *internal* to the ESFR system; all others are *external*.

A.1. ESFR – System Elements Overview

The term ***System Elements*** is defined as a collection of facilities[2] inside the identified *Nuclear Energy System* where diversion/acquisition and/or processing could take place.

For the ESFR, the following system elements are identified:

- LWR Spent Fuel Storage
- Fuel Cycle Facility
- ESFR Spent Fuel and New Fuel Storage Cell
- Fuel Service Facility Building (containing single fuel assembly staging/washing area and transfer tunnels for each reactor)
- Four identical sodium cooled fast reactors (each having an in-vessel storage basket)
- Waste Storage
- LWR spent fuel cask receiving and parking area
- Excess Uranium storage
- Uranium container parking area

[1] This ESFR description includes some material contributed by engineers from ANL and ANL-W (now part of INL) who are not part of the PR&PP group: C. Grandy, T. Fanning, M. Goff, and R. Kulak.

[2] According to IAEA Additional Protocol, *facility* means "*(i) A reactor, a critical facility, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or (ii) Any location where nuclear material in amounts greater than one effective kilogram is customarily used*" [IAEA 1998]. The implicit facility definition given above in the text is compatible with the IAEA one.

These are the facilities (locations) inside the ESFR system containing nuclear material or processes that could be attractive for proliferation. Current documentation for the nuclear facility upon which the ESFR is modeled does not explicitly include a storage facility for the receipt and temporary storage of LWR spent fuel elements or a Waste Storage Facility. For completeness, these are included as internal ESFR system elements.

The ESFR nuclear system, including the system elements listed above, is shown in Figure A.1.

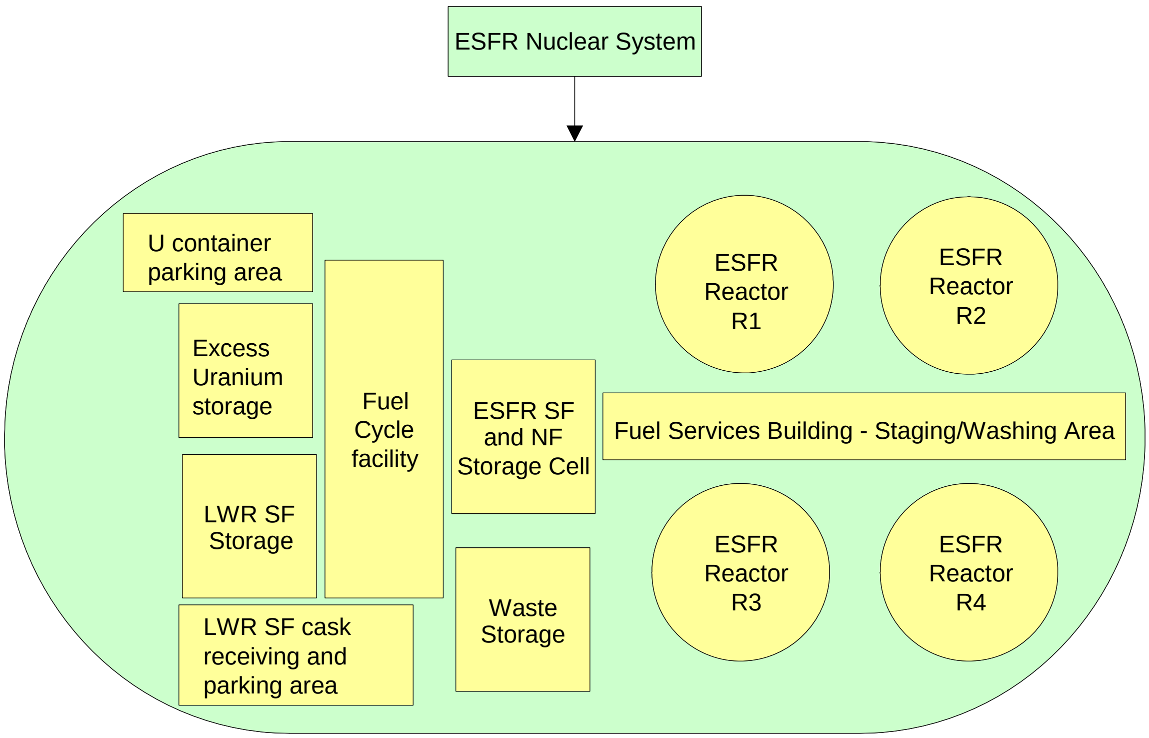


Figure A.1. Diagram of ESFR Nuclear System Elements.

A.2. Site Description

The operation characteristics of the pyroprocessing technology makes it amenable to small throughputs, providing the opportunity for co-location of a fuel cycle facility close to the power plants. This is the assumption made in the ESFR. The site consists of 4 power plants (nominally, 300 MW_e each) and a single fuel cycle facility serving the needs of the four power plants.

The site includes also a fuel services building that contains a spent fuel staging area used for washing spent fuel assemblies and transferring them to the fuel cycle facility. Fresh (recycled) fuel is also transferred from the fuel cycle facility to the reactors via the fuel services building. At the front of the fuel cycle facility, a spent fuel storage area is provided to allow for enough storage space to maintain steady operations of the facility and transfers to and from the reactors.

An artist's view of the site layout can be seen in Figure A.2. Potentially relevant details about security-related buildings, gates, fences, etc. have not been developed and the PR&PP group will need to make assumptions. Similarly, placement of auxiliary buildings has not been developed either. A possible overall site plan for the ESFR Nuclear Energy System is shown in Figure A.3. It should be noted, however, that Figures A.2 and A.3 do not contain all the system elements identified previously.

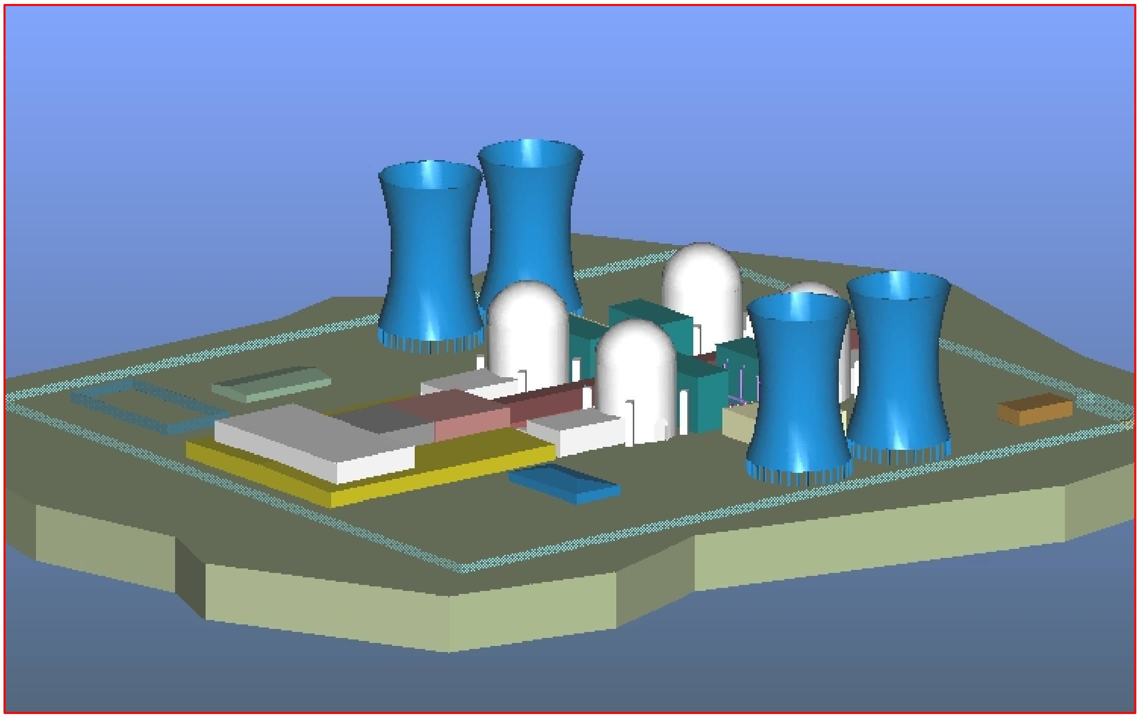


Figure A.2. Site view for the ESFR.

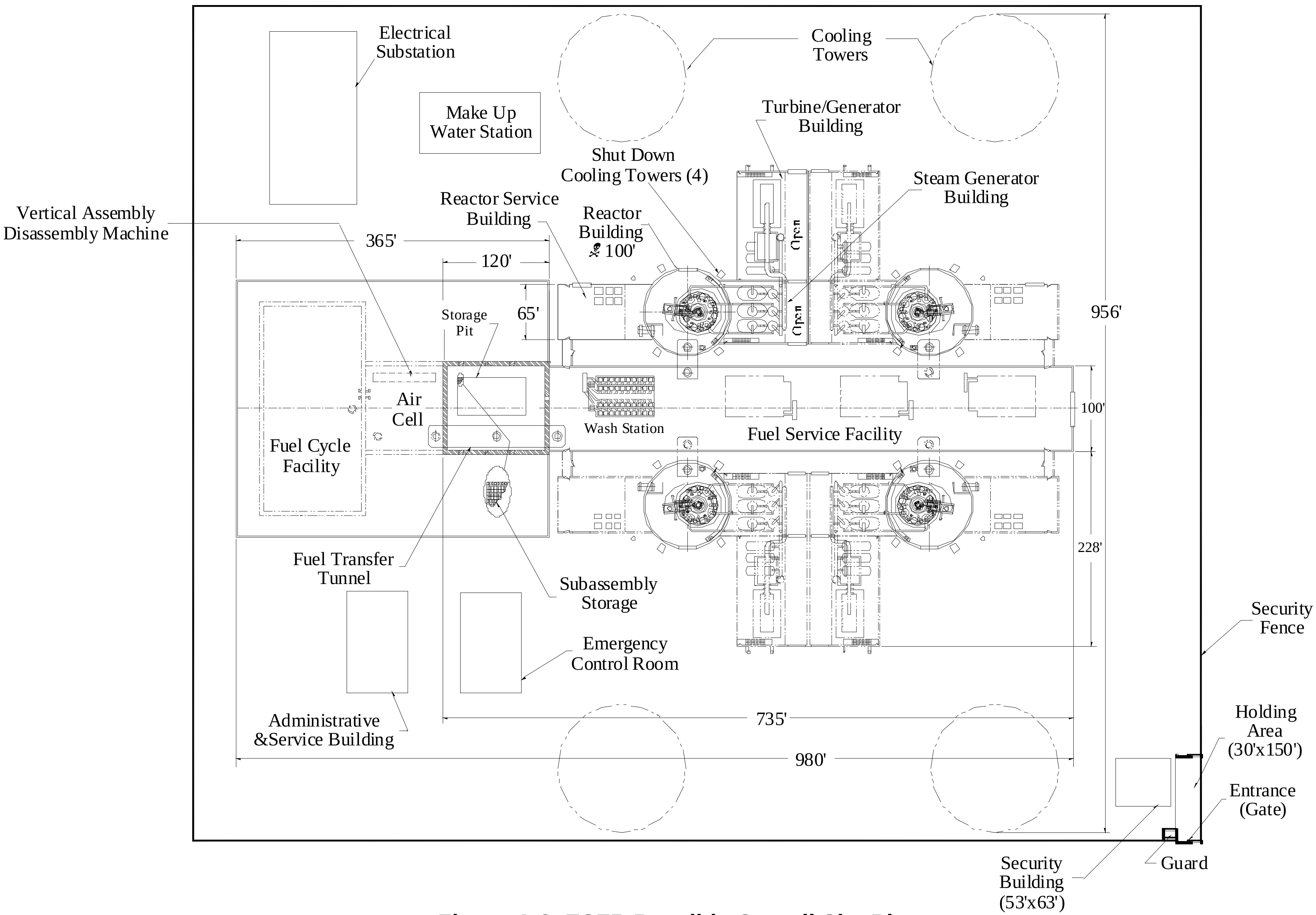


Figure A.3. ESFR Possible Overall Site Plan

For the baseline case of the ESFR system, it is assumed that the reactors will be operating in a net actinide burning mode, which is the assumption made in the Generation IV program for initial deployment of fast spectrum reactors with an actinide management mission. Therefore, the reactors will not operate in a self-sufficient mode and will require an external source of actinides for make up. Several options existed for the external source of actinides. Since the recycled fuel is fabricated in the on-site fuel cycle facility, the external source needs to be provided to that facility. The assumption made for the baseline ESFR system is that the external source is provided in the form of LWR spent fuel assemblies, which avoids the need to consider an external fuel cycle facility to reprocess the LWR spent fuel. The LWR oxide fuel will be processed in the on-site fuel cycle facility, which will require adding a front end step to reduce the oxide fuel to metal prior to processing in the electrorefiner.

A.2.1. Reactor Facilities Description

The reactor containment building encloses the entire primary reactor system. The building is assumed to be a steel-lined reinforced concrete containment, similar to those used in many light water reactor plants.

The major functions of the reactor containment building are as follows:

- Contain radioactive material following the unlikely event of an accidental radioactivity release from the primary reactor system;
- House and structurally support the primary tank vessel, guard tank, support structure of the primary reactor system and fuel handling equipment, biological shielding, and associated equipment and structures;
- Facilitate sodium and non-sodium fire protection for all safety equipment; this includes separation of redundant systems required for safe shutdown and for maintaining the reactor in safe shutdown condition;
- Provide protection for all safety equipment from the environment and natural phenomena such as floods, winds, tornadoes, and earthquakes;
- Maintain pressure within the containment boundary slightly negative with respect to the exterior, except during pressurization accidents;
- Limit leakage from the containment boundary to a certain fraction of the contained volume per day at a given internal pressure
- Maintain the integrity of the containment boundary during all design loadings.

The reactor containment building is a cylindrical structure with a hemispherical top closure and a reinforced concrete bottom closure (basemat). For the purpose of the ESFR, the building is assumed to have an approximate inside diameter of ~ 30 m and a height of approximately 70 m, with about 25 m of the building below grade. The reinforced concrete shell walls are assumed to be ~ 1 m thick.

The containment building is assumed to be designed to the rules of the current ASME Boiler and Pressure Vessel Code, Section III, Division 2, "Code for Concrete Reactor Vessels and Containments," Subsection CC for concrete containment. The design is also assumed to conform to the NRC regulatory guides (Federal Regulations 10 CFR 50 and 10 CFR 100) for seismic and other natural hazards, and must meet the general design criteria of the Federal Regulations.

Penetrations through the reactor containment building shell are required for access of personnel, equipment, freight, electrical conductors, and service fluids. All penetrations use pressure-tight seals consisting of appropriate materials. These seals are protected from the building atmosphere since this atmosphere could become hot enough to destroy the seals should a major sodium/air reaction occur. All seals are designed to withstand the same maximum design pressure for the building.

Large penetrations are comprised of three airlocks (personnel, emergency personnel, and equipment airlocks) and a freight access door. The airlocks allow equipment and personnel access to the reactor plant while maintaining building containment integrity at all times. All airlocks are cylindrical steel-welded shells that have a sealed door at each end. The doors are electrically or mechanically interlocked to allow only one door at a time to be opened. The equipment airlock is the largest of the three; it connects the reactor building to the Staging/Washing area. The personnel airlock connects the operating floor area of the reactor plant to the reactor service building and serves as the normal personnel entrance and exit. The emergency airlock is the smallest of the three. It provides an emergency exit from the reactor building should the personnel airlock become blocked.

A large freight access penetration is provided for use for the infrequent movement of large items. This penetration is closed during all reactor operations and fuel handling; it is opened only for transferring large items into and out of the reactor building.

Reactor Description

Note: Descriptive material from AFR-300 ICAPP paper [A.1].

There are four reactors in the ESFR site. Each reactor is assumed to be an AFR baseline design, with a size of 800 MW_{th} (approximately 300 MW_e).[3] The reactor has a large, low temperature (reactor inlet temperature) isothermal pool, which is considered a key element for safety and reliability. The pool provides a large heat capacity that allows for ample response time in multiple transients. The primary tank and its cover are exposed to a uniform temperature, thus reducing thermal stresses and ensuring a long design lifetime. Coolant circulation through the core is accomplished with loops immersed in the sodium pool. This allows forced flow through the core and intermediate heat exchangers (IHXs) during operation and facilitates passive cooling by natural circulation when the primary pumps are not available.

Inert gas (argon) blankets the sodium pool in the primary tank, and fills a gap between the tank and a guard vessel surrounding it. This allows monitoring of the system for leakages and remotely-controlled inspection of the primary tank. The entire primary tank structure is seismically isolated. Control rod drives, primary pump motors and fuel handling components are above the primary tank cover and accessible for maintenance. Sodium compatibility with the materials used in the primary components ensures the lack of corrosion products. Maintaining the primary tank sodium at a constant, moderately low temperature minimizes the formation and deposition of sodium aerosols, which can be removed through the cover gas purification system.

[3] Note: Descriptive material from AFR-300 ICAPP paper [A.1].

The reactor is contained in a vessel inside the primary tank, and the major primary components are connected by piping; leak tightness is not essential, since any sodium leakage from the connections in this piping or past the control rod drive penetrations in the reactor vessel cover is retained in the primary tank sodium pool and kept isolated from the atmosphere. Heat is transferred to a secondary sodium circuit through intermediate heat exchangers immersed in the primary tank sodium pool. The hot sodium from the core is piped directly to the heat exchangers. The entire primary system and sodium pool operate at nearly atmospheric pressure. Neither the primary nor the secondary circuit contains any valves. Table A.1 provides a summary of the main characteristics of a baseline ESFR system reactor. Figure A.4 shows the elevation view of the primary reactor systems.

Table A.1. Main characteristics of the power plant. (From reference [A.1]).

Nominal Electric Power	300 MW_e
Thermal Power	800 MW_{th}
Design Life	60 years
Thermal Characteristics	
Primary Hot Leg Temp	510 °C
Primary Cold Leg Temp	343 °C
Intermediate Hot Leg Temp	488 °C
Intermediate Cold Leg Temp	315 °C
Intermediate Heat Exchanger	
IHX Configuration	Counter Flow with Tube Side Primary Flow
Tube Configuration	Straight
Number of Tubes per IHX	3125
Tube Pitch	3.36 cm
Tube Sheet-to-Tube Sheet Length	518 cm
Shell OD	236 cm
Overall Length	1591 cm
Thermal Rating	267 MW_{th}
Design Margin	~11%
Steam Conditions	
Steam Generator Outlet	15.8 MPa, 457 °C
	Benson Cycle with double walled tubes, three tube sheets, leak detection
Turbine Throttle	15.1 MPa, 454 °C
Primary System Pumps	3
Intermediate Heat Exchangers	3
Secondary System Pumps	3
Steam Generators	3
Turbine Generator	1

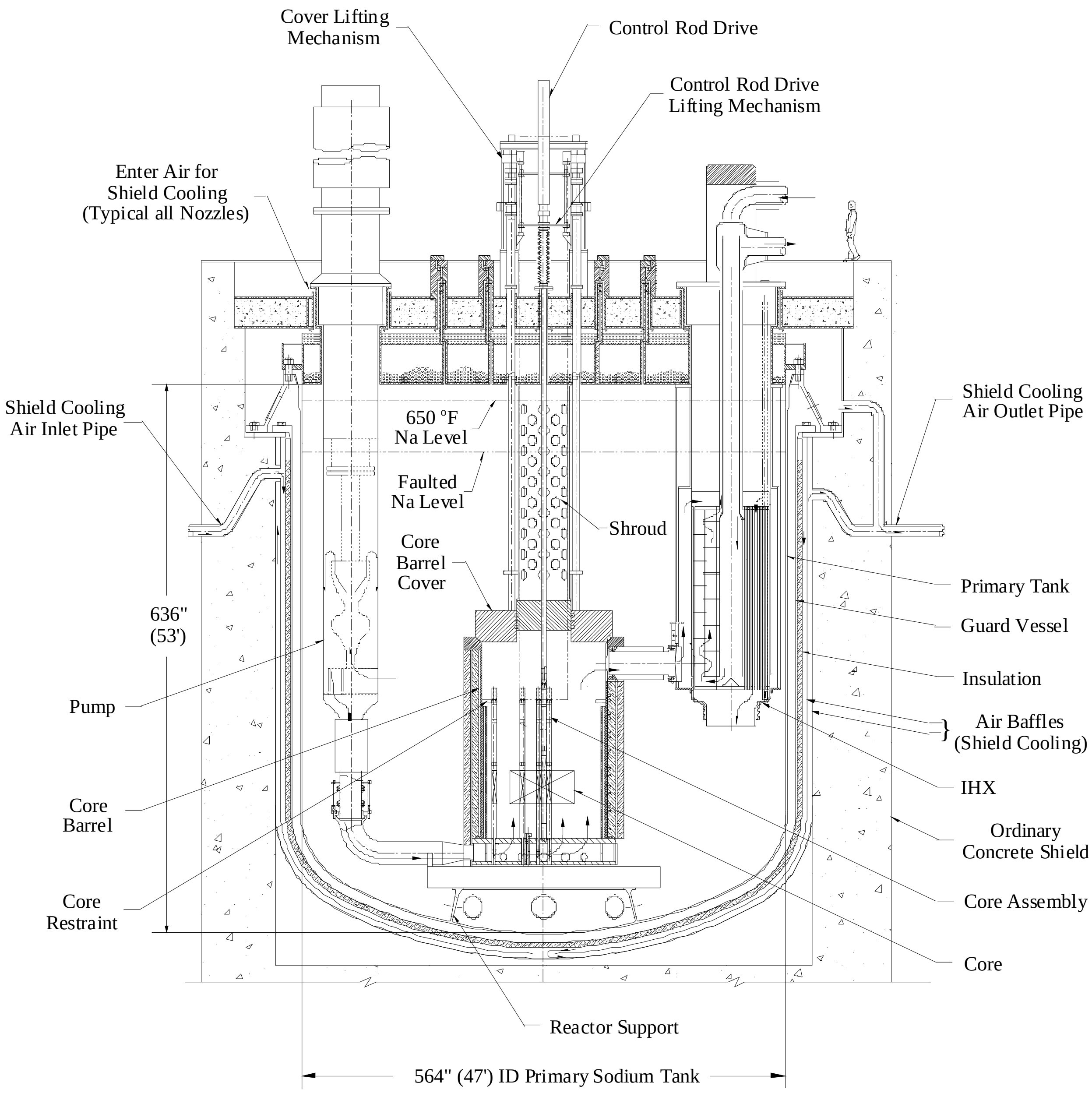


Figure A.4. Elevation View of the Reactor Primary Systems.

The reactor core has large margins between the operating and physical safety limits, high thermal conductivity metal fuel, and negative reactivity feedback characteristics. The fuel is injection cast as pins that are inserted into small diameter (OD of ~7.5 mm) high fluence ferritic steel cladding; liquid sodium is used to enhance heat transfer from the fuel to the cladding. The fuel pins are placed in close-packed, triangular-pitch hexagonal bundles. The compact core configuration operates at high power density (~350 kW/liter) with a fueled height of roughly 1.0 meter and fueled diameter of 1.75 meters. The reference core design (Figure A.5) includes 102 fuel assemblies in 2 enrichment zones and 18 control rods (15 primary and 3 secondary). On an equilibrium fuel cycle that replaces 1/3 of the core annually, the number of primary control rods is established to maintain individual rod worth below $1 accounting for the excess reactivity needed with the operating conversion ratio.

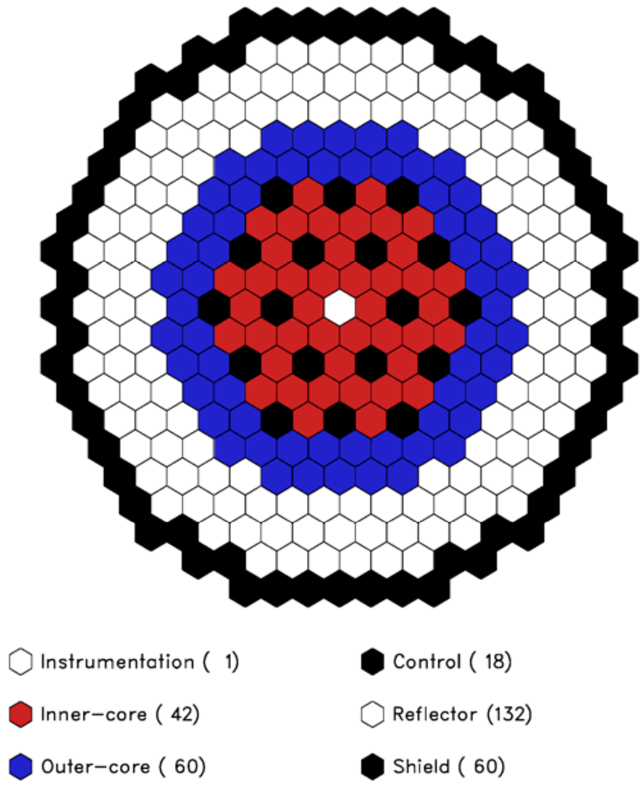


Figure A.5. Baseline 800 MW_{th} Reactor Radial Core Layout

There are three primary coolant loops, each with a mechanical pump and an intermediate heat exchanger (IHX). Natural circulation, which is sufficient to remove the decay heat from the core, is established through the primary circuit if a failure of the pumps occurs. The heat transfer systems are sketched in Figure A.6.

A passive approach to decay heat removal has been adopted in the AFR-300 design. The shutdown cooling system, if the secondary heat transport is not available, is performed with four shutdown coolers in the AFR-300. Each shutdown cooler assembly consists of a heat exchanger immersed in the sodium pool, and a heat exchanger outside the containment, connected by piping containing no pumps or valves. NaK eutectic circulates in the system. Decay heat can be removed from the primary tank through natural circulation in the intermediate loop if a heat sink in the steam generators is available, or by the shutdown coolers. In either case, decay heat removal is accomplished by completely passive means.

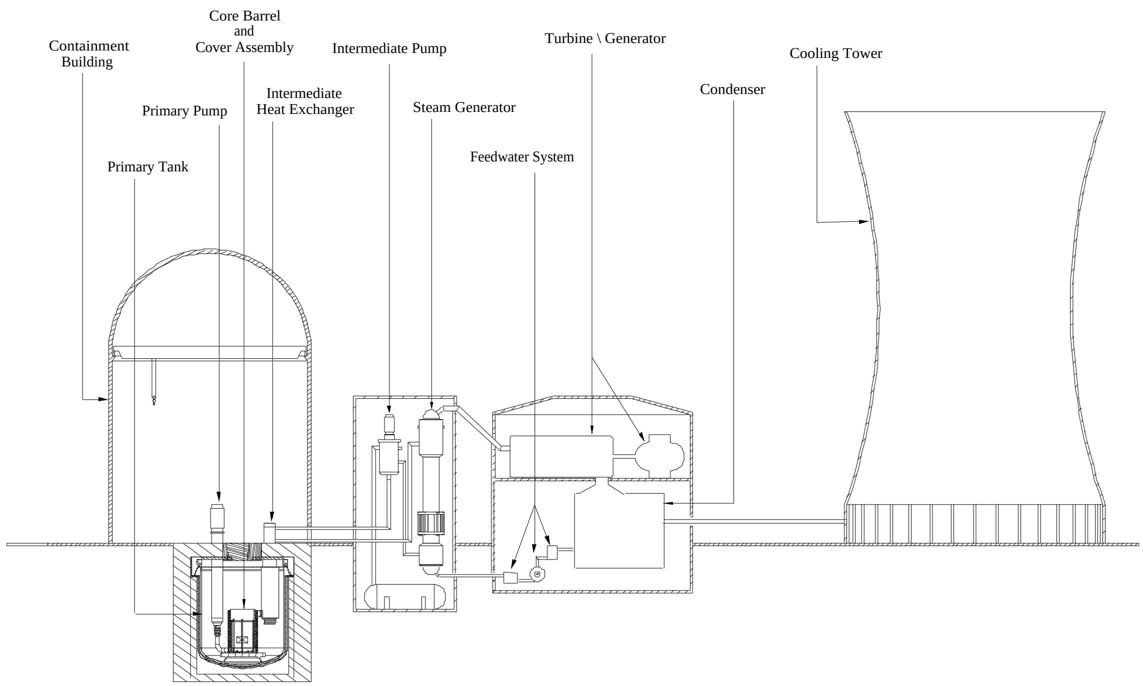


Figure A.6. Schematic of the Heat Transport Systems

Limited analyses of passive safety of the core and the natural circulation characteristics of the concept have been conducted in support of the design. The natural circulation calculations for AFR-300 were carried out with the SASSYS-1 LMR systems analysis code. Analysis of Shutdown Heat Removal Tests in the EBR-II reactor was used to validate the SASSYS-1 code for natural circulation conditions. The findings indicate that with the proper design choices it is possible to achieve proper natural circulation performance during transients.

In the absence of a full set of safety analyses for the specific design (with the specific conversion ratios used in the development study), the safety performance of the ESFR reactor will be assumed to be typical of metal-fueled sodium fast reactors, and the information from previous studies [A.3-A.6] will be used to assume the behavior during transients.

A.2.2. Refueling, Staging/Washing Area and Storage Buildings

The plant layout of the ESFR fuel handling system is shown in Figure A.7. An enlarged view of the fuel transfer path from the staging/washing area of the Fuel Services Facility to the shielded Fuel Storage building is shown in Figure A.8.

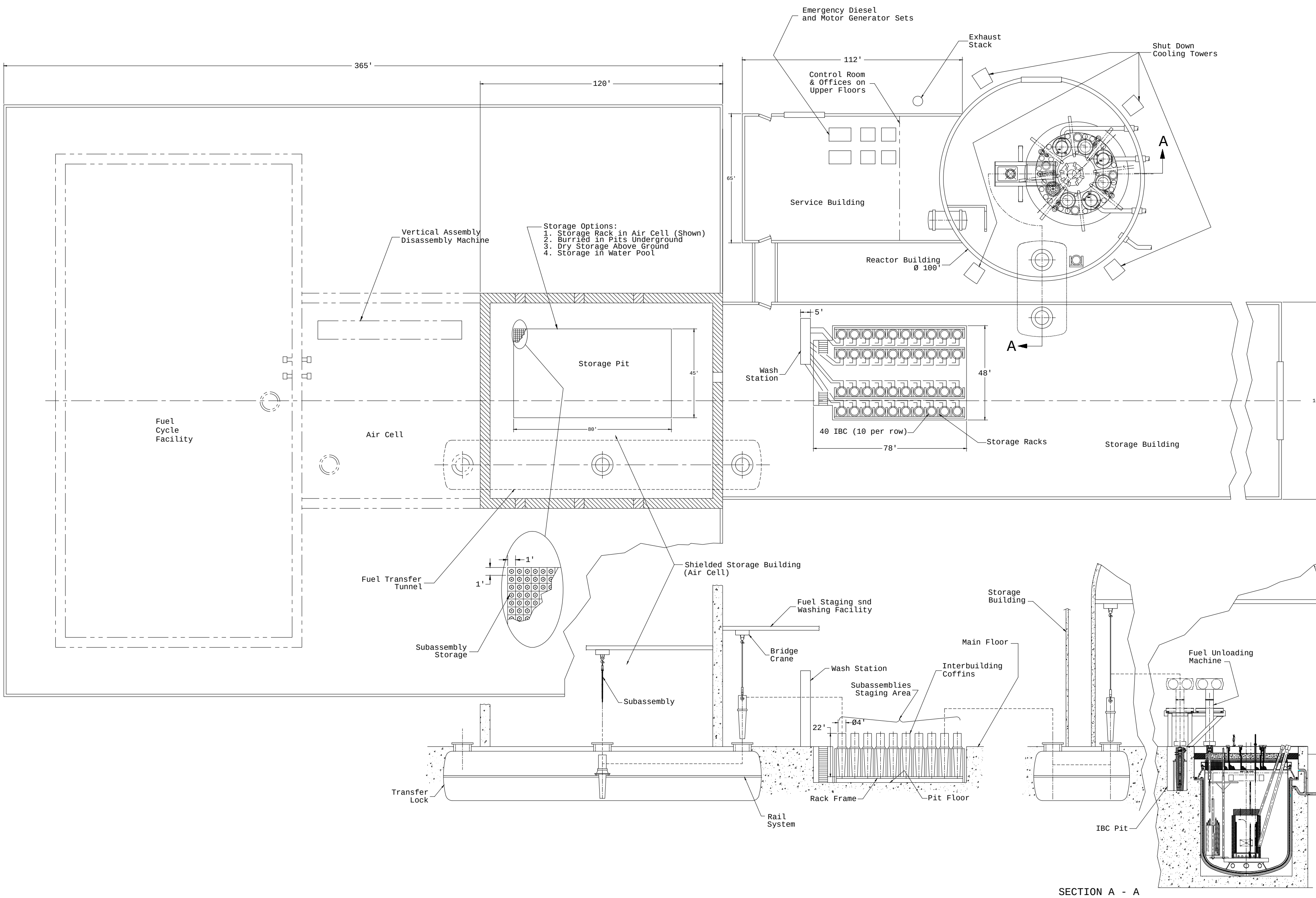


Figure A.7. Fuel Handling System - Plant Layout

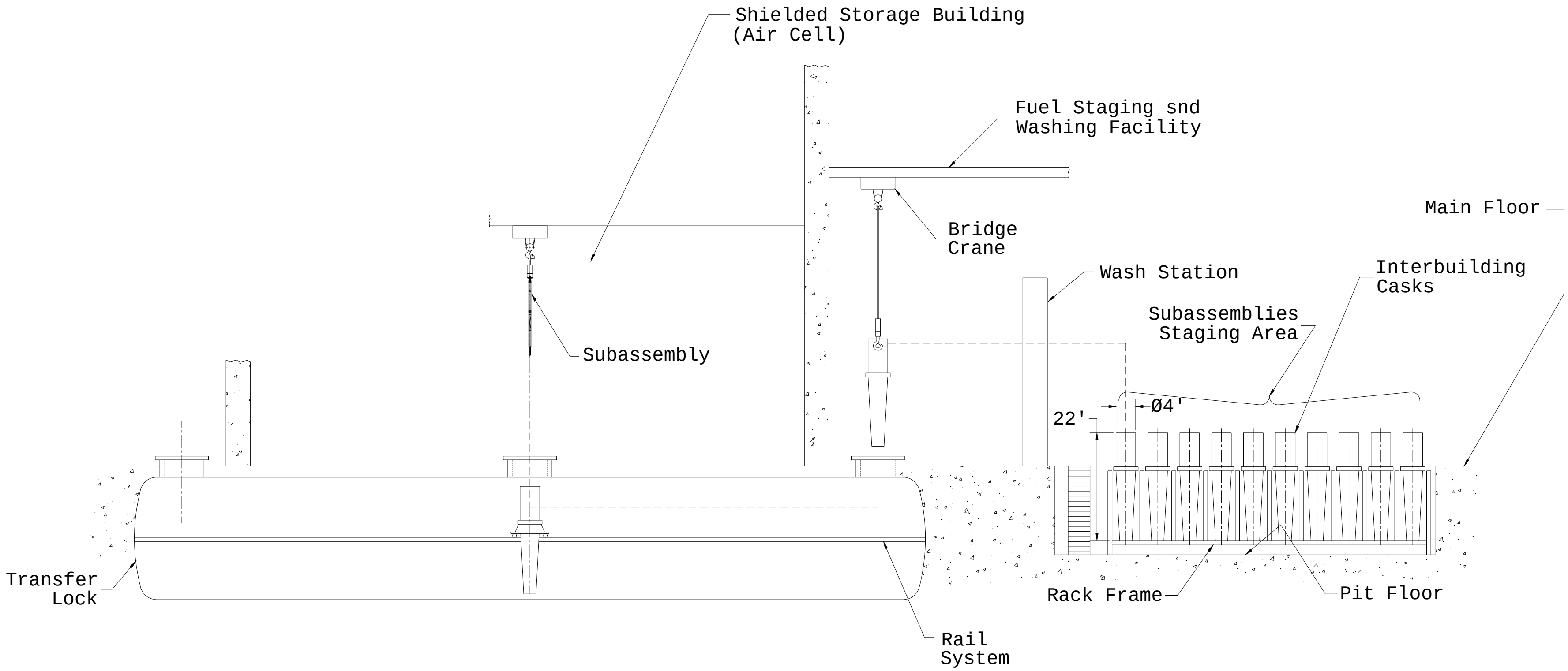


Figure A.8. Fuel Transfer from Fuel Staging/Washing Building to Storage Hot Cell

To reduce the refueling outages, restricted fuel handling (transfer of the fuel in and out of the primary vessel during reactor operation) is allowed by the design. The fuel handling system and process has been designed on the basis of co-location of several reactor units (4 in the reference 300 MW_e design) and a single fuel recycling facility with a fuel holding area connecting the different buildings. Refueling of the reactor is performed using a pair of eccentric rotating plugs on the primary tank cover that allow the positioning of the fuel handling system directly above any position in the core, thus allowing direct pull of the fuel assemblies. A storage basket inside the primary tank provides storage for both fresh and irradiated fuel, such that, during a refueling outage, only in-tank fuel transfer is needed; fuel transfers in and out of the storage basket can be performed during reactor operation. Once spent fuel is removed for storage or reprocessing, it does not need active cooling because of the time spent decaying in the primary tank.

The spent fuel is transferred from the primary tank by a Fuel Unloading Machine into an Inter-Building Cask. The Inter-Building Cask is then transferred to the Fuel Services Facility building for staging and washing to remove the residual sodium from each fuel assembly. After washing, the assembly is then transferred into a shielded storage cell for storage or into the Fuel Cycle Facility for recycling. Figure A.9 shows the transfer of fuel assemblies in and out of the tank and reactor building.

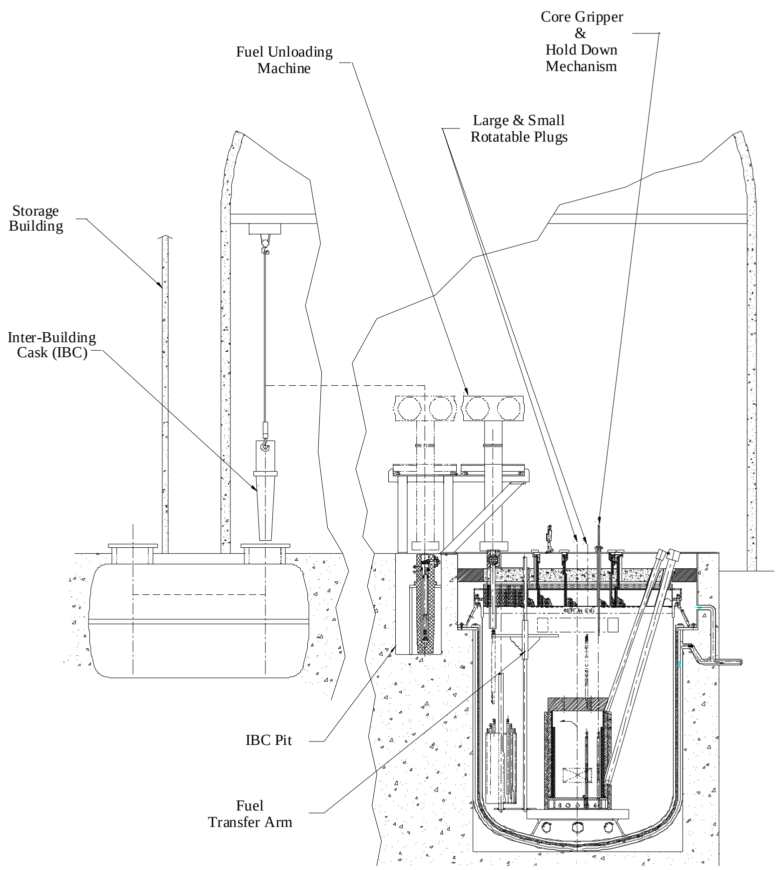


Figure A.9. Transfer of fuel assemblies in and out of the primary tank/reactor building

The Fuel Services Facility containing the Staging/Washing Area is assumed to be an industrial grade building with no containment or reinforced structures. Fresh or spent fuel is only present in the Washing area one assembly at a time, and contained inside the Inter-Building Cask (IBC). The IBC provides the necessary shielding and protection. The spent fuel assembly is not removed from the IBC for the wash operation.

The fuel transfer and washing sequence is assumed as follows:

- Fuel Assembly transferred from in-tank storage basket to fuel unloading machine – no active cooling is required.
- Fuel unloading machine transfers spent fuel assembly to an Inter-Building Cask for transfer to the Storage building
- Inter-building cask is moved through Reactor transfer lock to storage building and placed in washing station – 40 IBC capacity
- Fittings on Inter-building cask are mated with the washing station to provide inert gases and moisture for reaction of residual sodium
- Typical Washing sequence
  - flow moist air over the spent assembly (0.4 standard cubic feet per minute, scfm) to convert the sodium to sodium oxide
  - monitor thermocouple readings closely to determine reaction rate
  - after ~ 5 minutes, increase moist air flow to 7 scfm to convert sodium oxide to sodium hydroxide
  - Operation continues for 25 minutes
  - IBC is purged with argon gas at 30 scfm to remove any O2 or H2 gas
  - Then the spent assembly and IBC are flushed with demineralized water at 5 gpm (gallons per minute) to remove the sodium residue
  - The assembly is then dried for 30 minutes with a 30 scfm air flow
  - The IBC is then staged pending movement and transfer of the assembly to the Air storage cell

Storage buildings adjacent to the fuel cycle facility and the staging/washing area are also provided. One building stores LWR spent fuel brought to the site for the purpose of obtaining the makeup actinide material. Another storage building hosts the AFR-300 fuel assemblies. The building is divided into two sections, physically separated: a section for storage of fresh (recycled) fuel assemblies and another section for the spent fuel assemblies discharged from the reactors.

No designs exist for the storage facilities, but it is assumed that the buildings are reinforced structures that provide containment and shielding for the materials in storage. Containment requirements are expected to be less significant than for a reactor containment building, due to lower pressurization sources in the storage buildings. The LWR assembly storage is assumed to be under water that also provides shielding during the transfer of assemblies from the transportation cask to the storage rack. On the other hand, the facility storing fast reactor fuel (recycled or spent) assemblies is a dry storage facility and transfer operations occur remotely. The only penetration hatches are for the extraction and insertion of the fuel assembly from and to the transfer casks. Figure A.10 sketches the transfer operations from the washing area to the storage facility and to the fuel processing cells.

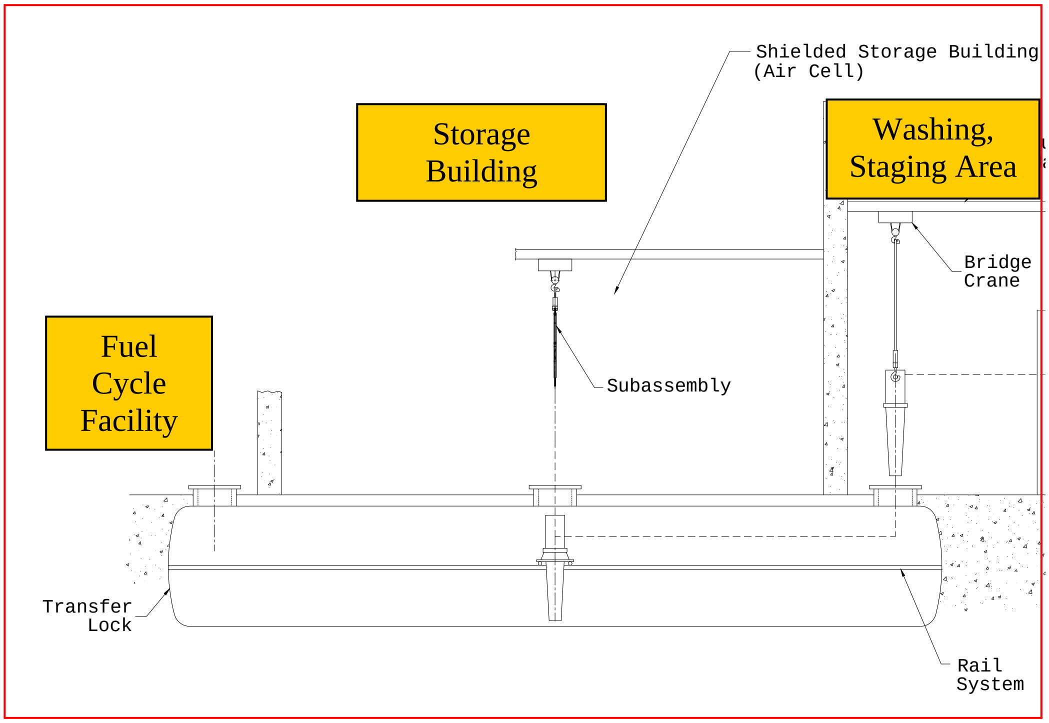


Figure A.10. Transfer of fuel assemblies from washing area to the storage building and the fuel processing facility.

A.2.3. Fuel Cycle Facility

The hypothetical Example Sodium Fast Reactor (ESFR) pyrochemical reprocessing (pyroprocessing) fuel cycle facility* is designed to accept the spent sodium-bonded, metallic fuel from four (4) advanced fast reactors and convert it into three output streams (new fuel assemblies, metal waste ingots, and ceramic waste forms) using pyrochemical processing technology. Fig. A.11 illustrates the assumed four-unit power station and co-located fuel cycle facility. Fig. A.12 illustrates the process operations performed in the fuel cycle facility.

* The term "fuel cycle facility" does not refer to any existing facilities, and in particular, it should not be confused with the Fuel Conditioning Facility located at Idaho National Laboratory. In this report, any use of the term “fuel cycle facility” or its acronym, FCF, refers to a generic nuclear fuel reprocessing facility--using a pyrochemical recycling process--which is co-located with a four-unit fast reactor power station. The power station and fuel reprocessing facility constitute the hypothetical Example Sodium Fast Reactor (ESFR) nuclear energy system considered by the PR&PP Expert Group in its previous Methodology Development Study (2004) and current Methodology Demonstration Study.

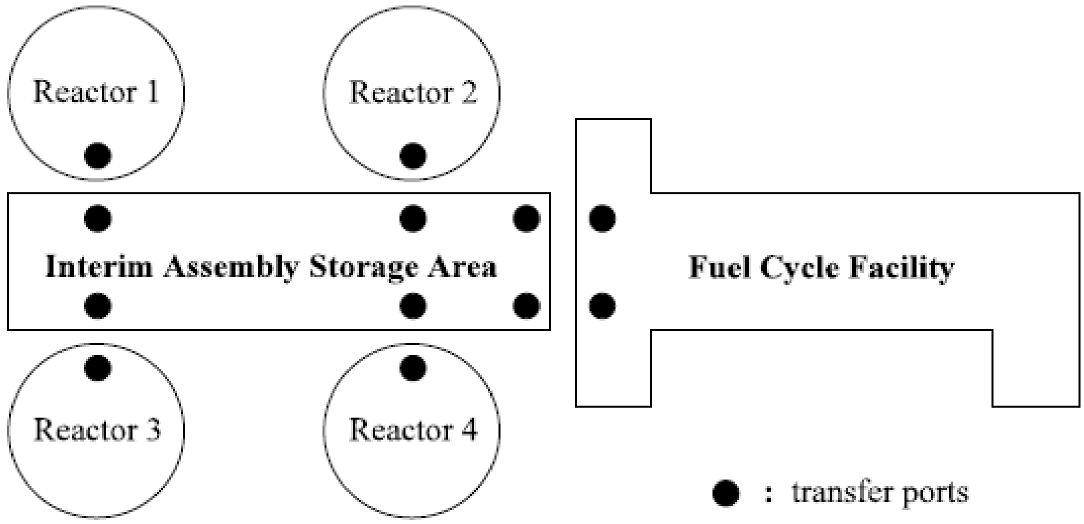


Figure A.11. Assumed four-unit power station and co-located fuel cycle facility.[4]

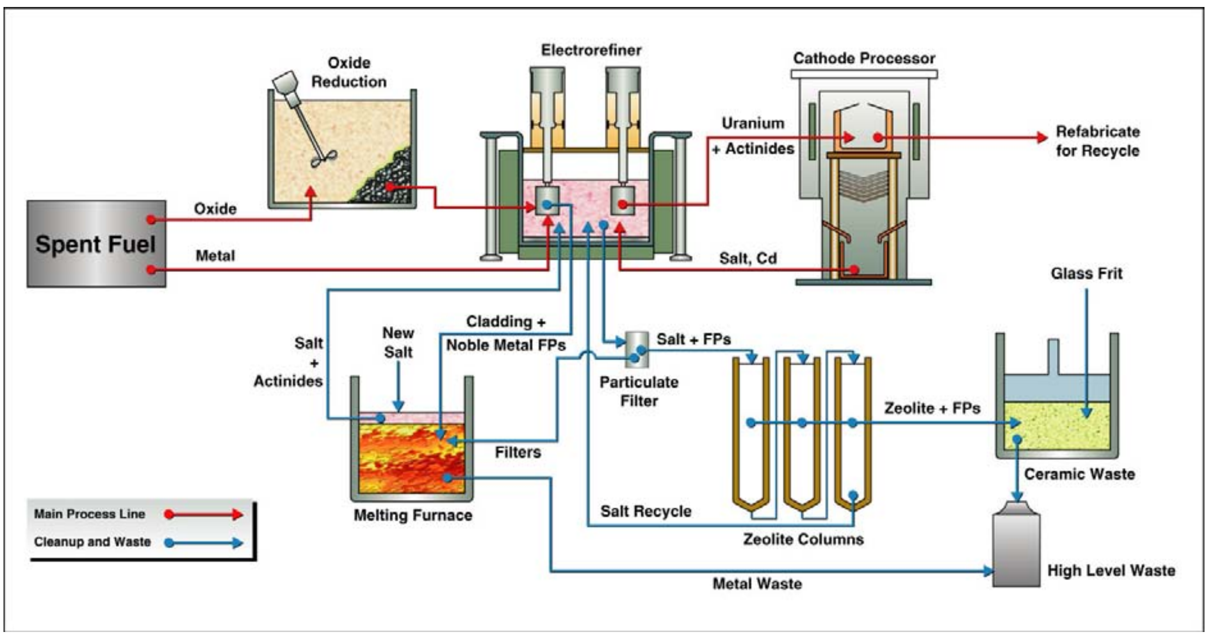
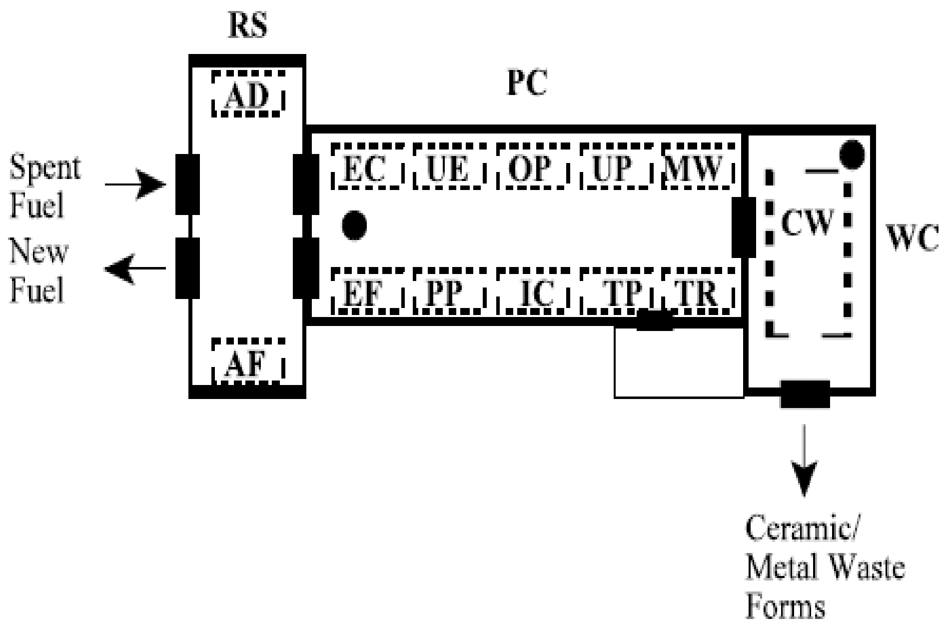


Figure A.12. Diagram of the fuel cycle facility operations.

[4] Figure was extracted from Garcia, H.E., et al, "Description of Facility Design and Description of the Reference Processes with Material Flows," Working Document, Argonne National Laboratory, October 2002, p. 2.

To sustain these reactors, a fuel cycle facility should be able to recycle 3 MTHM per reactor per year or 12 MTHM total per year, which is equivalent to 136 assemblies per year at 88 kg (heavy metal) per assembly. Assuming an annual facility availability of 67% (or 240 days per year), this annual throughput translates into 50 kg-HM/day, 154 elements/day, or 4 assemblies every week.

As illustrated in Fig. A.13, the proposed fuel cycle facility hosts a number of operations that are conducted in three shielded hot cells: Receiving/Shipping Cell (RS), Process Cell (PC), and Waste Cell (WC). RS is an air-atmosphere cell; PC and WC are argon-atmosphere cells. A safety-class exhaust system is provided. An emergency diesel system is located in an interconnected building. Operations involving intact fuel elements are carried out in the air-atmosphere cell. Those processes involving exposure of heavy metals or reactive metals are done in one of the two argon-atmosphere cells.



AD:	Assembly Disassembling	**IC:**	Injection Casting
EC:	Element Chopping	**PP:**	Pin Processing
UE:	Uranium Electro-refining	**EF:**	Element Fabrication
OP:	Oxidant Production	**AF:**	Assembly Fabrication
UP:	Uranium Product Processing	**MW:**	Metal Waste Processing
TR:	TRU/U Recovery	**CW:**	Ceramic Waste Processing
TP:	TRU/U Product Processing		

Figure A.13. Process Operations in the Hypothetical Pyroprocessing Facility[5]

[5] Ibid., p. 10.

The air cell is a concrete cell with thick shielding walls, and remote-controlled manipulators. Only encapsulated fuel materials are handled in this cell. The two argon cells have thick shielding concrete walls and a welded steel liner. All operations are done remotely. They have an inert atmosphere with a closed-loop cooling and purification system. Unencapsulated fuel materials are handled only in these cells. All three hot cells have remote repair/recovery capability for all active components of the handling systems.

The fuel cycle facility also contains a shielded repair area, which is located below the PC. The repair area has wet and dry decontamination equipment, shielded and unshielded glovewall workstations, and a crane. Contamination control and ventilation are provided by the air cell exhaust system. The hot cells and repair area are connected by an air-atmosphere transfer-tunnel system. No fuel or high-level waste materials are handled in the repair area, although significant contamination levels are allowed because it is designed for remote operations. Details on the fuel processing can be found in references [A.2, A.7, and A.8]

Operation of the equipment is supported by material handling devices, such as cranes, robot manipulators, electro-mechanical manipulators, and transfer carts. Briefly, material flows from the top left to the right and then from the bottom right to the left in a U-shaped path. These material flows can be divided into two process streams, as described below.

Product Stream

Essentially, the pyroprocessing technology as applied to spent nuclear fuel has five main process steps. First, spent fuel assemblies are disassembled at AD and the resulting fuel elements are mechanically chopped at EC. Second, chopped elements are electro-refined at UE to partially separate the uranium from fission products and actinide elements. This step generates a uranium material, which is further processed at UP to remove adhered salt and produce the uranium (U) product. This second step also generates metal waste resulting from undissolved cladding hull pieces. The third step consists of recovering the transuranic (TRU) material present in the salt used for uranium electro-refining. Similar to the uranium material, TRU/U material recovered at TR is further processed at TP to remove adhered salt and produce the TRU/U product. Fourth, the U product, TRU/U product, and fissile makeup material are combined at IC to produce fuel slugs used at PP. Fuel elements are fabricated at EF from these slugs and assembled into fuel assemblies at AF, then returned to the collocated reactors. The final fifth step consists of conditioning the metal and salt wastes generated by the second and third steps, respectively, and producing the ceramic/metal waste forms.

To support the above five steps, it is assumed that the following main equipment is used: 1) a disassembling/assembling device; 2) a chopper device; 3) a uranium electro-refiner, with associated uranium product processor for salt removal; 4) a TRU/U recovery device, with two associated TRU/U product processors for salt removal; 5) two casting furnaces with associated pin processing and fuel element fabrication workstations; and 6) waste processing equipment, as described below.

Waste Stream

Metal waste ingots are produced from processing the metal wastes (plenums and cladding hulls) generated by the chopping and uranium electro-refining steps (respectively). On the other hand, spent salt used in the uranium electro-refining and TRU/U recovery processes is transferred to the ceramic waste processing area, where it is processed, consolidated, and removed from the facility. While metal waste production involves metal consolidation and salt removal in a single furnace, the technique to treat spent salt has four process steps. First, chunks of salt are pulverized in a crusher. Second, the crushed salt is put into a mill/classifier and ground to a fine powder. Third, the salt powder is first mixed with zeolite in a heated vessel, and then glass powder is added. Finally, the resulting mixture is transferred to a crucible, which is placed in an oven where the material is consolidated to the point that the waste form is a solid block.

To support the above salt processing steps plus metal waste production, the following main equipment is used: 1) a metal waste form furnace, 2) a crusher, 3) a mill/classifier, 4) a heated mixing vessel, and 5) a pressureless consolidation furnace.

Process Assumptions and Definitions

The preliminary facility design described here is intended to receive approximately twelve metric tons of heavy metal (MTHM) in spent nuclear fuel assemblies per year, process the fuel using pyroprocessing technology, fabricate new fuel, and package the various processed wastes for shipment offsite.

Process Overview

Figure A.14 shows a process flow diagram for the fuel cycle facility with the option for TRU/U recovery using a two-stage electrolysis system. Input and output material streams are indicated for each operation by assigned numerals. (This flow diagram, taken from reference [A.9], has been modified slightly to match the flow description of the baseline case ESFR fuel cycle facility.)

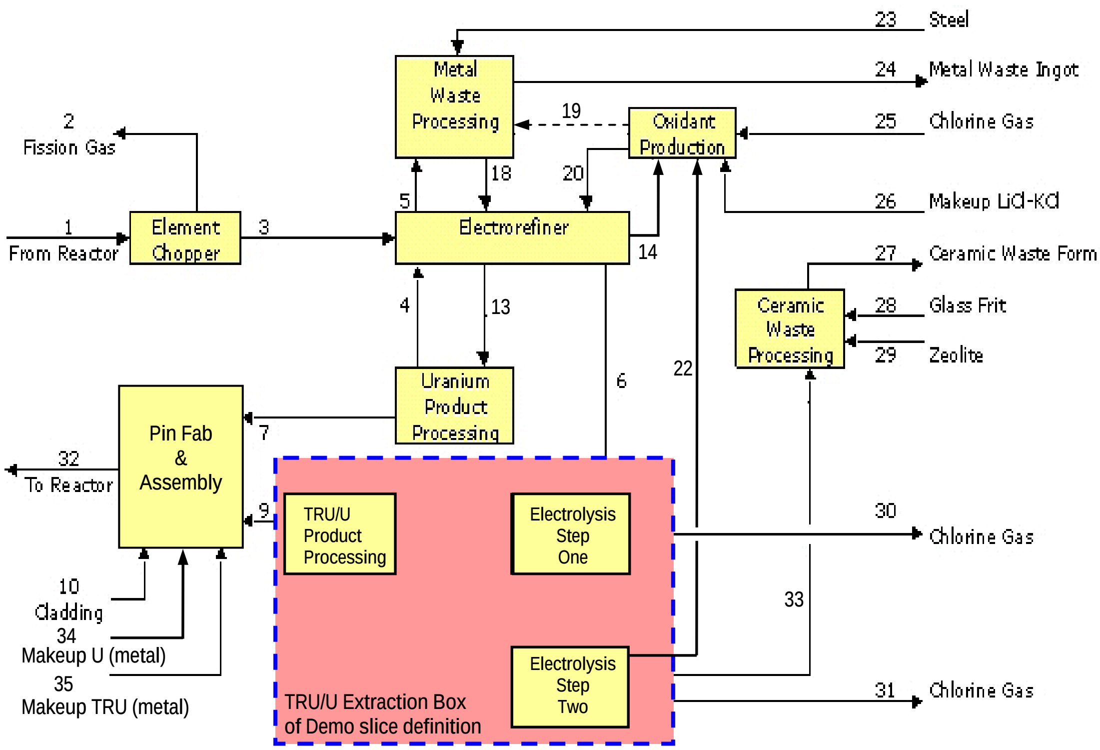


Figure A.14. Process Overview for Two-Stage Electrolysis Option

Equipment and Material Transfer Batch Sizes

Given the required daily material flows, both equipment and material transfer batch sizes are estimated. The design criteria for these batch sizes aim to balance multiple operations and safeguards-related objectives including most importantly the following ones:

i) minimize material transfers;
ii) optimize interfaces between consecutive process steps;
iii) minimize in-transit material inventory (especially to facilitate safeguards inspection efforts);
iv) facilitate the implementation of safeguards monitoring techniques by suggesting material transfer batch sizes that can be assayed, for example, using feasible NDA instrumentation;
v) minimize number of multiple process lines;
vi) satisfy criticality constraints;
vii) select equipment cycle times that would not demand significant R&D development but based on currently achievable operational values.

Criticality considerations limit equipment batch sizes, including the two TRU/U Product Processing and two Injection Casting units (TP and IC, respectively, in Figure A.13). It is assumed that the batch size of each TP unit is limited to 8 kg-HM and that the batch size of each IC unit is limited to 25 kg-HM.

To estimate material handling requirements, it is important to notice, for example, that the electro-refiner should complete four modules per day (with one U-product collector per module), including loading, electrotransporting, and unloading of each module. (A module consists of an anode and cathode pair.) This assumes an ER throughput of ~800 g-HM/hr/module. Regarding salt replacement requirements, it is assumed that 260 kg-salt would be removed from the ER every day in a single container and sent to TRU/U Extraction, and that 265 kg-salt would be added to the ER from OP every day in a single container (Streams 6 and 20, respectively, as indicated in Figure A.14). In addition, it is assumed that 18 kg-salt and 12 kg-salt, from UP and MW, respectively, would be added to the ER every three days using two containers (Streams 4 and 18, respectively, as indicated in Figure A.14).

Fuel Cycle Facility Operations

The fuel cycle facility operations described below include all the operations performed in the receiving/shipping cell and the process cell except for following process steps:

- Oxidant production
- Metal waste processing
- Ceramic Waste processing

Also, the ESFR does not include external source Pu as shown in the references. Instead, external source U and TRU is obtained from the processing of spent LWR fuel.

The following subsections contain brief descriptions of the processing steps carried out in the fuel cycle facility.

Note: For the purposes of this study, assumptions have been made about batch sizes and daily flow rates based on the desired annual throughput of the fuel cycle facility for the *baseline* ESFR. Estimates for process times, inventories, and residence times not explicitly assumed can be inferred in many instances from the assumed batch sizes and daily flow rates. Assumed batch sizes, daily flow rates, process times, etc., are not intended to accurately reflect potential fuel cycle facility operational characteristics.

Maintenance access time is not considered at present.

Disassembly

Irradiated fuel assemblies are received in this air filled hot cell and temporarily stored. Storage capacity is limited but sufficient for a few assemblies. Irradiated fuel pins are removed from assemblies and stored before being passed to the processing cell. Assembly hardware (metal waste not containing nuclear material) is passed back out of this cell for disposal.

Chopping

Operational Characteristics:
No. of Units: 1 Element Chopper (EC)
Input Batch size: assume 77 fuel pins per fuel pin transfer basket, 25 kg-HM/basket
Input Batches per period: 2 fuel pin transfer baskets per day
Output Batch size: 35.5 (chopped) fuel elements/anode basket, 12.5 kg-HM/anode basket
Outputs per period: 4 anode baskets per day

The chopper converts intact spent fuel pins to a form that can be processed directly in the ER. It is assumed that the spent fuel pins are chopped into pieces ~0.25" (~6.35 mm) long which weigh ~2-3g.[6] 4 anode baskets of chopped spent fuel are produced each day, assumed to contain a combined total of 10 kg of Pu. The chopped spent fuel, contained in anode baskets, exits the chopper unit operation and is sent to the Electro-refiner.

Assumed Chopper input and output streams may be summarized as follows:

- Chopper Input Streams:
    - Full fuel pins from Assembly disassembly (77 whole fuel pins/fuel pin basket, 25 kg-HM/basket)
    - New anode baskets (rarely)
    - Returned anode baskets from Metal Waste Processing (4 anode baskets/day, typically)
- Chopper Output Streams:
    - Chopped spent fuel pins in anode baskets to Electro-refiner (35.5 chopped fuel pins/anode basket, 12.5 kg-HM/anode basket, 4 anode baskets/day)
    - Fission gas

[6] Assuming a fuel density of 15 g/cm^3, a cladding density of 7.76 g/cm^3, a "smear" factor of 0.75 to allow for swelling of the fuel within the cladding, and fuel pins with 0.541 cm inner diameter and 0.737 cm outer diameter.

Electro-Refiner

Operational Characteristics:
No. of units: 1 Electro-refiner (>1000 kg-salt vessel)
Input: 4 anode baskets of chopped spent fuel pins/day
Batch size: 12.5 kg-HM per anode-cathode module
Batches per period: 4 modules/day
Products per period: 4 U-product collectors per day
Process time: Assumed to be 16 hours per module (assume operation on modules is concurrent with staggered inputs and outputs)

The purpose of the ER unit is to electrochemically separate uranium from other spent fuel constituents. Uranium trichloride in a 500ºC LiCl/KCl eutectic melt is used as an electrolytic medium. The reactivity of UCl3 is such that it oxidizes the more reactive metals that are present in the spent fuel (TRUs, sodium and reactive fission product metals such as Cs) and, thus, prevents them from accumulating with the uranium metal product on the cathode. During normal ER operation, essentially all of the uranium dissolves in the medium and electrochemically transports and deposits on the cathode as uranium metal. A portion of the U metal is subsequently transferred to the Uranium Product Processing (UP) unit. (A slightly smaller portion of the U metal product is sent to Oxidant Production (OP) to provide U metal for the production of UCl3 for fresh ER salt.) TRUs, active metal fission products, bond sodium, and a small amount of cladding metal are converted to chloride salts and dissolve in the ER salt medium, which then serve as feed for TRU/U Extraction. Undissolved cladding and noble metal fission products remain in the anode basket and are transferred to Metal Waste Processing (MW).

Assumed normal ER input and output streams may be summarized as follows:

- ER Input Streams:
    - Chopped spent fuel pins in anode baskets from Element Chopper
    - Salt recycle from TRU/U Product Processing (assume 18 kg-salt/container, 1 container every three days)
    - Salt recycle from Metal Waste Processing (assume 12 kg-salt/container, 1 container every three days)
    - Oxidant Feed – LiCl/KCl eutectic salt containing UCl_3 and chloride impurities from Oxidant Production (assume 265 kg-salt/container, 1 container/day)

- ER Output Streams:
    - Undissolved cladding and noble metal fission products in anode basket to Metal Waste Processing (4 anode baskets/day, assume 4 kg-metal/anode basket, and 1 kg-salt/anode basket) (Assuming 70 kg U/yr is sent to Metal Waste processing, implies that each 4 kg-metal/anode basket includes roughly 73 g U.)
    - Uranium metal product and adhered salt containing dissolved U/TRU/FP to Uranium Product Processing (Assume 2 U-product containers/day, assume 15 kg-HM/U-product container, and 3 kg-salt/U-product container)
    - U/TRU/FP dissolved in salt to TRU/U Extraction and TRU/U Product Processing (Assume 1 U/TRU/FP-salt container/day, assume 260 kg-salt/container)

- o Uranium metal product and adhered salt containing dissolved U/TRU/FP to Oxidant Production (Assume 2 U-product containers/day, assume 10 kg-HM/U-product/U-product container, and 2 kg-salt/U-product container)

During normal ER operation, effectively all of the plutonium and other TRU dissolve in the salt phase. The salt from the ER (containing dissolved U/TRU/FP) is assumed to be 1.3 wt% U, 4 wt% Pu, 6.25 wt% all TRU. Four anode baskets are removed each day assumed to contain ~160g of Pu in adhered salt (i.e., 40 g Pu/anode basket). Four cathodes are also removed and are assumed to contain ~200g of Pu in adhered salt (i.e., 50 g Pu/cathode). Assume the U-metal product and adhered salt are collected from the cathodes in U-product collectors by scraping the material off the cathodes. The U-product collectors are used to transfer U-metal from the ER to the UP or OP units.

Uranium Product Processing

Operational Characteristics:
No. of units: 1 Uranium Product Processor (UP)
Batch size: Assume 90 kg-HM with 18 kg-salt per UP container
Batches per period: 1 every 3 days
Products per period: Assume twenty-four 3.7 kg HM U-product ingots every three days
Process time: 24 hours (1/3 of batch in residence for ~72 hours, 1/3 in residence for ~48 hours, 1/3 in residence for ~24 hours)

The U Product Processing unit operation accepts uranium metal from the electro-refiner and melts it to form metal ingots. Adhering salt is recovered by vacuum distillation and sent to the TRU/U Extraction.

Assumed inputs and outputs are summarized as follows.

- UP Input Streams:
  - o Uranium metal product and adhered salt containing dissolved U/TRU/FP from Electro-refiner (Assume 2 U-product containers/day, 15 kg-HM/U-product container, and 3 kg-salt/U-product container) (salt content is the same as ER salt content)

- UP Output Streams:
  - o Salt containing dissolved U/TRU/FP recycled to Electro-refiner (Assume 1 container/3 days, 18 kg-salt/container) (salt content is the same as ER salt content)
  - o Uranium metal ingot products to the Product Prep (Assume 1 container/3 days, twenty-four 3.7 kg-HM U-product ingots/container)

During normal operations it is assumed that the U metal ingots contain very small amounts of TRU (0.025 wt% all TRU or 0.02 wt% Pu). The salt from the ER (containing dissolved U/TRU/FP) is assumed to contain 1.3 wt% U, 4 wt% Pu, 6.25 wt% U + TRU.

TRU/U Extraction and TRU/U Product Processing

Operational Characteristics:
No. of units: 2 stages in 1 TRU/U Extraction unit, 2 TRU/U Product Processors (TP)
TRU/U Extraction Input Batch size: Assume 260 kg-salt/container (each extraction stage)
Input Batches per period: 1 container/day

TRU/U Product Processing Output Batch per period: 1 container/day/unit, i.e., 2 containers/day (Assume two 4 kg HM TRU/U-product ingots/container, i.e., 16 kg-HM TRU/U-product/day)

The purpose of TRU/U Extraction is to recover TRU/U from the salt stream from ER by electrochemical reduction. The salt received from ER contains dissolved TRU, reactive fission products and small amounts of cladding and uranium. The TRU/U metal product is fed to the Product Prep unit. Salt recycled from the TRU Extraction unit is sent to Oxidant Production, with excess recovered salt being sent to Ceramic Waste Processing. The spent salt from the TRU/U Extraction and TRU/U Product Processing steps is assumed to be completely depleted of U and to contain only 0.107 wt% TRU. A chlorine off-gas stream also results.

Assumed inputs and outputs are summarized as follows:

- Input Streams:
  - Salt containing dissolved U/TRU/FP from Electro-refiner (assume 1 container/day, 260 kg-salt/container) (assume HM content of salt: 6.25 wt% U + TRU, 1.3 wt% U, 4 wt% Pu)
- Output Streams:
  - TRU/U metal product to Product Prep (1 container/TP unit/day, or 2 containers/day, assume two 4 kg-HM TRU/U-product ingots/container)
  - Chlorine off-gas
  - TRU salt to Oxidant Production (assume 1 container/day and 220 kg-spent salt/container) (Assume HM content of spent salt: 0.107 wt% all TRU, 0.09 wt% is Pu. Assume there is no uranium remaining in the spent salt. All the U is extracted.)
  - Spent salt to Ceramic Waste Processing (assume 1 container/day, 20 kg-spent salt/container, and 0.107 wt% all TRU, or 0.09 wt% Pu). This results from assuming 98% of all TRU is extracted from the salt. It is assumed then, that ~21 g TRU/day is transferred to Ceramic Waste processing, or roughly, 5 kg TRU/yr to Ceramic Waste.

Adhering salt is removed by vacuum distillation and recycled. The salt being processed contains significant amounts of Pu. Moreover, by design the TRU is separated from the fission products during this step. Each TRU Extraction container has 260 kg salt and 10 kg Pu. After the first stage, it is assumed that 100% of the U and 86% of the TRU is extracted from the salt. After the second stage it is assumed that 86% of the remaining TRU in the salt is extracted. This equates to a combined TRU extraction of 98%.

Product Prep

In the Product Prep unit, metal product from UP and TRU/U Product Processing are melted above 1200 ºC to serve as feed for fuel fabrication. Assume that injection casting will be the basis for fabricating new fuel pin slugs. Metal ingots are melted, mixed, and cast into TRU/U metal pins. In the injection casting step, U ingots, TRU/U ingots, and external source U ingots and TRU ingots are loaded into a crucible, which is then placed into an injection casting furnace. The material is heated until molten and the furnace is pressurized to drive the molten material up into an evacuated tube, where the metal freezes in the mold. The castings are removed from the molds and sheared to length to produce fuel pins or slugs. The slugs are inspected for correct weights and dimensions.

Assumed inputs and outputs are summarized as follows:

- PP Input Streams:
  - U metal product from U Product Processing (1 container/3 days, twenty-four 3.7 kg-HM U-product ingots/container)
  - TRU/U metal product from TRU/U Product Processing (2 containers/day, two 4 kg-HM TRU/U-product ingots/container)
  - External source U metal (1 container/day, 3.17 kg-U ingots/container)
  - External source TRU metal (1 container/day, 1.35 kg-TRU ingots/container)
- PP Output Streams:
  - TRU/U slugs (308 slugs/day) (There are 2 fuel slugs per fuel pin)

Pin Fabrication

In this step, the cast metal pins are inserted into metal clad. Sodium (often referred to as bond sodium) is used to fill the gap between the TRU/U pin and the clad for better heat transfer. The sodium bonded fuel pins are welded, leak tested, and inspected.

Assumed inputs and outputs are summarized as follows:

- PF Input Streams:
  - TRU/U metal slugs (308 TRU/U slugs/day)
  - Metal cladding material (zirconium and bond sodium)
- PF Output Streams:
  - TRU/U clad pins (154 fuel pins/day)
  - Reject cladding, sodium
  - Reject clad pins

Assembly

In this step clad pins are assembled into fuel assemblies. This step is carried out in the air filled shipping/receiving cell.
Assumed inputs and outputs are summarized as follows:

- Assembly Input Streams:
  - TRU/U clad pins (154 fuel pins/day)
  - Assembly hardware
- Assembly Output Streams:
  - New fuel assemblies (~4 assemblies/week, or ~1.75 days/assembly)
  - Reject assembly hardware
  - Damaged clad pins

A.3. Baseline ESFR Material Flows and Main Assumptions

The ESFR study has to be limited to the time and resources available. System boundaries have to be established, as long as they provide sufficient scope for testing the methodology (e.g., sufficient for defining meaningful pathways for both PR and PP).

Even with limited boundaries, the number of possible pathways increases to an unmanageable size if transient periods (startup) for the site are considered. For example, startup will require fresh fuel that by necessity either (1) needs to be fabricated elsewhere or (2) fabricated at the site with LWR spent fuel. The latter option would require large amounts of material to be processed and the fuel cycle facility starting up several years before the reactors do[7]. This could result in additional pathways for diversion of fuel during site construction. A full assessment should consider all these scenarios. However, for the purpose of the ESFR development study to test the viability of the methodology, additional assumptions are needed to limit the scope of work. These additional assumptions are hereafter highlighted.

Assumption 1:

The system elements are defined as:

- ESFR site: reactors plus fuel cycle facility, transfer areas and fuel (LWR, ESFR recycled and fresh) storage
- External source of LWR spent fuel

Assumption 2:

In the ESFR system definition, the site is assumed to be operating at steady state for material flows.

Assumption 3:

The initial core loads, and the initial reloads are assumed to be brought from outside rather than fabricated in the on-site fabrication facility[8].

Assumption 4:

The transportation of the initial cores or the initial reloads will not be considered in the pathway analysis. Thus, the flows of materials (Figure A.15 and Figure A.16) are provided for a site that is already working in equilibrium.

The operating characteristics of the reactor are typical for sodium-cooled reactors. Table A.2 provides typical values for a reactor core with these characteristics. The numbers have been rounded off for simplicity for the purpose of the ESFR study.

Assumption 5:

The assemblies discharged form the reactor are placed in the in vessel storage basket, where they are maintained for a cycle (approximately 11 months) for cooling. With the reactor in operation, the spent fuel assemblies are removed from the basket and transferred to the fuel cycle facility (with a stop at the wash station).

[7] Note: See Attachment 1.A, Estimate 1, contributed by Jor Shan Choi, LLNL, for a calculation of the times needed to process LWR (PWR) spent fuel elements to provide the first charge and the necessary reloads.
[8] Note: See Attachment 1.B, Estimate 2, contributed by G. Cojazzi and G. Renda, JRC-Ispra, with estimates for possible different scenarios for arrival of initial reloads on site.

Table A.2. Baseline ESFR Core and Discharge Characteristics.

Nominal Electric Power	300 MW_e
Thermal Power	800 MW_{th}
Fuel cycle length	365 days
Capacity factor	85%
Number of fuel batches	3
Fuel residence time	930 days
Average discharge BU	80 MWd/kg, 8.4%
Conversion ratio	0.8
TRU conversion ratio	0.64
TRU consumption ratio	80 kg/yr
Total Assemblies	102
Enrichment zones	2 (60 assemblies high enrichment ~27% TRU; 42 assemblies low enrichment ~22% TRU)
Pins per assembly	271
Fuel composition	Metallic U-TRU-Zr
Heavy Metal per assembly	88 kg HM
Core loading	8970 kg HM
Discharge per year	34 driver assemblies (14 low enrichment zone; 20 high enrichment zone)

Assumption 6:

As assemblies are being unloaded from the storage basket, new fuel is placed in the basket in preparation for refueling. 34 assemblies are discharged per year. For ESFR the maximum capacity of the basket is assumed to be 34 fresh fuel and 6 additional locations.

Assumption 7:

It is assumed that the refueling outages for the 4 reactors do not occur simultaneously (in fact, they always occur more than 34 days apart). The assemblies are always transferred inside the transfer cask. See diagrams for transfer paths (Figures A.8 – A.10).

The discharged assemblies are washed (while remaining inside the transfer cask) at the wash station in the staging/washing area and then transferred to the spent fuel storage area at the fuel cycle facility, where they are removed from the transfer cask.

Assumption 8:

In a period of 1 day 1 spent fuel assembly is removed from the basket, washed, and transferred to the spent fuel storage area. During the same period a new assembly has been loaded into the in vessel storage basket. One washing station is sufficient, for the whole site needs; moreover there is no need to store assemblies out of the basket before washing.

Assumption 9:

The material flow of Figure A.15 assumes that the spent fuel is in storage for 1 year and in process (electrorefining and fabrication) for another year.

Assumption 10:

Concerning PWR Spent Fuel feed for the fuel cycle facility, about 3 shipments per year are assumed, each one implying the transfer of 21 spent fuel elements (standard transportation cask). Moreover, it is assumed an Up to 3 months worth of storage for operational purposes. PWR casks arrive on the site and are stored temporarily in the LWR storage building next to the Fuel Cycle Facility. From there, they are taken and processed (on average one PWR spent fuel assembly every six days) in the Fuel Cycle Facility (See Figure A.16).

Assumption 11:

Fuel cycle facility inventory: in the physics calculations it has typically been assumed that the fuel takes 1 year in process, this includes storage of recycled assemblies before they are inserted in the reactor: to this aim it has been assumed that recycled assemblies are stored in the storage cell.

Assumption 12:

In the ESFR design Reflectors are made of steel. They are replaced (inner rows) about every 4 years.

Assumption 13:

It is assumed for the purposes of the ESFR study that 99% of the TRU material is recovered in the fuel cycle facility. On these assumptions, ~88 kg of TRU per year are needed for make up for each reactor.

Assumption 14:

A parking area is needed for the LWR spent fuel assembly containers/casks

Assumption 15:

A Uranium storage area/bldg is needed for excess U recovered from LWR spent fuel assemblies (~25 MT/yr)

Assumption 16:

A parking area for the containers/casks that will transport the excess U off site.

Assumption 17:

The neutron flux in the in-vessel storage basket is expected to be very low. Assume a peak (i.e., in the central core region) fast flux of $\sim 1 \times 10^{15}$ as a good estimate. This fast flux component represents ~65% of the total flux (i.e., fast flux plus thermal flux). This would suggest that the peak total flux in the central core region is $\sim 1.54 \times 10^{15}$.

Furthermore, assuming that the peak-to-average *flux* ratio is similar to, but slightly higher than, the peak-to-average *power* ratio, which is ~1.6, say ~1.7 for the flux ratio, then the *average total flux* in the core would be $\sim 9.0 \times 10^{14}$.

The AFR-300 is based on the major successful design features of the EBR-II. Experience with EBR-II indicated a low neutron flux outside the core. The core barrel design includes neutron shielding around the outside of the core barrel. Material in the in-vessel storage basket can not be irradiated to produce substantial quantities of WG-Pu in a reasonable time for purposes of proliferation. Very little activation occurs in the in-vessel storage basket. So Pu-239 production would be minimal and it would take extremely long to accumulate.

Assumption 18:

On-load re-fueling operation is not technically possible. To remove fuel from the core, the core cover needs to be raised. The reactor can not operate with the core cover in the raised position. Modifying the reactor to allow on-load refueling would be a major modification. It would require reactor shutdown and draining of the sodium, followed by a complete re-design of the system.

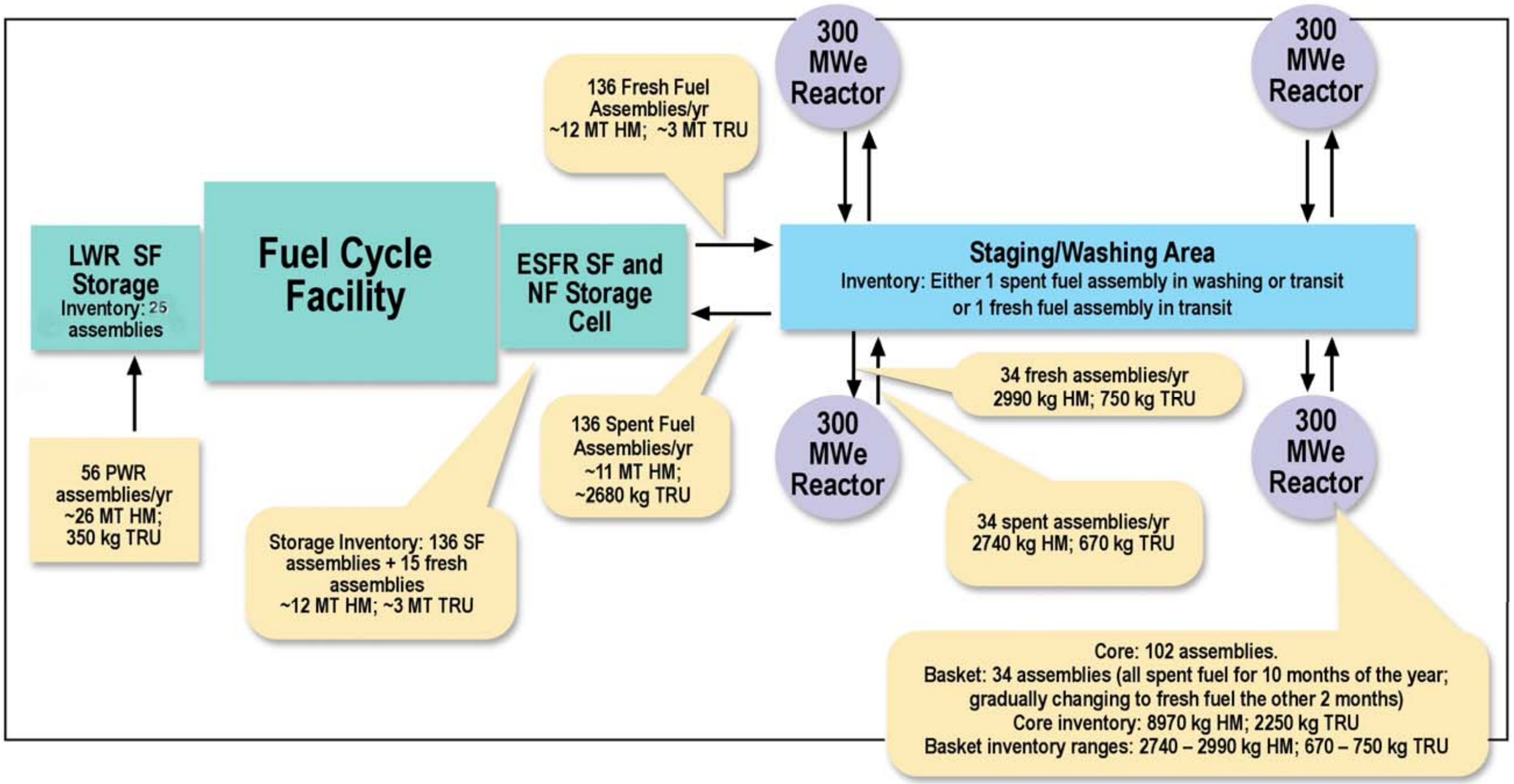


Figure A.15. Annual Material Flows in the Baseline ESFR site.

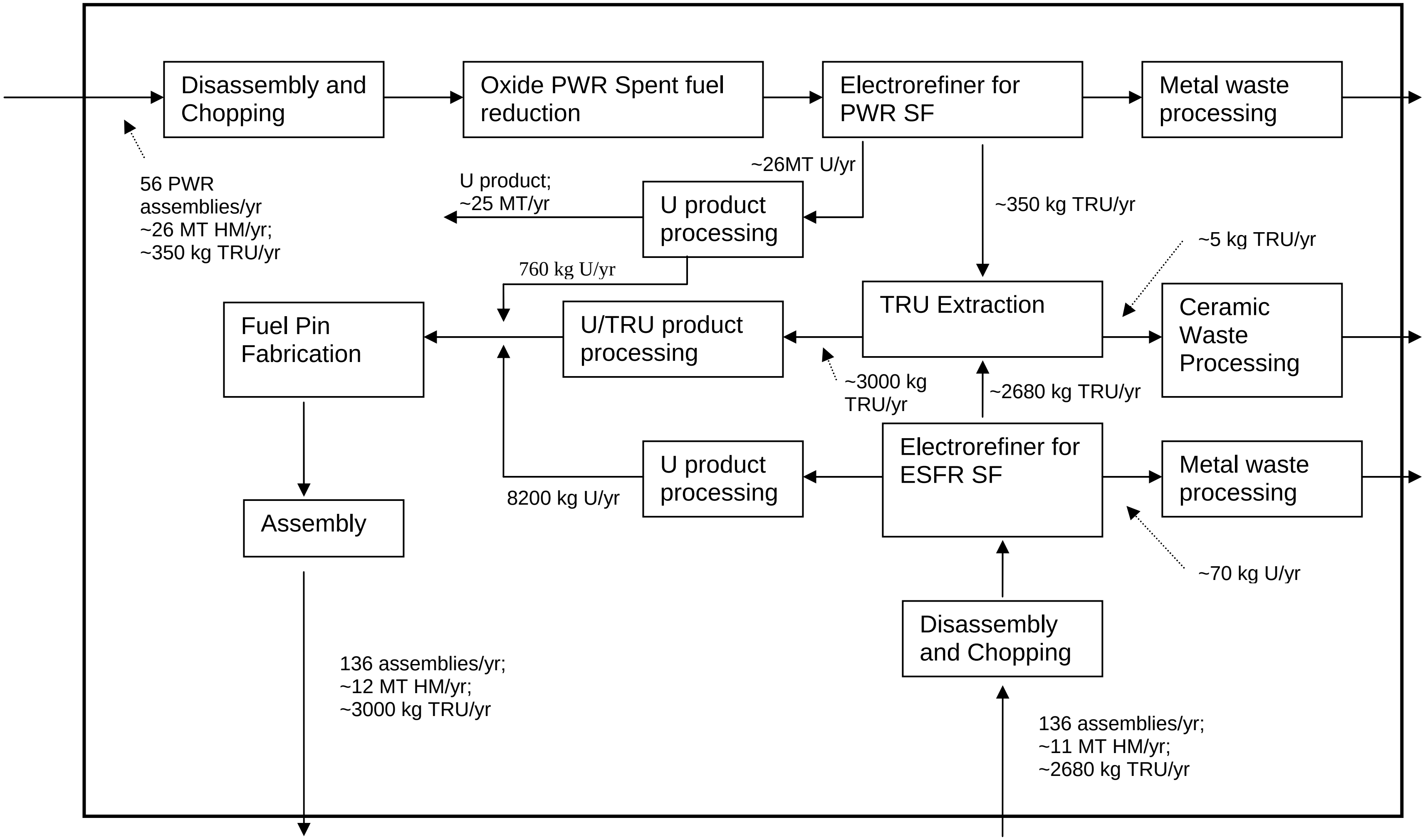


Figure A.16. Annual Material Flows in the Fuel Cycle Facility for the Baseline ESFR System

A.4. ESFR Reactor Transient Behavior

Note: Extracted from material in reference [A.3].

The assumptions for the approach to safety embodied in the Example Sodium-Cooled Fast Reactor (ESFR) are based on those studied for previous metal-fueled sodium-cooled fast reactors [A.3]. The basic attributes are: large margins between the operating conditions and physical safety limits; reliance on passive processes to hold power production in balance with heat removal; and totally passive removal of decay heat, independent of the equipment and structures in the balance-of-plant. Should equipment in the balance-of-plant or control system fail, ESFRs will passively regulate their own power so as to remain undamaged for all such initiators, even in the anticipated transient without scram (ATWS) scenarios. Decay heat is removed through a heat-transport path that operates at ambient pressure, is contained along with the reactor core in a double-walled top-entry tank of coolant, has large thermal inertia, is driven by natural convection, is completely independent of the balance-of-plant equipment, and is always in operation.

Even for accidents of extremely low probability, lying far beyond the design basis, the ESFR system has an inherent, designed-in response that prevents release of radioactivity. Processes that are innate consequences of the materials and geometry cause dispersal of fuel early enough to avoid prompt criticality and its accompanying energy release, and assure subcriticality and coolability inside an intact reactor vessel should significant fuel pin failures cause an accumulation of debris.

The operating margin between normal coolant outlet temperature and the sodium boiling point is nearly 400°C. The high thermal conductivity of the metal keeps the operating temperature of the fuel low—less than 200°C above the coolant—consequently with low stored energy at operating conditions. The low fuel temperature also means a low Doppler reactivity to be overcome upon startup-—yielding a reduced control-reactivity requirement, and, more importantly, a reduced positive feedback to be overcome by negative passive feedbacks when the power is passively reduced in an unprotected accident.

Analysis specific to the AFR-300 has not been carried out, but the response is expected to be typical of similar designs based on pool type configuration and metal fuel. Passive self-regulation of power without core damage in response to unprotected loss of flow (LOF), unprotected single rod run out transient overpower (TOP) and unprotected loss of heat sink (LOHS) accident initiators is illustrated here for the case of a 3500 MWt core design.

Unprotected Loss of Flow

The unprotected loss of flow (ULOF) accident is assumed to be initiated by a total loss of offsite power. The pumps in the primary and intermediate loops coast down according to their inertial characteristics. The resulting reactivity transient and its components are depicted in Figure A.17. As the rate of flow through the core drops, the outlet temperature of the coolant rises, inducing reactivity feedback effects. The net effect of the passive feedbacks-none of which exceeds a few tens of cents-is negative.

Power reduction is retarded because of delayed-neutron holdback, preventing the power decrease from keeping up with the flow rundown and causing the core outlet temperature to overshoot temporarily while delayed neutrons die away. After the delayed neutrons come into equilibrium, the end state is in thermal balance at a few percent of nominal power with natural circulation cooling.

Unprotected Control-Rod-Runout Transient Overpower Accident

The hypothetical incident of a transient overpower accident (UTOP) involving unprotected run out of a single control rod has been assessed for a 3500 MWt, the assumptions being that no control rods scram and all pumps continue to run [A.3]. The run out reactivity increase causes the power to increase raising fuel and coolant temperatures. The course of the accident is determined by the amount of reactivity added to the core, the reactivity feedbacks caused by the higher temperatures, and the capability of the balance-of-plant to absorb the power generated. When rod motion terminates, removal and production of heat are in balance, with the entire system at a higher temperature than under normal operating conditions. The ESFR assumption is for a core design that limits the burnup reactivity swing, so that control rod worths are small and the single rod run out event is benign, resulting in an equilibrium condition at temperatures only moderately higher than those at normal operating conditions.

Unprotected Loss of Heat Sink

The unprotected loss of heat sink accident (ULOHS) assumes the loss of heat removal capability through the steam generators with failure to scram. Pumps in the primary and intermediate loops are assumed to continue operating. The reactor power changes only in response to the thermal reactivity feedbacks. The transient ends when the system temperatures have increased to the point where the fission process is shut down, and the decay-heat generation rate is within the capacity of the decay heat removal system. Figure A.18 contains reactivity and coolant histories for this transient. The temperatures reached are well below the sodium boiling temperature, and substantially below the temperature which could cause long-term damage to full element integrity.

Until low-power equilibrium is established, the decay heat greatly exceeds the heat removal capability of the decay heat removal system, so the entire contents of the primary tank heat up until the thermal feedback reduces reactivity, causing the power to decline, eventually reaching an equilibrium where the power matches the capability of the passive decay heat removal system. The time to reach the equilibrium is determined by the heat capacity of the sodium and structures in the primary tank. The higher the heat capacity, the longer it is before heat removal must take over to keep temperatures from becoming unacceptable, and the smaller the needed capacity, of the decay heat removal system.

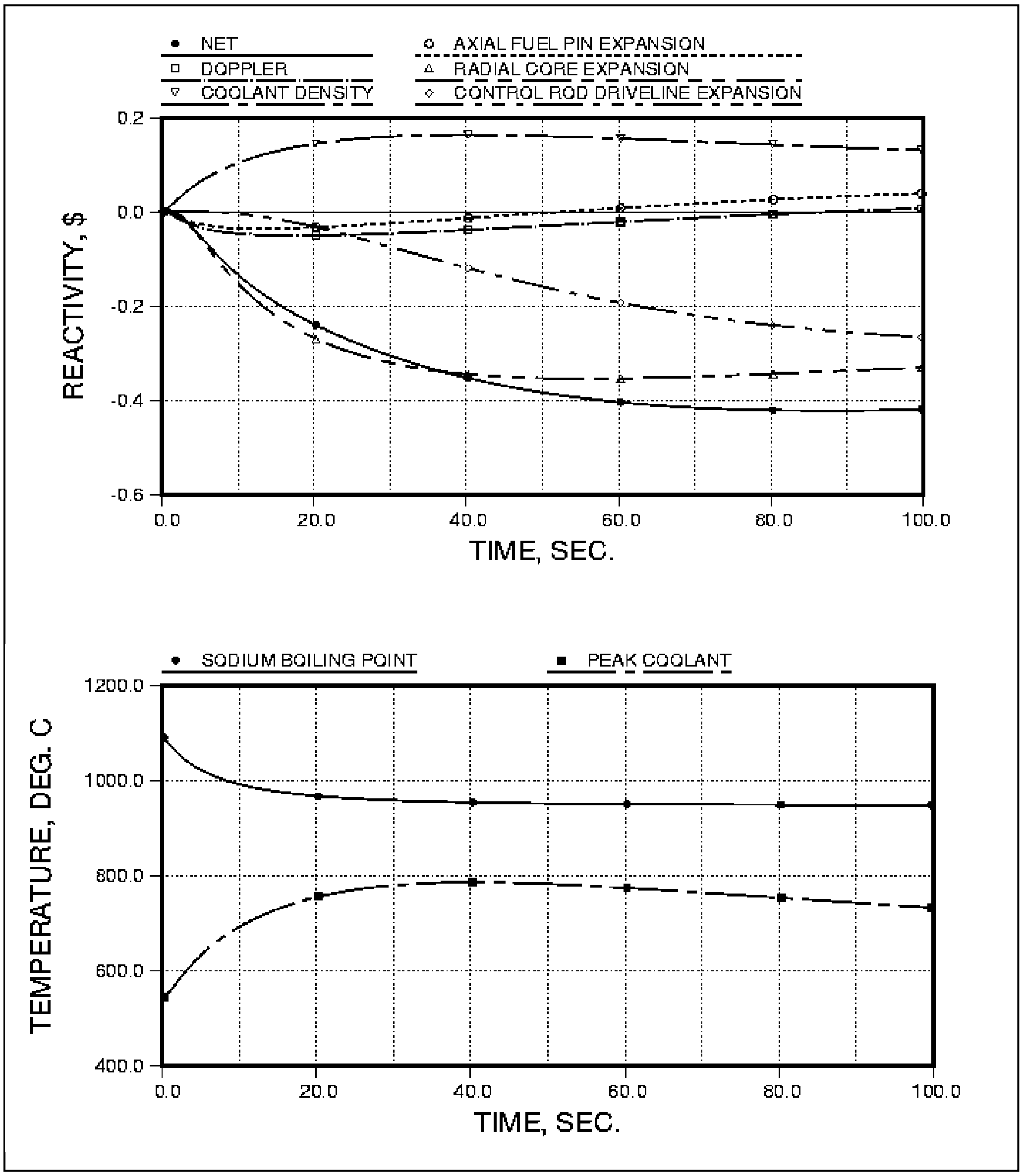


Figure A.17. Reactivity and Temperature History for a ULOF Transient – 3500 MWe Plant, Reference [A.3].

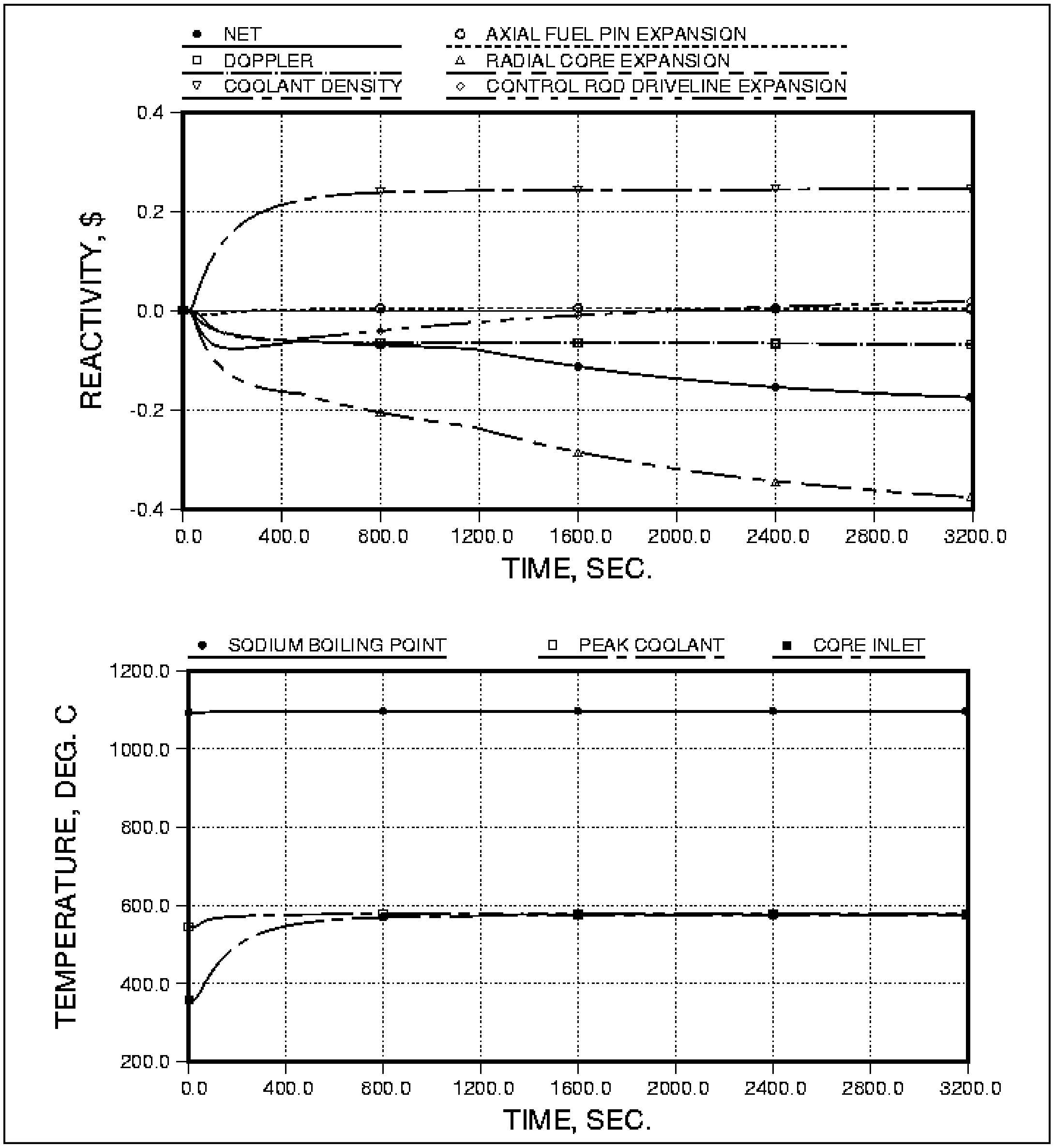


Figure A.18. Reactivity and Temperature History for a ULOHS Transient – 3500 MWe Plant, Reference [A.3].

A.5. ESFR Design Variations

The baseline ESFR system examined in Year 1 of the Case Study consisted of four 800 MW_{th} sodium-cooled fast reactors operating in a net actinide burning mode with a TRU CR=0.64. Researchers at Argonne National Laboratory have conducted design sensitivity studies of a 1000 MW_{th} sodium-cooled fast reactor to achieve low and high conversion ratios [A.10]. The PR&PP Working Group made use of the data available from those studies for its Case Study design variations. Therefore, the design variations considered consist of a system of four 1000 MW_{th} sodium-cooled fast reactors and comprise the following four cases:

- Design Variation 0 (DV0): TRU CR = 0.73
- Design Variation 1 (DV1): TRU CR = 0.22
- Design Variation 2 (DV2): TRU CR = 1.00
- Design Variation 3 (DV3): TRU CR = 1.12

DV0 (TRU CR = 0.73) is a net actinide burner comparable to the baseline ESFR system (TRU CR = 0.64), but with a larger core. In DV1, a deep actinide burner core case is examined. DV2 is the case of a break-even core without any fertile blanket assemblies, whereas DV3 is a breeder core case with both radial and internal fertile blanket assemblies. Further information for each of the design variation cases is provided in the following figures and tables.

Table A.3. Key Core Performance Parameters of Various Conversion Ratio Cores

	Baseline ESFR	Design Variation 0	Design Variation 1	Design Variation 2	Design Variation 3
	800 MW_{th} TRU CR = 0.64	Reference 1000 MW_{th} TRU CR = 0.73	1000 MW_{th} TRU CR = 0.22	1000 MW_{th} TRU CR = 1.00 No Blankets	1000 MW_{th} TRU CR = 1.12 Radial & Internal Blankets
Nominal Electric Power, MW_e	300	350	350	350	350
Thermal Power, MW_{th}	800	1000	1000	1000	1000
Fuel composition (core / blanket)	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-20Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / U-Zr
Cycle length, months	12	12	6.6	12	12
Capacity factor	85%	90%	90%	90%	90%
Number of assemblies (core / blanket)	102 / -	180 / -	180 / -	180 / -	108 / 72
Number of batches (core / internal / radial)	3 / - / -	4 / - / -	8 / - / -	4 / - / -	4 / 4 / 6
Residence time, days (core / internal / radial)	930/ - / -	1300/ - / -	1445/ - / -	1300/ - / -	1300/1300/1970
Pins per assembly (core / internal / radial)	271 / - / -	271 / - / -	324 / - / -	271 / - / -	271 / 127 / 127
Structural pins per assembly	0	0	7	0	0
Average TRU enrichment, %	24.9	22.1	58.5	14.4	19.3
Fissile/TRU conversion ratio	0.8 / 0.64	0.84 / 0.73	0.55 / 0.22	0.99 / 1.00	1.07 / 1.12
HM/TRU inventory at BOEC, MT	9.0 / 2.2	13.2 / 2.9	6.9 / 3.9	18.5 / 2.8	20.5 / 2.5
Discharge burnup (ave/peak), MWd/kg	80 / ?	93 / 138	185 / 278	67 / 103	92 /146
TRU consumption rate, kg/year	80	81.6	241.3	-1.2 (gain)	-33.2 (gain)

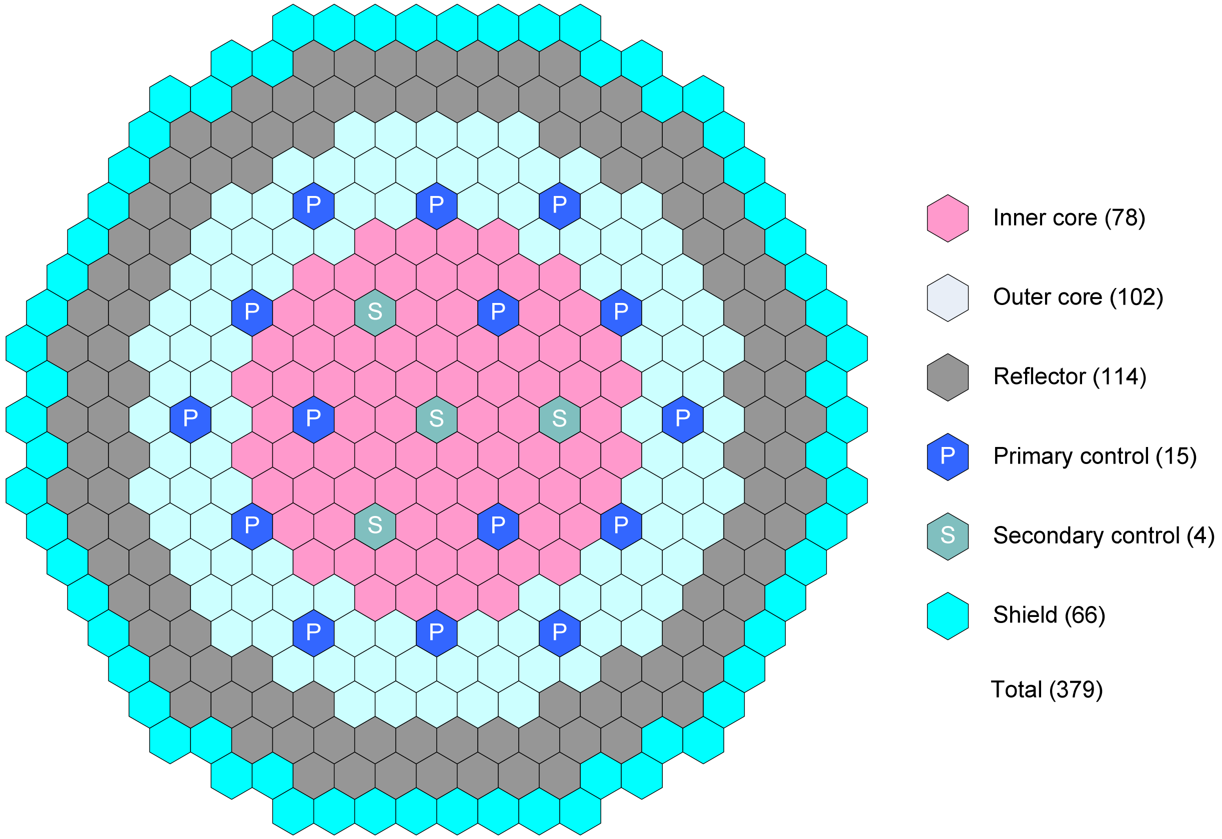


Figure A.19. 1000 MW_{th} Reactor Radial Core Layout
Design Variation 0: TRU CR=0.73;
Design Variation 1: TRU CR=0.22;
Design Variation 2: TRU CR=1.00

Table A.4. Assembly Design Parameters of Design Variation 0: Reference 1000 MW_{th} Core

	Fuel	Reflector	Shield	Control
Assembly data				
- Number of pins	271	91	19	7
- Assembly pitch, cm	16.142	16.142	16.142	16.142
- Inter-assembly gap, cm	0.432	0.432	0.432	0.432
- Duct outside flat-to flat distance, cm	15.710	15.710	15.710	15.710
- Duct thickness, cm	0.394	0.394	0.394	0.394
- Gap between duct and interior duct, cm	-	-	-	0.400
- Interior duct thickness, cm	-	-	-	0.394
- Interior duct inside flat-to-flat distance, cm	-	-	-	13.334
- Overall duct height, cm	477.52	477.52	477.52	477.52
Pin data				
- Pin material and type	U-TRU-Zr	HT9	a) B_4C	b) B_4C
- Bond material	Na	-	He	He
- Overall pin length, cm	332.7	332.7	332.7	86.3
- Active core height, cm	81.3	-	-	-
- Pellet smeared density, % TD	75.0	-	81.0	85.0
- Pellet diameter, cm	0.557	1.541	2.553	4.193
- Cladding material	HT9	-	HT9	HT9
- Clad outer diameter, cm	0.755	-	3.337	4.688
- Pin pitch-to-diameter ratio	1.180	1.001	1.001	1.029
- Cladding thickness, cm	0.056	-	0.250	0.070
- Wire wrap diameter, cm	0.131	-	-	0.133
Volume fraction at fabrication, %				
- Fuel or Absorber	29.2	-	43.1	42.8
- Bond	9.8	-	10.1	7.6
- Structure	25.7	84.5	29.7	20.8
- Coolant	35.3	15.5	17.1	28.8

a) Natural boron. b) Natural and 60% enriched boron for 4^{th} and 7^{th} row primary control assemblies, respectively.

Table A.5. Driver Assembly Design Parameters of Varied Conversion Ratio Cores

	Design Variation 0	Design Variation 1	Design Variation 2	Design Variation 3
	Reference 1000 MW_{th} TRU CR = 0.73	1000 MW_{th} TRU CR = 0.22	1000 MW_{th} TRU CR = 1.00 No Blankets	1000 MW_{th} TRU CR = 1.12 Radial & Internal Blankets
Assembly data				
- Number of pins	271	324	271	
- Structural pins	0	7	0	
- Spacer type	Wire wrap	Grid	Wire wrap	
- Assembly pitch, cm	16.142	16.142	16.142	
- Inter-assembly gap, cm	0.432	0.432	0.432	
- Duct material	HT9	HT9	HT9	
- Duct thickness, cm	0.394	0.394	0.394	
- Overall duct length, cm	477.5	477.5	477.5	
Pin data				
- Pin material and type	U-TRU-10Zr	U-TRU-20Zr	U-TRU-10Zr	
- Bond material	Na	Na	Na	
- Fuel pin diameter, mm	7.55	5.50	8.08	
- Overall pin length, cm	332.74	387.4	332.74	
- Active core height, cm	81.3	109.2	96.5	
- Pellet smeared density, % TD	75.0	75.0	75.0	
- Pellet diameter, cm	0.557	0.372		
- Cladding material	HT9	HT9	HT9	
- Clad outer diameter, cm	0.755	0.550	0.808	
- Pin pitch-to-diameter ratio	1.180	1.590	1.106	
- Cladding thickness, cm	0.056	0.060	0.056	
- Wire wrap diameter, cm	0.131	-	0.081	
Volume fraction at cold, %				
- Fuel or Absorber	29.2	15.6	34.3	
- Bond	9.8	5.7	11.4	
- Structure	25.7	22.8	25.8	
- Coolant	35.3	55.9	28.5	

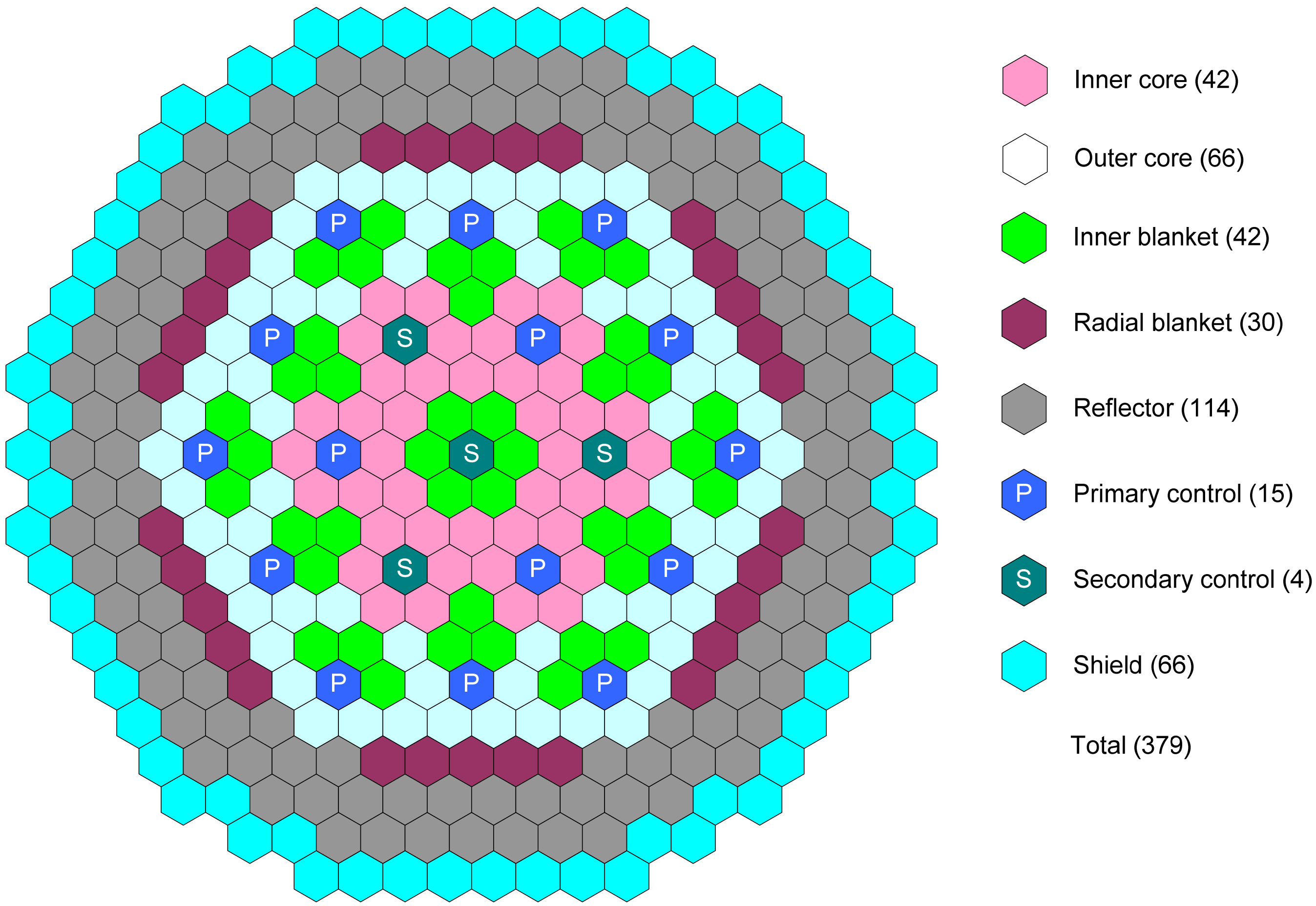


Figure A.20. 1000 MW$_{th}$ Reactor Radial Core Layout Design Variation 3: TRU CR=1.12

Table A.6. Design Variation 0 Core Mass Flow

Design Variation 0: TRU Conversion Ratio = 0.73
12 month cycle length

1/3 Core Mass Flow (kg)

	Inner Core Mass					Outer Core Mass				
Cycle	0	1	2	3	4	0	1	2	3	4
U-234	0.00	0.02	0.03	0.04	0.05	0.00	0.03	0.05	0.08	0.10
U-235	0.81	0.64	0.50	0.40	0.32	0.97	0.83	0.71	0.61	0.52
U-236	0.00	0.04	0.06	0.08	0.10	0.00	0.03	0.06	0.08	0.10
U-238	402.60	390.50	378.76	367.39	356.37	482.92	472.93	463.17	453.62	444.27
NP237	1.09	0.97	0.87	0.79	0.72	2.91	2.63	2.38	2.17	1.98
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	2.49	2.29	2.18	2.07	1.96	4.30	4.15	4.11	4.07	4.00
PU239	43.11	43.40	43.35	43.03	42.52	77.11	73.48	70.26	67.37	64.77
PU240	26.92	26.20	25.55	24.95	24.39	46.31	45.36	44.39	43.41	42.42
PU241	3.81	3.77	3.72	3.65	3.58	7.97	7.54	7.18	6.87	6.59
PU242	6.14	5.92	5.71	5.51	5.32	11.01	10.75	10.49	10.22	9.96
AM241	2.55	2.24	1.99	1.78	1.60	5.33	4.96	4.63	4.33	4.06
AM242	0.19	0.19	0.18	0.17	0.16	0.29	0.32	0.33	0.33	0.33
AM243	2.07	2.02	1.96	1.91	1.85	3.51	3.46	3.41	3.36	3.31
CM242	0.01	0.14	0.15	0.14	0.13	0.02	0.20	0.23	0.22	0.21
CM243	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
CM244	1.30	1.33	1.34	1.34	1.34	2.06	2.08	2.09	2.09	2.09
CM245	0.35	0.34	0.34	0.34	0.34	0.53	0.52	0.52	0.52	0.52
CM246	0.19	0.19	0.19	0.19	0.19	0.28	0.28	0.28	0.28	0.28
Total mass(kg)	493.63	480.19	466.89	453.80	440.95	645.52	629.57	614.30	599.64	585.52
TRU mass (kg)	90.22	89.00	87.53	85.88	84.11	161.63	155.75	150.31	145.25	140.53

	1/3 core	full core		
Charge HM (kg)	4383.5	13150.6	Avg. Assembly Charge HM (kg)	73.058894
Discharge HM (kg)	4270.9	12812.6	Avg. Assembly Discharge HM (kg)	71.180987

	1/3 core	full core		
Charge TRU (kg)	965.6	2896.7	Avg. Assembly Charge TRU (kg)	16.092919
Discharge TRU (kg)	938.4	2815.1	Avg. Assembly Discharge TRU (kg)	15.639328

Table A.7. Design Variation 1 Core Mass Flow

Design Variation 1: TRU Conversion Ratio = 0.22
6.6 month cycle length

1/3 Core Mass Flow (kg)

Inner Core Mass

Cycle	0	1	2	3	4	5	6	7	8
U-234	0.00	0.01	0.02	0.03	0.04	0.05	0.05	0.06	0.07
U-235	0.15	0.13	0.11	0.10	0.09	0.08	0.07	0.06	0.06
U-236	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03
U-238	72.71	71.40	70.12	68.87	67.63	66.42	65.23	64.06	62.92
NP237	1.19	1.07	0.96	0.86	0.78	0.70	0.63	0.57	0.52
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	3.12	2.95	2.84	2.75	2.66	2.57	2.47	2.38	2.28
PU239	16.50	15.62	14.83	14.12	13.48	12.89	12.36	11.87	11.43
PU240	21.60	20.94	20.30	19.67	19.05	18.45	17.87	17.31	16.76
PU241	3.99	3.88	3.77	3.65	3.55	3.44	3.34	3.23	3.14
PU242	8.21	8.02	7.83	7.65	7.46	7.28	7.10	6.93	6.76
AM241	2.81	2.58	2.37	2.19	2.02	1.87	1.74	1.62	1.51
AM242	0.21	0.21	0.21	0.20	0.20	0.19	0.18	0.17	0.16
AM243	2.87	2.82	2.77	2.73	2.68	2.63	2.58	2.53	2.48
CM242	0.02	0.13	0.17	0.18	0.18	0.17	0.16	0.15	0.14
CM243	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
CM244	2.08	2.10	2.12	2.13	2.14	2.14	2.14	2.14	2.13
CM245	0.60	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
CM246	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Total mass(kg)	136.41	132.83	129.40	126.10	122.92	119.86	116.91	114.06	111.31
TRU mass (kg)	63.56	61.29	59.13	57.09	55.15	53.30	51.54	49.85	48.25

Outer Core Mass

Cycle	0	1	2	3	4	5	6	7	8
U-234	0.00	0.02	0.04	0.05	0.07	0.08	0.10	0.11	0.12
U-235	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.07	0.06
U-236	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03
U-238	57.75	57.00	56.26	55.52	54.80	54.09	53.38	52.69	52.01
NP237	3.32	3.07	2.83	2.62	2.42	2.24	2.08	1.92	1.78
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	4.90	4.79	4.75	4.73	4.70	4.67	4.62	4.55	4.48
PU239	39.28	36.38	33.75	31.37	29.20	27.23	25.43	23.80	22.31
PU240	36.78	36.06	35.32	34.57	33.81	33.04	32.27	31.49	30.73
PU241	8.37	7.95	7.57	7.23	6.93	6.64	6.39	6.15	5.93
PU242	13.29	13.08	12.87	12.66	12.44	12.22	12.00	11.78	11.57
AM241	5.77	5.48	5.20	4.94	4.69	4.46	4.25	4.04	3.85
AM242	0.28	0.31	0.32	0.34	0.34	0.34	0.34	0.34	0.33
AM243	4.33	4.30	4.26	4.22	4.18	4.13	4.09	4.05	4.00
CM242	0.02	0.19	0.26	0.28	0.28	0.27	0.26	0.25	0.24
CM243	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
CM244	2.89	2.90	2.91	2.92	2.92	2.92	2.92	2.92	2.91
CM245	0.80	0.79	0.79	0.79	0.79	0.79	0.78	0.78	0.78
CM246	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Total mass(kg)	178.39	172.90	167.71	162.79	158.13	153.69	149.47	145.44	141.59
TRU mass (kg)	120.52	115.77	111.31	107.12	103.16	99.43	95.89	92.55	89.37

	1/3 core	full core		
Charge HM (kg)	2287.0	6861.0	Avg. Assembly Charge HM (kg)	38.116606
Discharge HM (kg)	2225.1	6675.3	Avg. Assembly Discharge HM (kg)	37.085008

	1/3 core	full core		
Charge TRU (kg)	1296.6	3889.9	Avg. Assembly Charge TRU (kg)	21.610809
Discharge TRU (kg)	1250.2	3750.6	Avg. Assembly Discharge TRU (kg)	20.836602

Table A.8. Design Variation 2 Core Mass Flow

Design Variation 2: TRU Conversion Ratio = 1.00
12 month cycle length

1/3 Core Mass Flow (kg)

	Inner Core Mass					Outer Core Mass				
Cycle	0	1	2	3	4	0	1	2	3	4
U-234	0.00	0.01	0.01	0.02	0.02	0.00	0.01	0.02	0.03	0.04
U-235	1.21	0.98	0.80	0.65	0.54	1.50	1.31	1.15	1.00	0.88
U-236	0.00	0.05	0.09	0.11	0.13	0.00	0.04	0.08	0.11	0.14
U-238	603.71	587.88	572.47	557.49	542.90	749.95	736.82	723.95	711.31	698.91
NP237	0.47	0.48	0.48	0.49	0.49	0.84	0.83	0.82	0.81	0.80
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	0.93	0.89	0.89	0.89	0.89	1.67	1.62	1.61	1.61	1.61
PU239	51.99	54.63	56.44	57.59	58.22	93.14	91.60	90.09	88.60	87.13
PU240	21.81	21.86	21.98	22.14	22.31	39.08	39.01	38.91	38.79	38.64
PU241	2.52	2.62	2.71	2.77	2.83	4.51	4.59	4.65	4.70	4.73
PU242	1.85	1.85	1.85	1.86	1.86	3.31	3.30	3.30	3.30	3.30
AM241	1.28	1.18	1.10	1.04	0.99	2.30	2.23	2.18	2.13	2.09
AM242	0.09	0.09	0.09	0.09	0.09	0.16	0.16	0.16	0.16	0.16
AM243	0.52	0.52	0.52	0.52	0.52	0.93	0.93	0.93	0.93	0.93
CM242	0.01	0.06	0.07	0.07	0.07	0.01	0.08	0.09	0.09	0.09
CM243	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
CM244	0.29	0.30	0.30	0.31	0.32	0.51	0.52	0.52	0.53	0.53
CM245	0.07	0.07	0.07	0.08	0.08	0.13	0.13	0.13	0.13	0.13
CM246	0.04	0.04	0.04	0.04	0.04	0.07	0.07	0.07	0.07	0.07
Total mass (kg)	686.78	673.51	659.92	646.15	632.28	898.12	883.26	868.67	854.31	840.20
TRU mass (kg)	81.86	84.59	86.55	87.88	88.69	146.67	145.08	143.48	141.86	140.23

	1/3 core	full core		
Charge HM (kg)	6170.7	18512.2	Avg. Assembly Charge HM (kg)	102.84556
Discharge HM (kg)	6058.3	18174.9	Avg. Assembly Discharge HM (kg)	100.97188

	1/3 core	full core		
Charge TRU (kg)	918.0	2753.9	Avg. Assembly Charge TRU (kg)	15.299366
Discharge TRU (kg)	918.4	2755.1	Avg. Assembly Discharge TRU (kg)	15.305947

Table A.9. Design Variation 3 Core Mass Flow

Design Variation 3: TRU Conversion Ratio = 1.12

12 month cycle length

1/3 Core Mass Flow (kg)

	Inner Core Mass					Outer Core Mass				
Cycle	0	1	2	3	4	0	1	2	3	4
U-234	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.02	0.02	0.03
U-235	0.63	0.51	0.41	0.33	0.27	0.88	0.76	0.66	0.57	0.50
U-236	0.00	0.03	0.05	0.06	0.07	0.00	0.03	0.05	0.07	0.08
U-238	313.31	304.70	296.33	288.19	280.29	439.77	431.26	422.92	414.76	406.77
NP237	0.33	0.33	0.32	0.32	0.31	0.84	0.81	0.78	0.75	0.72
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	0.47	0.46	0.46	0.47	0.47	1.18	1.15	1.15	1.16	1.16
PU239	38.89	37.95	37.02	36.10	35.18	97.78	90.64	84.41	78.97	74.20
PU240	13.03	13.24	13.40	13.52	13.60	32.76	32.89	32.87	32.72	32.47
PU241	1.40	1.50	1.57	1.63	1.68	3.53	3.63	3.71	3.77	3.81
PU242	0.76	0.78	0.80	0.82	0.83	1.92	1.94	1.96	1.98	2.00
AM241	0.64	0.59	0.55	0.53	0.51	1.60	1.56	1.52	1.50	1.48
AM242	0.04	0.04	0.04	0.04	0.04	0.10	0.11	0.11	0.11	0.11
AM243	0.18	0.19	0.19	0.19	0.20	0.46	0.47	0.47	0.48	0.48
CM242	0.00	0.03	0.04	0.04	0.03	0.01	0.06	0.07	0.07	0.07
CM243	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM244	0.09	0.09	0.10	0.10	0.11	0.23	0.23	0.24	0.24	0.24
CM245	0.02	0.02	0.02	0.02	0.02	0.05	0.05	0.05	0.05	0.06
CM246	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Total mass(kg)	369.81	360.47	351.32	342.38	333.64	581.14	565.61	551.01	537.24	524.20
TRU mass (kg)	55.87	55.23	54.53	53.79	53.00	140.49	133.55	127.36	121.82	116.82

	Internal Blanket Mass					Radial Blanket Mass						
Cycle	0	1	2	3	4	0	1	2	3	4	5	6
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.94	0.78	0.65	0.54	0.45	0.45	0.40	0.36	0.33	0.29	0.26	0.24
U-236	0.00	0.03	0.06	0.08	0.09	0.00	0.01	0.02	0.03	0.03	0.04	0.04
U-238	466.56	456.03	445.75	435.72	425.92	222.17	219.48	216.83	214.21	211.62	209.06	206.53
NP237	0.00	0.04	0.08	0.12	0.14	0.00	0.01	0.02	0.03	0.04	0.04	0.05
PU236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PU238	0.00	0.00	0.01	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.01
PU239	0.00	8.35	15.06	20.43	24.69	0.00	2.27	4.29	6.07	7.65	9.04	10.27
PU240	0.00	0.13	0.48	0.99	1.61	0.00	0.02	0.09	0.20	0.33	0.50	0.68
PU241	0.00	0.00	0.01	0.03	0.07	0.00	0.00	0.00	0.01	0.01	0.02	0.03
PU242	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AM241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AM242	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AM243	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM242	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM243	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM244	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM245	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CM246	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total mass(kg)	467.50	465.37	462.11	457.93	453.01	222.62	222.20	221.61	220.87	219.99	218.98	217.86
TRU mass (kg)	0.00	8.54	15.65	21.59	26.55	0.00	2.31	4.40	6.31	8.04	9.61	11.05

	1/3 core	full core	Avg. Inner Core Assembly	Avg. Outer Core Assmbly	Avg. Internal Blnkt Assmbly	Avg. Radial Blnkt Assmbly
Charge HM (kg)	6838.14	20514.41	101.71	101.59	132.35	132.63
Discharge HM (kg)	6725.79	20177.38	99.13	99.00	131.32	132.15

	1/3 core	full core	Avg. Inner Core Assmbly	Avg. Outer Core Assmbly	Avg. Internal Blnkt Assmbly	Avg. Radial Blnkt Assmbly
Charge TRU (kg)	819.10	2457.30	15.67	23.78	3.27	3.07
Discharge TRU (kg)	830.16	2490.47	15.47	22.71	5.17	4.17

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Attachment 1.A: Flow and Inventory including Startup Period—Estimate 1

Contributed by Jor Shan Choi

The type and # of fuel assemblies handled in the ESFR:

	Per Reactor	Per Plant
Initial core: TRU: Ext. LWR SF feed*: # of PWR SF assemblies**: Reloads (3 batches): TRU: Ext. LWR SF feed: # of PWR SF assemblies:	(PWR SF) 2,250 kg 160.7 Mg 350 2,250 kg 160.7 Mg 350	(PWR SF) 9,000 kg 642.8 Mg 1400 9,000 642.8 Mg 1400
Make-up: TRU: Ext. LWR SF feed: # of PWR SF assemblies:	(PWR SF) 88 kg/y 6.3 Mg/y 14	(PWR SF) 352 kg/y 25.2 Mg/y 56
Recycle (HM Inventory): Mg/plant In core: 36 In-Vessel Storage (in core): 11 Staging/Storage (spent fuel): 22 In-Process: 11 Storage (fresh fuel): 12	(SFR-L2) # of assemblies: 102 34 68 34 34	(SFR-L2) # of assemblies: 408 136 272 136 136

* 50 MWd/kg, 10-year old, assuming ~1.4% TRU content

** ~460 kgHM/Assembly, ~3 times more if these are BWR assemblies

Fuel assembly characteristic:

Per Assembly	PWR	SFR-L2
# of fuel pins	264 (17x17)	271
Total Heavy Metal (HM), kg	~460	88
Quantity of TRU, kg	In spent fuel: ~6.4	In spent fuel: 19.7 In fresh fuel: 22.0
Quantity of Pu	In spent fuel: ~5.5	In spent fuel: 17.6 In fresh fuel: 19.7
Quantity of Pu-239	In spent fuel: ~3.1	In spent fuel: 8.8 In fresh fuel: 9.9

"Lead-time" requirement (in Year) for the Fuel Cycle Facility (FCF, i.e., time to process PWR SF before start-up of SFR-L2 reactor):

Inventory Requirement **FCF Through-put**	**160.7** Mg (Initial core, for 1Reactor)	**321.4** Mg (Initial core + 3 reloads, for 1 Reactor)	**642.8** Mg (Initial core, for 4 reactors)	**1285.6** Mg (Initial core + 3 reloads, for 4 reactors)
11 Mg (HM/y/plant requirement)	15	30	60	120
22 Mg (2 x plant requirements)	7.5	15	30	60
44 Mg (4 x plant requirements)	3.75	7.5	15	30

There are 136 SFR-L2 fuel assemblies handled "In-Process" in the fuel cycle service facility, assuming the facility operates 300 days/y, on average, there will be 1 assembly handled in ~every other day.

Attachment 1.B: Flow and Inventory including Startup Period—Estimate 2

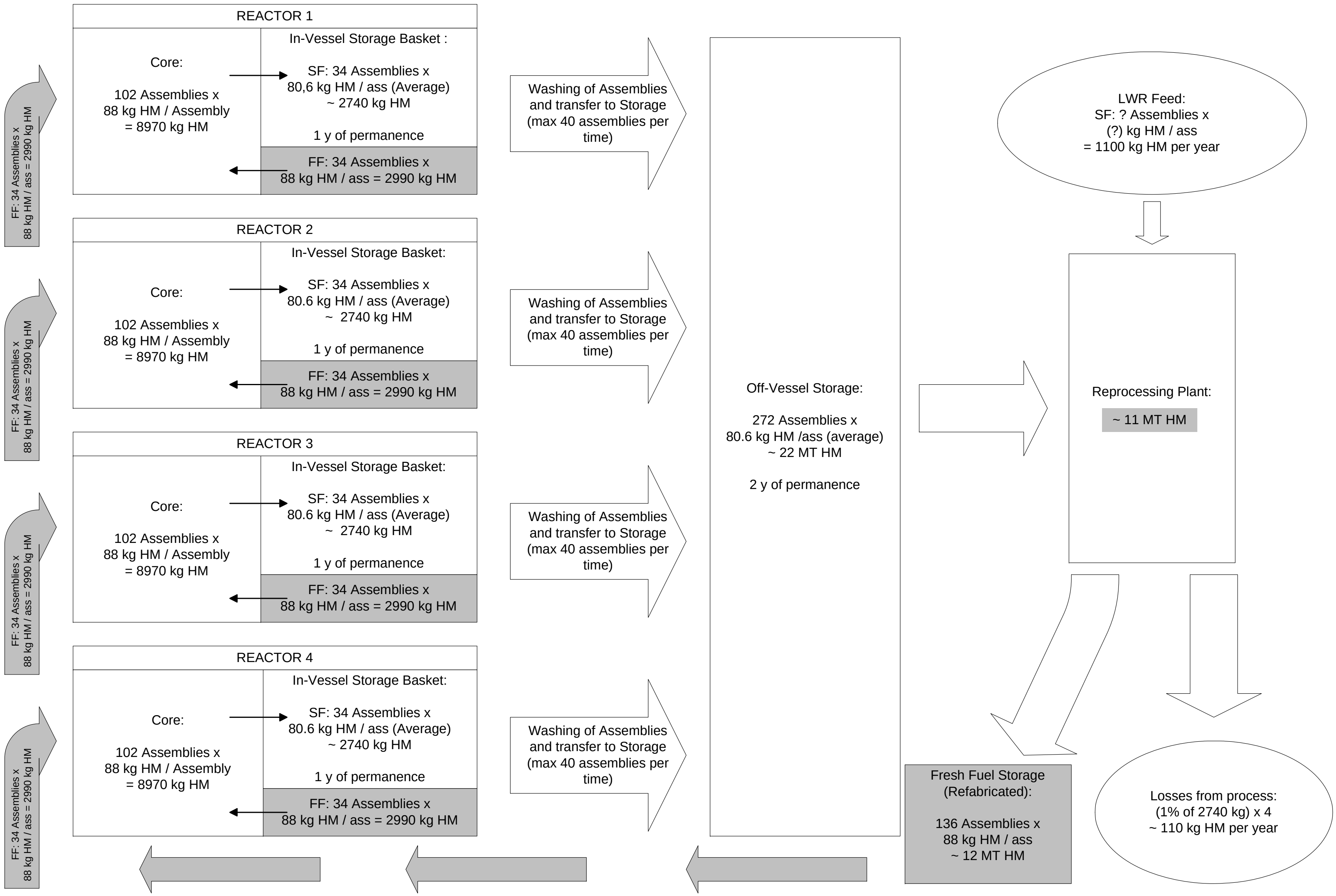
Contributed by Giacomo Cojazzi and Guido Renda

Boxes reported in grey refer to the same material and have to be accounted only once for accountancy purposes.

The picture should report the situation at regime, a situation that should be reached during the fifth year of operation.

In this case it is assumed that, once having reprocessed the SF, the reprocessing facility is emptied and a batch of new fresh fuel has been created and stored or in transit somewhere (boxes in grey).

Year 1) $0 \leq t < 1$ year, Fuel in core (12 MT HM), (+FF fuel stored and waiting for 2 year etc??)
Year 2) 1 year $\leq t < 2$ years, Fuel in core, SF in basket, (+FF fuel from fuel previously stored?? or to be fed)
Year 3) 2 years $\leq t < 3$ years, Fuel in core, SF in basket, SF in storage (11 MT HM)…
Year 4) 3 years $\leq t < 4$ years, Fuel in core, SF in basket, SF in storage (22 MT HM)…
Year 5) 4 years $\leq t < 5$ years, Fuel in core, SF in basket, SF in storage (22 MT HM), SF in reprocessing (11 MT HM) and then in transit and ready for refuelling.


REACTOR 1
Core:
102 Assemblies x
88 kg HM / Assembly
= 8970 kg HM
In-Vessel Storage Basket :
SF: 34 Assemblies x
80,6 kg HM / ass (Average)
~ 2740 kg HM
1 y of permanence
FF: 34 Assemblies x
88 kg HM / ass = 2990 kg HM
FF: 34 Assemblies x
88 kg HM / ass = 2990 kg HM
Washing of Assemblies and transfer to Storage (max 40 assemblies per time)
REACTOR 2
Core:
102 Assemblies x
88 kg HM / Assembly
= 8970 kg HM
In-Vessel Storage Basket:
SF: 34 Assemblies x
80.6 kg HM / ass (Average)
~ 2740 kg HM
1 y of permanence
FF: 34 Assemblies x
88 kg HM / ass = 2990 kg HM
REACTOR 3
REACTOR 4
Off-Vessel Storage:
272 Assemblies x
80.6 kg HM /ass (average)
~ 22 MT HM
2 y of permanence
LWR Feed:
SF: ? Assemblies x
(?) kg HM / ass
= 1100 kg HM per year
Reprocessing Plant:
~ 11 MT HM
Fresh Fuel Storage
(Refabricated):
136 Assemblies x
88 kg HM / ass
~ 12 MT HM
Losses from process:
(1% of 2740 kg) x 4
~ 110 kg HM per year

Appendix B: Safeguarding the ESFR Nuclear Energy System

Contributed by G. Renda, L. Dechamp, G.G.M. Cojazzi, EC JRC-IPSC

The GEN IV Proliferation Resistance and Physical Protection Expert Group is aimed at developing an evaluation methodology to be used to analyze the proliferation resistance and physical protection robustness of future GEN IV nuclear energy systems.

A Development Study has been set up in order to further develop the above-mentioned methodology, and the Expert Group selected the hypothetical ESFR (acronym for Example Sodium Fast Reactor) as the nuclear energy system to be "evaluated" by this study. The development study has been followed by a demonstration study. It has been debated that one of the needs to advance with the case study of the ESFR nuclear energy system is to define some sort of safeguards approach for the ESFR itself. For example, in order to proceed with the estimation of the measures defined by the methodology, a Nuclear Safeguards approach for the system has to be developed. JRC volunteered to contribute to drafting such an approach. Ideally this would involve:

a) Review the available design information for ESFR nuclear energy system;
b) Check documentation for the need of setting up a minimum safeguards approach on the basis of current safeguards goals;
c) Identify relevant safeguards approaches;
d) Define Material Balance Areas (MBAs) and Strategic Points;
e) Define type of measurements and possible equipment types;
f) Propose Inspections schemes.

This note will briefly cover points a) to e), reasoning on the following subjects:

1 Level of detail of the existing documentation describing the ESFR nuclear energy system;
2 Identification of the suitable safeguards requirements for ESFR nuclear energy system;
3 Definition and identification of illustrative MBAs for the ESFR system on the basis of the available documentation;
4 Definition and identification of strategic points inside the ESFR MBAs on the basis of the available documentation;
5 Reasoning on the measures to be adopted at the various strategic points;
6 Preliminary conclusions;
7 Possible way forward.

The work has to be regarded as an exercise connected to PR&PP activity and is in no way to be considered as a guideline for designing a safeguards approach for Sodium Fast Reactors and/or Pyroprocessing facilities.

B.1 Level of detail of the available ESFR System Description & Layout Assumptions

The description of the ESFR nuclear energy system made available to PR&PP group is in [B.1], and therefore will not be repeated here. Additional information used is the one of the various presentations on the ESFR performed during the January 2004 PR&PP meeting in Argonne National Laboratory [e.g. B.2 – B.4] and the material related to the ESFR Demonstration Study [B.5]. As working rule it has been decided to use only information officially released within the PR&PP group. The level of detail of the study will be proportional to the information available (progressive approach). Figure B.1 [B.1] illustrates the ESFR site, and Figure B.2 [B.2] shows the nuclear energy system's layout.

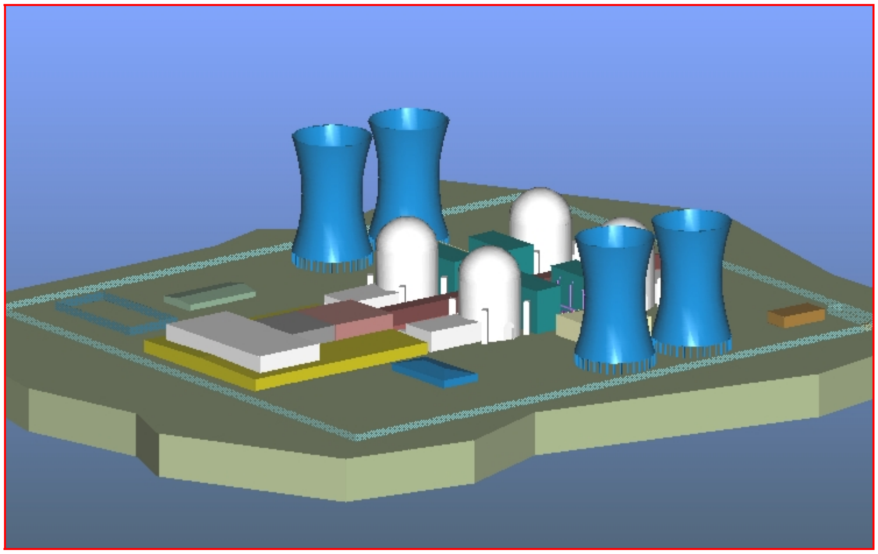


Figure B.1. ESFR Site View [B.1].

The preliminary analysis of the system's layout [B.2] carried out at JRC put in evidence that the provided site map needs some additional entries, and in particular it should comprise:

1. A **parking area** for the containers/casks that will transport the LWR spent fuel assemblies.
2. A **LWR spent fuel storage**, where LWR spent fuel assemblies used as external feed by the reprocessing phase are to be kept. It is assumed an aqueous type of storage, by means of a spent fuel pool;
3. A **Uranium "waste" storage**, where the exceeding U recovered during the reprocessing/fabrication phase is to be stored;
4. A **parking area** for the containers/casks that will transport the Exceeding recovered Uranium out of the site.

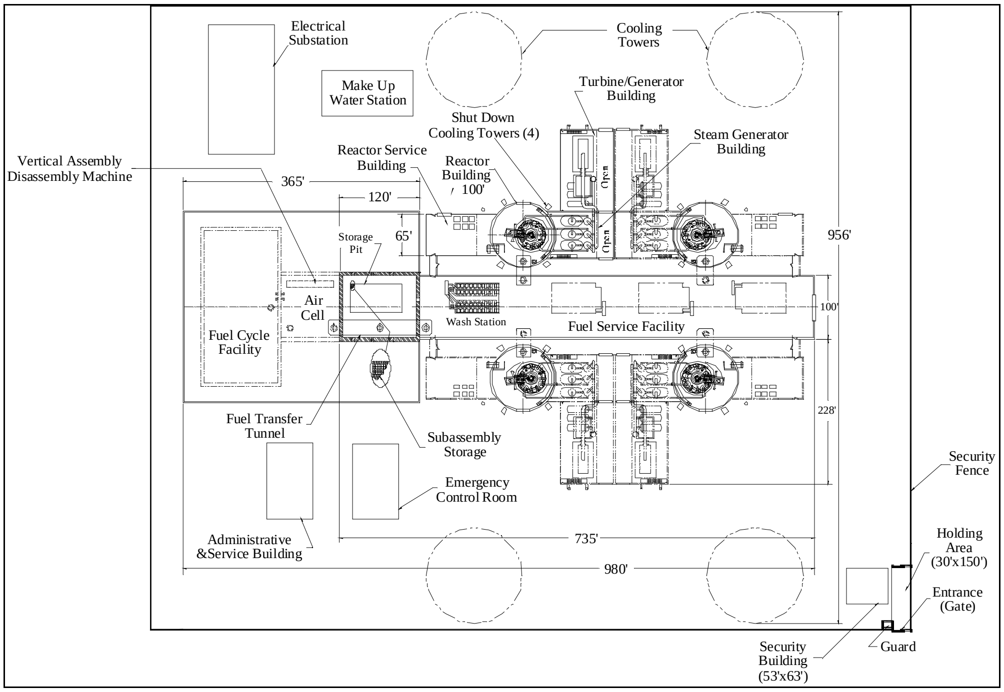


Figure B.2. ESFR Layout [B.2].

In this note the existence of the above-mentioned areas is assumed, moreover:

5 The activities carried out inside the Fuel Cycle Facility (FCF) (Pyroprocessing and refabrication of ESFR fresh fuel) have been analysed in detail during the demonstration case study performed in FY 2006. Since the details of an illustrative safeguards approach for part of the FCF have been described in [B.5], they will be not treated here. The FCF will be considered as a black box, and both the facility description and the proposed safeguards approach will be consistent with the information in [B.5].

6 The **pyroprocessing will produce wastes**, better characterised in [B.5]. For the time being, this note will not treat wastes in detail.

7 The **start up of the ESFR**, together with the production and safeguarding of the initial fuel for loading the four reactors is not considered, as it is also assumed in [B.1].

8 The safeguarding of **the feed of ESFR fresh fuel elements** necessary for the start-up of the reactors or in case of unavailability of the fuel cycle facility, will not be considered.

9 Coherently with Assumption 7 in [B.1], irradiated ESFR assemblies in the storage pit are stored outside their casks. Being a dry storage, it is assumed that the radiation levels inside the storage prevent accessibility.

10 Coherently with Assumption 10 in [B.1], it is foreseen that LWR spent fuel assemblies will be shipped to the ESFR site three times per year, each shipment being made of 21 assemblies.

11 The safeguards measures here identified are supposed to be mainly performed automatically in an unmanned way.

12 ESFR refabricated fuel assemblies don't contain any short-lived fission product.

13 The ESFR reactor units are operated in burner configuration, no fertile targets are loaded in the core in any way.

In order to keep track of items 6-8, as above, two arrows (see figure B.3) on the FCF will indicate the need for ESFR fresh fuel passage and the need for waste passage. The description of the physical transfer passages needed for the above-mentioned operations is considered to be unavailable.

Another issue is related to the type of nuclear safeguards regime to be implemented. The GEN IV nuclear energy systems are supposed to work under Integrated Safeguards, but in order to set up an Integrated Safeguards approach, information about the State's nuclear fuel cycle should be provided. For the purpose of this note, an INFCIRC/153 approach will be implemented.

In order to avoid additional variables to be considered in this analysis, the following exercise considers the State's fuel cycle as coincident with the ESFR nuclear energy system. The needed LWR SF Assemblies are assumed to be imported from abroad.

B.2 Identifying the suitable guidelines for designing the ESFR Safeguards approach

The design of the ESFR reactor is noticeably different from a LWR one. The majority of the commercial power plants currently under IAEA safeguards are LWR reactors, and the approach adopted for safeguarding them is not directly adaptable to the ESFR design. In particular it is possible to identify a number of aspects that make the safeguarding of the ESFR different from the one of a typical LWR:

- Nuclear material is often in difficult to access areas, immerged in liquid sodium inside inert atmosphere areas;
- Radioactivity levels of ESFR (re-fabricated) fresh fuel assemblies are expected to be significantly higher than the one of their LWR counterparts;

Given the above considerations, it is expected that remote controlled handling of fuel assemblies will be widely used.
The fact that almost all the inventory areas result to be not accessible for verification requires implementing a monitoring system that will allow inferring the type and amount of material in these areas from the monitored/recorded material flows.

These issues are common to most existing FBR nuclear reactors, which can therefore provide a sound basis for designing the ESFR safeguards approach at least at the level of the reactor buildings.

In order to define properly the safeguards implementation for a nuclear energy system, the IAEA produced a set of safeguards criteria to be used as guidelines for implementing the necessary measures on each system. The IAEA glossary [B.6] defines the safeguards criteria in the following way:

> *The set of nuclear material verification activities considered by the IAEA as necessary for fulfilling its responsibilities under safeguards agreements. The Criteria are established for each facility type and location outside facilities (LOF), and specify the scope, the normal frequency and the extent of the verification activities required to meet the quantity and the timeliness components of the inspection goal at facilities and LOFs (see Nos 3.23 and 3.24). In addition, the*

> *Criteria specify verification activities to be carried out in a co-ordinated manner across a State. The Criteria are used both for planning the implementation of verification activities and for evaluating the results therefrom.*

The ESFR nuclear energy system is an innovative system for which ad hoc criteria would be needed, but as a first approximation it is possible to conceive it as a system integrating on the same site the following facilities:

- Four Fast reactors units;
- A reprocessing facility;
- A fuel fabrication facility.

Each of the above types of facilities is addressed by existing safeguards criteria, and it would be therefore possible to take advantage of the existing documentation when tackling the problem of safeguarding the ESFR nuclear energy system. Being the reprocessing and fabrication facilities enclosed in the ESFR Fuel Cycle Facility, they will not be taken into consideration in the following paragraphs. As a consequence, the following paragraphs will mostly be inspired by current practice for fast breeder reactors.
Assuming that all the nuclear material in the nuclear energy system is at least under a single C/S system, the following **assumptions** are here made:

I. A **Physical Inventory Verification (PIV)** is to be performed each calendar year. As a general rule, no more than 14 months should pass between two consecutive PIVs;
II. At each **PIV** the following actions should be performed:
   a. Fresh ESFR fuel which is not in a difficult to access area and which is under single C/S should be item counted, verified by serial number identification (if possible) and re-measured with 10% detection probability for gross defects[1]. In case where dual C/S is available, only evaluation of both C/S systems might be performed.
   b. Fresh ESFR fuel which is in a difficult to access area: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems. Inventory is calculated via difference of items entered in the area and items exited from the area.
   c. Irradiated (spent) ESFR fuel which is not in a difficult to access area and which is under single C/S: evaluation of the C/S system should be performed, together with item counting.
   d. Irradiated (spent) ESFR fuel which is in a difficult to access area: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems. Inventory is calculated via difference of items entered in the area and items exited from the area.
   e. ESFR Core fuel: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems.

[1] The definitions of gross, partial and bias defects are given in [B.6]:
(a) Gross defect refers to an item or a batch that has been falsified to the maximum extent possible so that all or most of the declared material is missing.
(b) Partial defect refers to an item or a batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present.
(c) Bias defect refers to an item or a batch that has been slightly falsified so that only a small fraction of the declared amount of material is missing.

f. Uranium solutions, metal or compounds should be verified with medium[2] detection probability for gross, partial and bias defects.
g. LWR spent fuel which is not in a difficult to access area and which is under single C/S should be item counted and C/S system evaluation performed. In case where dual C/S is available, only evaluation of both C/S systems should be performed.
h. LWR spent fuel which is not under C/S should be item counted and verified with medium detection probability for gross defects[3].

III. Any time fresh or irradiated fuel **enters or leaves a difficult to access area**, the following actions should be taken:
a. ESFR Fresh Fuel entering a difficult to access area: measures are taken to confirm operator’s declaration regarding the transfers, and items are verified with high detection probability for gross defect. Since assemblies are transferred inside casks, casks should be item counted and non destructive techniques used for determining the content of the casks.
b. ESFR Irradiated (spent) Fuel leaving a difficult to access area: measures are taken to confirm operator’s declaration regarding the transfers, and items are verified with high detection probability for gross defect. Since assemblies are transferred inside casks, casks should be item counted and non destructive techniques used for determining the content of the casks.
c. Uranium solutions, metal or compounds leaving a difficult to access area: should be verified with medium detection probability for gross, partial and bias defects.
d. LWR Spent fuel entering a difficult to access area should be item counted and their ID verified. In addition verification with high detection probability for gross defects is requested.

IV. Interim inspections should be performed, following the following scheme:
a. Core fuel should be verified four times in each calendar year at quarterly intervals.
b. ESFR Spent and Fresh Fuel should be verified four times per year at quarterly intervals. For items under dual C/S, evaluation of both C/S systems should be performed, for items under single C/S, evaluation of the C/S system and item counting should be performed.
c. Uranium solutions, metal or compounds should be verified one time per year, with medium detection probability for gross, partial and bias defects.
d. LWR spent fuel should be verified four times in each year at quarterly intervals. For items under dual C/S, evaluation of both C/S systems should be performed, for items under single C/S, evaluation of the C/S system and item counting should be performed.

V. LWR assemblies received at the ESFR site are assumed to have been item counted and verified at the shipping facility and shipped under seal. On arrival, the seal is verified and continuity of knowledge is maintained over the contents until unloading is completed;

VI. For **Design Information Verification (DIV)**, one inspection per year is expected, to check for undeclared design variations.

From Assumptions I to V, it is possible to deduce that the safeguards approach will have to rely heavily on containment and surveillance measures. In particular, all areas with low accessibility will have to put under a dual C/S system. Being the inventory areas of

[2] If not differently specified, usual probability values are: 90% for high, 50% for medium and 20% for low.
[3] This is a situation that should not occur during routine operation of the ESFR system.

the facility in low accessibility areas, inventory verification will not be achieved through traditional accounting, but through the verification of the dual C/S system coupled with attribute verification of items entering and exiting the low accessibility area.
Table B.1 presents a résumé of the assumed inspection activities in terms of frequencies of inspections and activities performed.

Table B.1. Inspection activity on the ESFR site.

	Interim Inventory Verification	Physical Inventory Verification
Frequency	One every three months	One per year
Activity	Book audit C/S verification Item counting	Same activity as IIV NDA measurement

Few FBR exist under IAEA safeguards, and even less have a (partially) undisclosed documented description of the implemented safeguards. The measures identified in this exercise for the ESFR reactor buildings are similar to the ones developed for the Japanese Monju [B.7] and Joyo [B.8] nuclear reactors. The differences are mainly due to the differences between the design of the ESFR and the above mentioned plants (mainly with respect to in-vessel -ESFR- vs. ex-vessel storage basket -Monju-).
On the basis of the above assumptions it is possible to proceed in defining the Material Balance Areas (MBAs), the related strategic points (including Key Measuring Points) and the types of measures needed at the various strategic points.

B.3 Material Balance Areas Identification

Material Balance Areas (MBAs) identification is the first step for defining a safeguards approach implementation. The MBA definition given by the IAEA Glossary [B.6] is the following:

An area in or outside of a facility such that:

a) *The quantity of nuclear material in each transfer into or out of each 'material balance area' can be determined; and*
b) *The physical inventory of nuclear material in each 'material balance area' can be determined when necessary, in accordance with specified procedures, in order that the material balance for Agency safeguards purposes can be established.*

The labeling of MBAs is generally made of four characters, and is based on the following taxonomy: AB(B)(n)n, where A is a character related to the State in which the nuclear system is placed, B is a character (or two) identifying the nuclear system, and nn are two numbers (or one, depending on the amount of characters reserved for the system identification) identifying the various MBAs inside the nuclear system. For the ESFR the MBA taxonomy is assumed to be XEnn, X identifying a fictitious State X, E identifying the ESFR nuclear energy system and nn being a progressive number given to the MBAs inside the system.
On the basis of the above definitions, ten MBAs have been currently identified for the ESFR system (see Figure B.3), namely:

- XE(01 to 04): this MBA contains ESFR Reactor 1 to 4, and therefore includes Reactor 1 to 4 core and the related in-vessel storage basket;

- XE05: this MBA contains the ESFR area inside the Fuel Service Facility, and includes the wash station and the related area;
- XE06: this MBA contains the Storage Pit used for storing both ESFR fresh fuel assemblies and ESFR irradiated fuel assemblies;
- XE07: this MBA contains the ESFR Fuel Cycle Facility. This MBA will eventually be divided into smaller MBAs, but since this part of the site has been widely investigated during the slice demo study, In this note the whole facility will be considered as a black box.
- XE08: this MBA contains the exceeding recovered U storage, where the exceeding U recovered from the Fuel Cycle Facility will be kept until removal;
- XE09: this MBA contains the LWR SF storage pool;
- XE10: this MBA contains the LWR SF containers/casks parking area outside the LWR SF storage pool.

Table B.2 illustrates the type of nuclear material contained in each defined MBA and the level of accessibility.

Table B.2. Type of nuclear material contained in each defined MBA, and related level of accessibility.

MBA Label	Description	Type of nuclear material contained	Level of accessibility
XE(01 to 04)	Reactor 1 to 4	Item: ESFR fresh fuel ESFR spent fuel	Low inside primary tank Normal elsewhere
XE05	Fuel service facility	Item: ESFR fresh fuel ESFR spent fuel	Normal
XE06	Storage pit	Item: ESFR fresh fuel ESFR spent fuel	Low
XE07	Fuel cycle facility	Bulk & Item: Not considered	Low[4]
XE08	Exceeding recovered U storage	? Uranium	Normal
XE09	LWR SF storage pool	Item: LWR spent fuel	Normal
XE10	LWR SF containers/casks parking area	Item: LWR spent fuel	Normal

The identification of the ESFR MBAs should be considered as illustrative: at this level what is really important is the identification of the strategic points.

It is worthy to notice how the number of identified MBAs might well be varied without being in need of modifying the identified Strategic points (Section 4). In particular MBAs XE01 to XE06 might be collapsed in a single MBA, since they involve the same kind of material in item form and are contiguous. The same consideration applies to MBAs XE09 and XE10.

[4] In this note, the fuel cycle facility will be considered as a black box, and therefore assumed as having low accessibility.

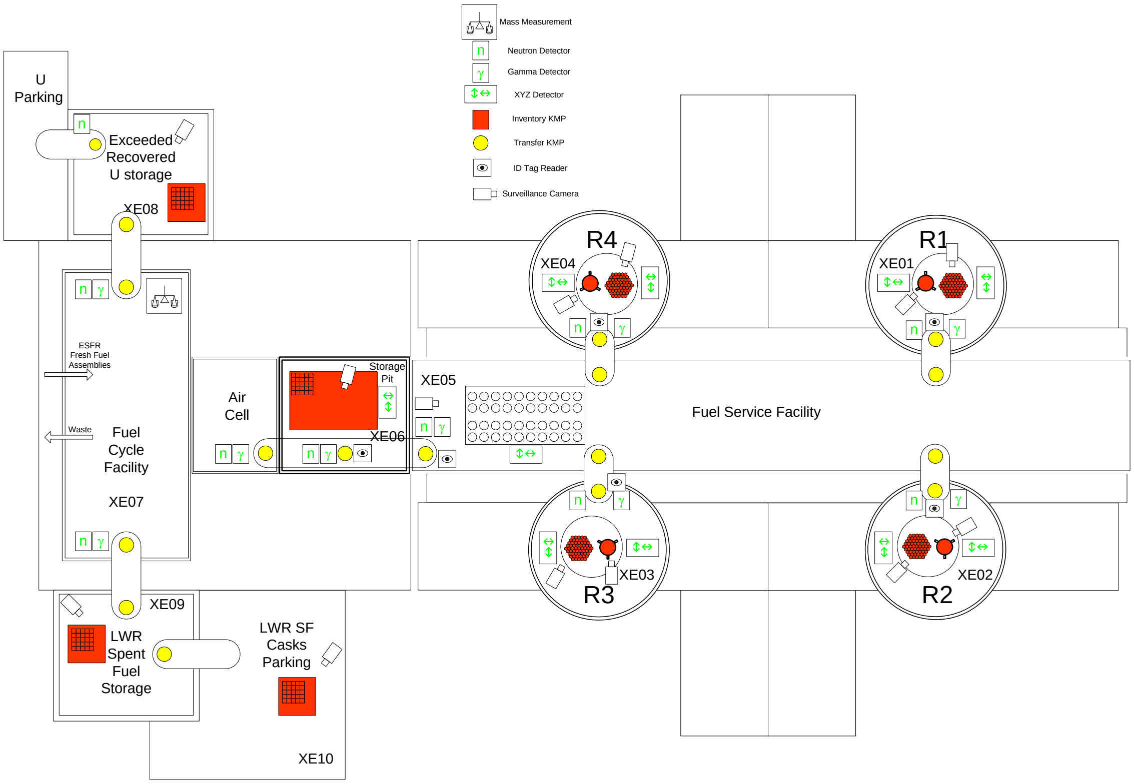


Figure B.3. ESFR Nuclear Energy System MBAs and SPs. Note that: a) Waste and fresh fuel assemblies input to the FCF are not further considered.

B.4 Strategic Points Identification

Inside each MBA, a number of *strategic points* are identified, where the necessary measurements and data fetching can be performed. The IAEA Glossary defines a strategic point as [B.6]:

> *A location selected during examination of design information where, under normal conditions and when combined with the information from all 'strategic points' taken together, the information necessary and sufficient for the implementation of safeguards measures is obtained and verified; a 'strategic point' may include any location where key measurements related to material balance accountancy are made and where containment and surveillance measures are executed.*

A particular type of strategic point is the Key Measurement Point (KMP). The IAEA Glossary defines a KMP as [B.6]:

> *A location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. 'Key measurement points' thus include, but are not limited to, the inputs and outputs (including measured discards) and storages in material balance areas.*

For the labeling of strategic points, the chosen taxonomy foresees six characters, the first four being the name of the MBA inside which the strategic point is located, the fifth one being a "-" symbol, and the final character being a progressive number identifying univocally the strategic point inside the considered MBA: XEnn-m.

XE01

This MBA covers the Reactor 1 core and in-vessel storage basket. In Figure B.4 [B.1] a detail of the equipments for transferring the fuel assemblies in and out of the MBA is shown, and in Figure B.5 a schematic representation of the MBA together with the identified strategic points is offered. From [B.1], it is understood that the refueling is done on a yearly basis: one third of the core is discharged i.e. 34 assemblies and replaced with re-fabricated fuel elements.

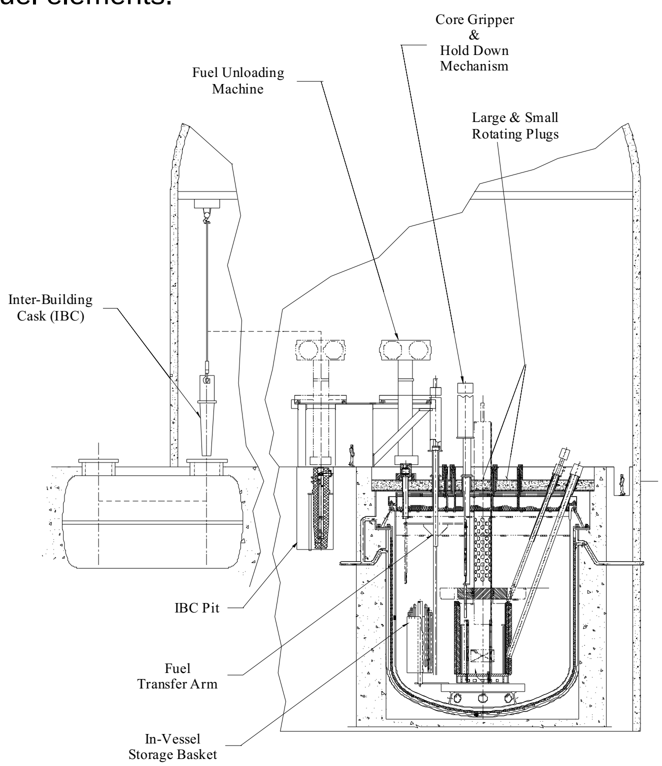


Figure B.4. Detail of the Reactor Core and related fuel transfer system [B.1].

From Figure B.4 it is possible to notice how two different fuel transfer machines operate inside the MBA:

- A fuel unloading machine used for transferring the ESFR fuel assemblies from the inter-building cask pit (IBC pit) to the in-vessel storage basket and vice versa;
- A fuel handling machine positioned inside the primary tank used for transferring the ESFR fuel assemblies from the in-vessel storage basket to the reactor core and vice versa.

In addition, a third transferring crane seems to exist, used for transferring the Inter Building Cask (IBC) from the IBC pit to the transfer area connecting the reactor building with the Fuel Service Facility.

The nuclear material contained inside this MBA (ESFR fresh and spent fuel) is considered to have a low accessibility when inside the primary tank, and normal when outside the primary tank. Three strategic points have been identified; their description and scope are illustrated in Table B.3.

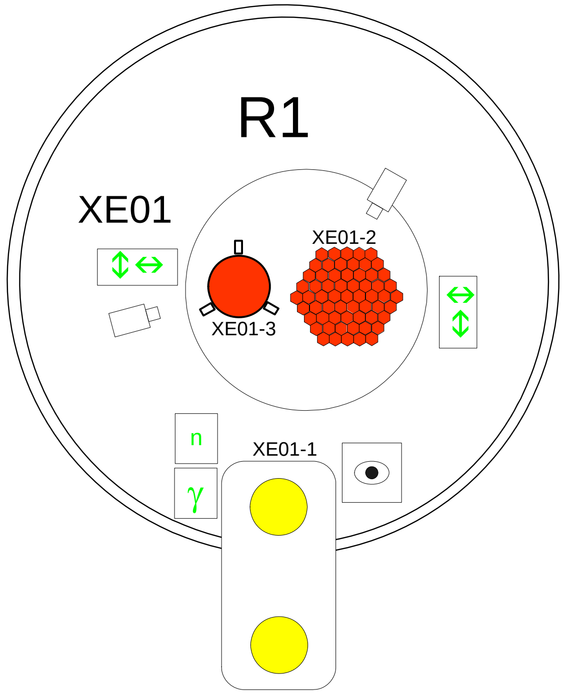


Figure B.5. XE01 MBA.

Table B.3. XE(01 to 04) Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE(01 to 04)-1	Strategic point located at the transfer tunnel connecting Reactor 1 to the Fuel Service Facility. Covers the IBC[5] pit and the transfer tunnel. Physically coincides with XE05-1	a) To keep track of the ESFR fuel elements movements b) To discriminate (dummy, fresh and irradiated) and perform attribute verification on the fuel elements in transit	Ass IIIa. Ass IIIb.	a) Casks are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on casks content.	HRGS[6] coupled with passive neutron measurement. Equipment is located at IBC pit.
XE(01 to 04)-2	Strategic point covering Reactor 1 core. It is an inventory KMP.	a) To keep track of the fuel elements movements b) To maintain continuity of knowledge of the nuclear material inventory	Ass IIe. Ass IVa.	The dual C/S system is evaluated	a) x-y-z positioning system that keeps track of the positioning of the fuel handling machine used for transferring the fuel elements between the core and the in-vessel storage basket b) A set of surveillance cameras monitoring the reactor's rotating plugs, fuel handling machine, and fuel unloading machine.

[5] Inter-Building Cask.
[6] High Resolution Gamma Spectrometry.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE(01 to 04)-3	Strategic point covering Reactor 1 in-vessel storage basket. It is an Inventory KMP.	a) To keep track of the fuel elements movements b) Maintain continuity of knowledge of the nuclear material inventory	Ass IIb. Ass IId. Ass IVb.	The dual C/S system is evaluated	a) x-y-z positioning system keeping track of the positioning of the fuel handling machine used for transferring the fuel elements between the in-vessel storage basket and the Reactor Core. b) x-y-z positioning system keeping track of the positioning of the fuel unloading machine used for transferring the fuel elements between the in-vessel storage basket and the IBC pit. c) A set of surveillance cameras monitoring the reactor's rotating plugs and fuel handling machine, and fuel unloading machine.

XE02, XE03, XE04

Because the four reactor units are identical, the MBAs of the four reactors are defined in the same way of XE01. For this reason, the description of these SPs will be omitted, since are analogous to the ones of XE01. Labeling of the SPs vary accordingly to the previously defined rules.

XE05

This MBA covers the Fuel Service Facility and is illustrated in Figure B.6. Basically it is a transfer area where one fuel element at a time (see Assumption 8 in [B.1]) remains only the period of time necessary to washing them in the wash station. Inside this area, the fuel assembly is kept inside its inter-building cask. Accessibility of this MBA is considered to be normal.

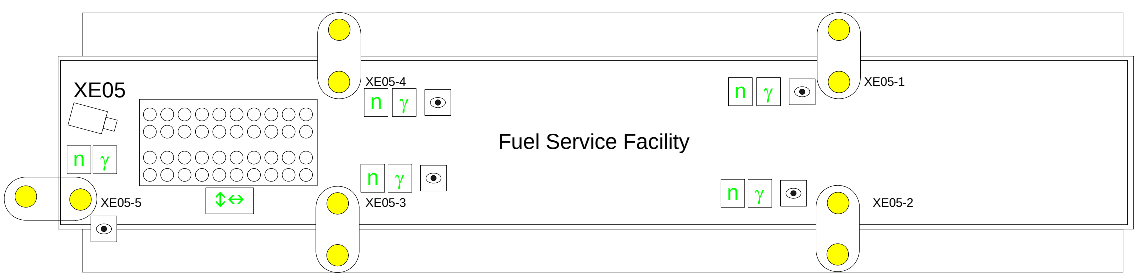


Figure B.6. XE05 MBA.

From Figure B.6 it is possible to see that this MBA has five identified strategic points, described in Table B.4.

Table B.4. XE05 Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE05-(1to4)	Strategic point located at the transfer tunnel connecting Reactor (1to4) to the Fuel Service Facility. Physically coincides with XE(01to04)-1	a) to keep track of the ESFR fuel elements movements b) To discriminate (dummy, fresh and irradiated) and perform attribute verification on the fuel elements in transit	Ass IIIa. Ass IIIb.	a) Casks are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on casks content.	HRGS coupled with passive neutron measurement.
XE05-5	Strategic point located at the transfer tunnel connecting the Fuel Service Facility to the storage pit	a) to keep track of the ESFR fuel elements movements b) To discriminate (dummy, fresh and irradiated) and perform attribute verification on the fuel elements in transit	Ass IIIa. Ass IIIb.	a) Casks are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on casks content. c) The C/S system is evaluated.	a) HRGS coupled with passive neutron measurement. b) A set of cameras monitoring the area.

XE06

This MBA covers the Storage Pit used for both fresh re-fabricated ESFR fuel elements and spent ESFR fuel elements. The MBA is illustrated in Figure B.7. Since the storage is a dry one, and no penetrations for personnel are considered, this MBA is assumed to have low accessibility.

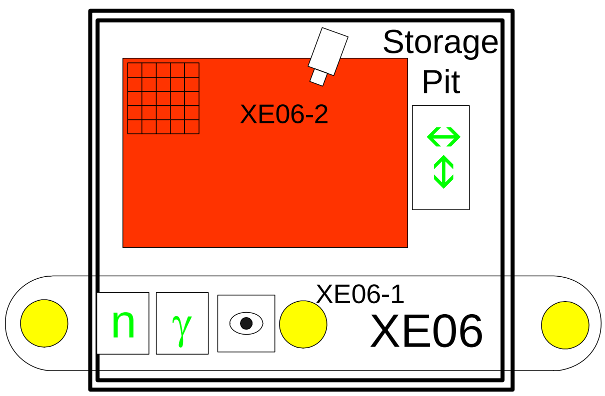


Figure B.7. XE06 MBA.

Currently this MBA has two identified strategic points, described in Table B.5.

Table B.5. XE06 Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE06-1	Strategic point located at the transfer tunnel connecting the storage pit to the Fuel Cycle Facility on one side and to the Fuel Service Facility on the other side	a) To keep track of the ESFR fuel elements movements b) To discriminate (dummy, fresh and irradiated) and perform attribute verification on the fuel elements in transit.	Ass IIIa. Ass IIIb.	a) Casks are counted and their ID tags checked. When removed from the casks, assemblies are counted and their ID tags are checked b) NDA techniques are used to identify / perform attribute verification on the assemblies.	HRGS coupled with passive neutron measurement.
XE06-2	Strategic point located at storage pit. It is a n inventory KMP	a) To allow the fuel elements inventory inside the storage pit. b) To keep track of the fuel elements movements.	Ass IIb. Ass IId. Ass IVb.	a) The dual C/S system is evaluated b) NDA techniques are used to identify / perform attribute verification on assemblies.	a) HRGS coupled with passive neutron measurement b) A x-y-z positioning system that keeps track of the positioning of the assemblies handling machine used for transferring the fuel elements inside and outside the storage pit c) A set of cameras monitoring the storage area.

XE07

This MBA covers the Fuel Cycle Facility and is illustrated in Figure B.8. Due to the lack of detailed information about the processes carried out inside this facility, it will be considered as a black box, and assumed to have a low accessibility.

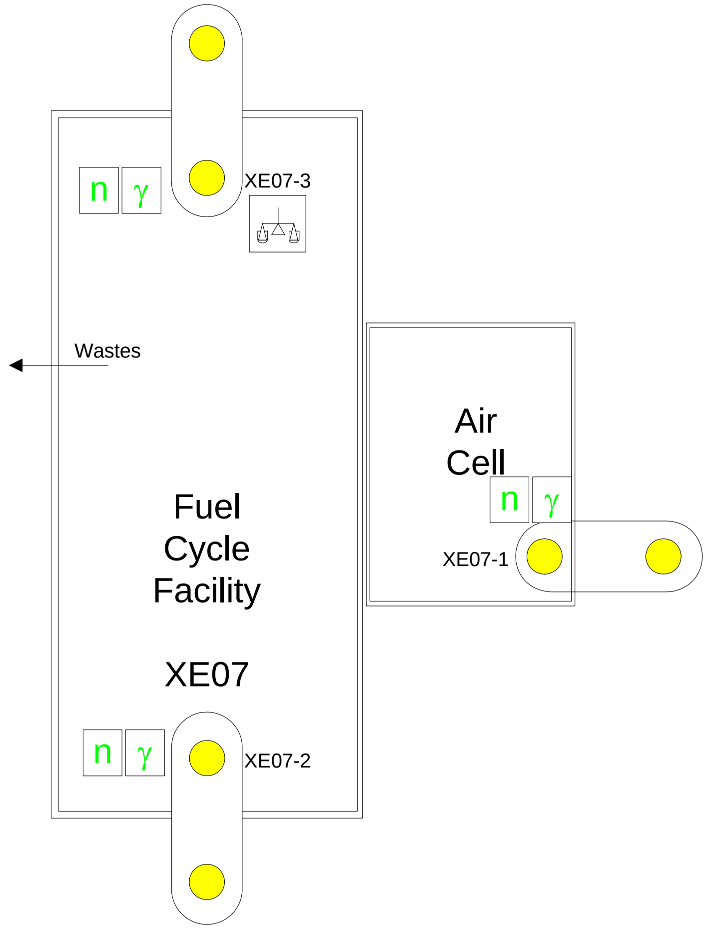


Figure B.8. XE07 MBA[7].

The identified strategic points are described in Table B.6.

[7] Since the figure refers to the baseline system in routine operation, no arrow indicating the possibility of introducing ESFR fresh fuel assemblies fabricated elsewhere is present. This possibility is depicted in Figure B.3.

Table B.6. XE07 Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE07-1	Strategic point located at the transfer tunnel connecting the storage pit to the Fuel Cycle Facility	a) To keep track of the ESFR fuel elements movements b) To discriminate (dummy, fresh and irradiated) and perform attribute verification on the fuel elements in transit.	Ass IIIa Ass IIIb	a) Assemblies are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on assemblies.	HRGS coupled with passive neutron measurement.
XE07-2	Strategic point located at the transfer tunnel connecting the SF LWR storage to the Fuel Cycle Facility Physically coincides with XE09-1	a) To keep track of the SF LWR fuel elements movements b) To perform attribute verification on the fuel elements in transit	Ass IIId	a) Assemblies are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on assemblies.	HRGS coupled with passive neutron measurement.
XE07-3	Strategic point located at the transfer tunnel connecting the Fuel Cycle Facility to the exceeding recovered U storage Physically coincides with XE08-1	a) To keep track of the exceeded U movements b) To characterise the material in transit (enrichment, …)	Ass IIIc	a) U mass is measured U enrichment is measured	Gamma/x/weighing (GXW) [B.9] might be a viable option. A neutron detector is present for detecting illicit diversion of Pu

XE08

This MBA covers the Exceeding Produced U Storage, and is illustrated in Figure B.9. Its accessibility is considered to be normal. No information is currently available on the chemical form of uranium waste, and it is therefore not possible to select suitable measurement techniques.

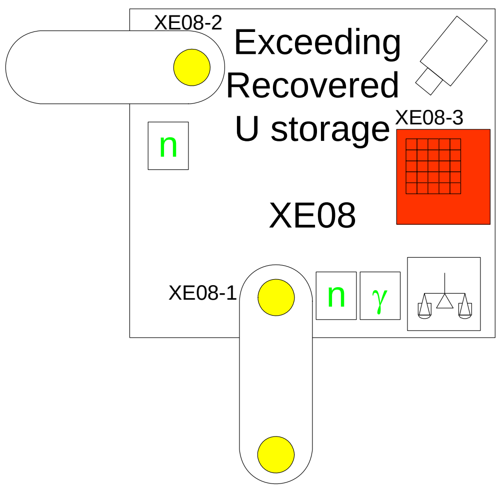


Figure B.9. XE08 MBA.

The three identified strategic points are described in Table B.7.

Table B.7. XE08 Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE08-1	Strategic point located at the transfer tunnel connecting the Fuel Cycle Facility to the exceeding recovered U storage. Physically coincides with XE07-3.	a) To keep track of the exceeded U movements b) To characterise the material in transit (enrichment, …).	Ass IIIc	a) U Mass is measured b) U Enrichment is measured	Gamma/x/weighing (GXW) [B.9] might be a viable option. A neutron detector is present for detecting illicit diversion of Pu
XE08-2	Strategic point located at the connection between the exceeding recovered U storage and the U parking.	To keep track of the exceeded U movements		Check against Pu diversion	A neutron detector is present for detecting illicit diversion of Pu
XE08-3	Strategic point located at the exceeding recovered U storage. It is an inventory KMP	a) To allow the inventory of the exceeding recovered U inside the storage. b) To keep continuity of knowledge concerning the nuclear material inventory	Ass IIf Ass IVc	a) U Mass is measured b) U Enrichment is measured	Gamma/x/weighing (GXW) [B.9] might be a viable option. A set of cameras to monitor the area

XE09

This MBA covers the LWR spent fuel storage, and is illustrated in Figure B.10. Since an aqueous storage is considered, the accessibility of this MBA is assumed to be normal.

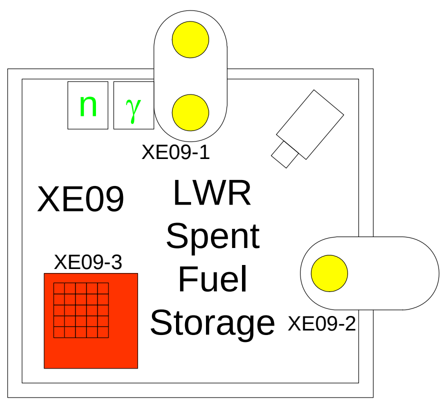


Figure B.10. XE09 MBA.

The three identified strategic points are described in Table B.8.

Table B.8. XE09 Strategic Points.

Strategic Point Label	Description	Scope	Assumption requesting it	Actions taken	Technique adopted
XE09-1	Strategic point located at the transfer tunnel connecting the SF LWR storage to the Fuel Cycle Facility. Physically coincides with XE07-2.	a) To keep track of the SF LWR fuel elements movements b) To perform attribute verification on the fuel elements in transit	Ass IIId.	a) Assemblies are counted and their ID tags checked b) NDA techniques are used to identify / perform attribute verification on assemblies.	HRGS coupled with passive neutron measurement.
XE09-2	Strategic point located at the connection between the SF casks parking and the SF LWR storage.	a) To keep track of the SF LWR fuel elements movements	Ass V	a) Seal is verified b) Continuity of knowledge has to be maintained for all the duration of the unloading /transfer.	A set of cameras monitoring the operations
XE09-3	Strategic point located at the SF LWR storage. It is an inventory KMP.	To allow the inventory of the LWR SF inside the storage.	Ass IIg. Ass IVd.	a) Assemblies are item counted b) The C/S system is evaluated.	A set of cameras monitoring the stored assemblies CVD might be used for qualitative attribute verification of assemblies.

XE10

This MBA represents the SF casks parking where LWR SF assemblies arrive to the ESFR site. Casks are sealed at the beginning of shipment. Currently this MBA has only one identified Strategic point, which is an inventory KMP, labeled XE10-1. Its purpose is to allow the inventory of the LWR SF inside the SF casks. The parking is not to be considered to be a storage for LWR spent fuel assemblies, which are to be stored in the LWR spent fuel pond. No surveillance measures are considered for this area.

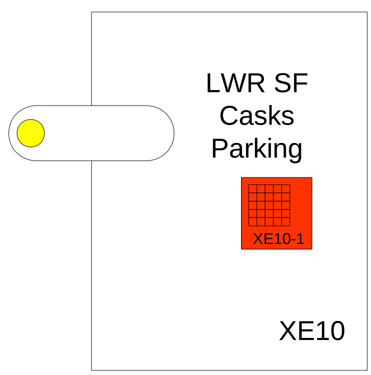


Figure B.11. XE10 MBA.

B.5 Concerning the Techniques adopted at various Strategic Points

A preliminary analysis of the layouts and processes highlighted a *possible* set of measures necessary in order to characterize and to keep track of the nuclear material inside the nuclear energy system.

ESFR Fuel Elements

Some kind of *Identification Tags* are supposed to be available on each ESFR fuel element and inter-building cask.
On the basis of current practice:

- On each fuel assembly (on his head) there is an identification tag, typically a serial number;
- Inter building casks are also identified by a serial number.

In order to be able to monitor continuously the material movement, some *x-y-z positioning systems* able to keep track of the positioning of the various unloading and handling machines inside each reactor building has been considered. This is used for continuity of knowledge purposes, and provides also information about a possible misuse of the system elements where the xyz positioning system is located.
In addition, a set of *measurement techniques for performing attribute verification* on the Fuel elements should be considered. The related measurements are to be performed in order to be able to verify that the declarations concerning the element are compatible with the physical reality.
The motivation for these measurements is to be able to discriminate e.g. between:

- Dummy elements;
- Fresh fuel elements;
- Irradiated fuel elements (MBAs XE01to7, XE09).

The measurements may consist in a High Resolution Gamma spectrometry and passive neutrons counting on the items in transit.

Although the overall safeguards approach is inspired by the safeguarding activities set up for the Japanese Monju fast reactor, the difference in the type of fresh fuel used in the Monju unit from that of the ESFR reactors might raise questions on the possibility to a) discriminate between ESFR fresh and irradiated fuel and b) to be able to characterize them via NDA techniques. In order to have a preliminary answer to these questions, an interview with a NDA senior researcher has been performed, leading to the following outcomes:

a) Possibility to discriminate between ESFR fresh and irradiated fuel via NDA techniques
The information about the ESFR fuel characteristics, plus the assumption of absence of short-lived fission products inside the ESFR fresh fuel led to the conclusion that discrimination between fresh and spent fuel via n-gamma measurements is possible. In particular, the gamma signature of the fresh fuel is expected to be sensibly different from that of the irradiated fuel.

Concerning the passive neutron measurement, it could be used principally as a trigger for the presence of an assembly, because the levels of Cm present in both fresh and irradiated fuel make the discrimination by means of this technique potentially difficult.

b) Possibility to characterize ESFR fresh and irradiated fuel via NDA techniques
Characterization of irradiated fuel via NDA techniques is a hard task, and presents a large amount of difficulties even for LWR irradiated fuel assemblies with more than 10 years cooling time. On these items, rather than a real characterization, attribute verification is generally performed.
Characterization of the ESFR fresh fuel assemblies could be performed inside the Fuel Cycle Facility via DA tests just before the fabrication stage. This analysis, coupled with a measurement of the fresh assembly's n-gamma signature before its loading in the in-vessel storage basket and subsequently in the core for irradiation, could provide a characterization of the fresh fuel assemblies' composition.

Since all assemblies have an ID tag, it is possible to re-measure the assembly's n-gamma signature after the irradiation in reactor and the cooling down period in the in-vessel storage basket. This activity would be performed during the transfer of the assembly from the in-vessel storage basket to the washing/staging machine. By comparing this measurement with the DA characterization and the n-gamma signature of the fresh assembly it is possible to confirm the assembly's declared burn-up. Hence, once the declared burn-up is confirmed, the estimate of the assembly's composition is validated.

Note that each fuel assembly contains more than a significant quantity (in each fuel assembly of spent fuel there are 17.6 kg of Pu -8.8 of Pu 239-).
Inside the primary tank of the reactor buildings an additional surveillance system covering the material inside the core and the in-vessel storage basket has to be set up. This might be common for both KMPs or one per each. This system might be a set of cameras monitoring the primary tank's rotating plugs and the various machines aimed at moving fuel assemblies. The need of this (these) additional surveillance system is foreseen by assumption IIb, IId. and IIe.

LWR Spent Fuel Elements

Some kind of Identification Tags might turn out to be needed on each LWR fuel element.
In order to be able to monitor continuously the material inside the storage area, a surveillance system should be set up. It is assumed that the selected surveillance system consists in a set of cameras monitoring the area.

In addition, a set of measurements for performing attribute verification on the Fuel elements should be considered. The related measurements are to be performed at the "transfer" strategic point located at the transfer tunnel between the storage and the fuel cycle facility.

The motivation for these measurements is to be able to discriminate between dummy elements, and irradiated fuel elements when having to enter a low accessibility area (e.g. transfer from MBA XE09 to MBA XE07). The measurement technique may consist in High Resolution Gamma spectrometry coupled with passive neutrons counting on the items in transit. This kind of technique would be able to return estimates of LEU, average burn-up, Pu mass. The average time needed for the measurement is around ten minutes

[B.9]. On the basis of [B.9] the related measurement errors might be expected to be 0.1% for random errors and 2-5% for systematic errors.

A Cherenkov glow analysis while assemblies to be transferred are still in the pond can be considered for attribute verification during PIV. In this case an Improved Cerenkov Viewing Device (ICVD) might be used [B.10].

Exceeding Recovered Uranium

At the current level of detail of the available documentation, a discussion about the measurements to be done on the exceeding recovered uranium is not possible. However, a characterization of the material in transit should certainly be done, at least in terms of U mass and enrichment.

A check to ensure that no plutonium is diverted through this channel might also be necessary. For this purpose, a neutron detector is placed at transfer gates.

Materials inside the fuel cycle facility

A large inventory of nuclear material in various forms (item, bulk, etc.) will be present in the fuel cycle facility. A possible approach for this facility is available in [B.5].

Wastes

Ceramic and metal wastes will be produced by the fuel cycle facility. It is supposed that these wastes do not have to be put under international safeguards. Although some form of surveillance on the material exiting is to be expected, this aspect will not be implemented in this document.

B.6 Preliminary Conclusions

Although being an innovative nuclear energy system, an ESFR Safeguards approach might be conceived by taking advantage of the analogies available with existing nuclear energy systems. While this might work fairly well for the reactors and related buildings and storages, the viability of such an approach for the design of safeguards measures for the fuel cycle facility might be less straightforward.

Acknowledgments

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Special thanks are due to M. Senzaki (JAEA), who kindly provided JRC with documentation about the Safeguards implementations adopted in Joyo and Monju nuclear reactors including refs. [B.7, B.8], and to P. Peerani (EC -RC) for his insights on the possibility to apply NDA measures in an effective way: his suggestions were implemented in rev4.

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Appendix C: ESFR Physical Protection System

C.1. Physical Protection Strategies

Theft of nuclear materials or information involves actions by non-host-state actors, who may be sophisticated thieves, terrorists, or agents of rogue states. Both information and material is attractive to these actors. Information related to technologically challenging systems, such as electrochemical processing and even some aqueous extraction processes are sensitive and access to this information requires control. Nuclear facilities also have physical protection systems that restrict access to and prevent theft of nuclear materials. The barriers to theft of nuclear materials and information include both intrinsic characteristics of the materials (mass, bulk, radiation levels, encryption) and intrinsic characteristics of the locations where the materials/information are stored and handled (vaults, controlled locations), as well as extrinsic measures associated with the design of the physical protection system which can detect, delay and neutralize adversaries and control the effects of insider actions (alarms, motion sensors, armed security forces).

The Generation IV Proliferation Resistance and Physical Protection (PRPP) Expert Group has developed an evaluation methodology to analyze the proliferation resistance and physical protection robustness of future Generation IV nuclear energy systems. The report: Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Revision 5, November 30, 2006 is the reference document for this study.

A Physical Protection (PP) Development Study has been performed to develop the above-mentioned methodology using the Example Sodium Fast Reactor (ESFR). The focus is on the theft of nuclear material and sabotage of nuclear systems, to demonstrate the aforementioned methodology. To begin this study, a physical protection approach for the ESFR is required.

The first primary strategy for reducing the risk of theft of nuclear materials or reducing the risk of sabotage releasing radioactive materials involves achieving a globally uniform level of physical protection (via both intrinsic and extrinsic measures) for the plant site that is commensurate with local threats and with the intrinsic material barriers that impede the theft of materials. Because effective physical protection can be expensive to implement, the second primary strategy involves nuclear energy system R&D to increase the intrinsic material barriers that impede theft/sabotage and to improve physical protection system technology to achieve equivalent protection levels at a reduced cost. Included is an improved 'security by design' process that emphasizes the early incorporation of physical protection considerations during the evolution of facility design. Such considerations will consider the physical arrangement of a facility to identify access and location of targets to make maximum advantage of intrinsic features. The third primary strategy involves reducing long-term risks via the global system architecture, which is largely comprised of institutional measures. This is accomplished through mechanisms, such as spent fuel return, that prevent very long-term storage of nuclear materials in dispersed locations where resources for applying appropriate physical protection may not be available in the future.

This study addresses only the first two primary strategies; a globally uniform level of physical protection and increasing intrinsic material barriers.

C.2 Physical Protection System Approaches

The physical protection of nuclear facilities should be considered as an institutional process or regime. The physical protection regime (PPR) includes all physical protection activities of a State for the protection of nuclear material and nuclear facilities (including transport). The PPR encompasses the legislative and regulatory framework, designation of competent authorities, defining the responsibilities between the state and the owner/operator in regard to PP, the administrative measures and technical features at a facility (or transport) to prevent the unauthorized removal of nuclear material and the sabotage of nuclear facilities or transports, and the measures taken to facilitate the mitigation of the consequences of such a malicious act were it to occur. A basic principle of Physical Protection is to implement a Physical Protection Regime that is effective and efficient for the full lifecycle of nuclear facilities.[1]

The physical protection of a nuclear facility is the responsibility of the host state of the facility. Protection against theft or unauthorized removal of nuclear material by a sub-national group is provided by host State security personnel and systems. Additionally, if such theft or removal were to occur, it is primarily the host State resources that would be applied to securing and returning the material to proper control. The level of rigor applied to the physical protection of the facility will be a function of the type of nuclear material at the facility, the total quantity, how difficult it would be to remove, and knowledge of local conditions and threats, as well as other considerations that concern the host State.

The IAEA is interested in the physical protection measures in place at nuclear facilities to ensure that they are complete and thorough, and that the facility is indeed protected. Guidelines (INFCIRC 225, INFCIRC 274) have been created against which a given physical protection regime can be compared. Stated broadly (Ref. INFCIRC 225) the objectives of a host State physical protection program is to 1) minimize the possibilities for unauthorized removal of nuclear material or for sabotage, and 2) provide information and assistance in support of rapidly recovering missing nuclear material or minimizing the consequences of sabotage.

[1] Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems INPRO Manual — Physical Protection Volume 6 of the
Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

C.2.1 Elements of a Host State Physical Protection Regime

The following elements need to be present as part of the host State physical protection regime:

1. Appropriate Legislation and Regulation
2. Responsibility, Authority, and Sanctions
3. Licensing and Other Procedures to Grant Authorization
4. Analysis of Threats
5. Physical Protection Requirements for Nuclear Material in Use and Storage and During Transport and for Nuclear Facilities
6. Additional Physical Protection Requirements for Nuclear Material During Transport
7. Nuclear Facility siting, layout, and design.
8. Trustworthiness Program
9. Reporting of Information
10. Confidentiality
11. Evaluation of the Implementation of Physical Protection Measures

These elements need to be present to varying degrees based upon the host State's design basis threat, and the category of the nuclear material to be protected.

C.2.2 Standard Elements of Physical Security Implementation

The implementation of physical security at any nuclear facility will have many common elements:

1. Design Basis Threat Definition
2. Outer boundary
3. Site Area
4. Limited Area
5. Protected Area
6. Exclusion Area
7. Restricted Area
8. Vital Areas
9. Security and Response Force Personnel
10. Detectors
11. Barriers (active and passive)
12. Alarm Assessment Tools

These elements form a defense in depth against sub-national attempts at theft of nuclear material or sabotage. For most nuclear facilities the physical protection context is similar until the vital areas are reached. For reactors, the primary vital areas to consider in regards to theft of nuclear material will be the fresh fuel storage area and the spent fuel storage area.

At the ESFR there are three types of areas that house nuclear material targets: outdoor areas, commercial-grade buildings, and hot cells. The cask parking area is an outdoor parking lot within the Protected Area. The LWR Spent Fuel Storage and

Staging/Washing Area of the Fuel Cycle Facility are standard commercial buildings. The Fuel Cycle Facility contains concrete hot cells, both air and inert, with little structural difference between the two cell types. All three of these areas will fall within the site wide physical protection systems.

C.2.3 Site Wide Physical Protection Approach

The site wide physical protection approach includes

- Site boundary fences or barriers
- Sensors (camera, motion) and alarms that cover the site boundary
- Security Forces, including roving patrols
- A PIDAS (Perimeter Intrusion Detection and Assessment System) that surrounds the target areas (either individually or as a whole)
- Access control (both vehicular and personnel) at the site boundary
- Security weaponry external to the target areas (remote operated weapons, security vehicles)

These mostly extrinsic security features provide the ability to detect a threat before any nuclear material is at risk, observe and track the threat as the scenario progresses, and the security forces and capability to deter neutralize the threat.

C.3 Identification of Potential Threats

C.3.1 LWR Spent Fuel Cask Parking

While the spent fuel cask parking area is the most accessible to an adversary, it also contains the least attractive material. However, since radiological sabotage, must also be considered a threat, the cask parking area must be protected.

Detection can include numerous types of sensors and visual observation. The parking area or the entire ESFR facility can be surrounded by a Perimeter Intrusion Detection and Assessment System (PIDAS), which is a fencing and detection system, and have access controls to ensure only authorized personnel can enter or exit. This system must include an element of 3D space, that is, detection and potentially barricades must go vertically above grade and below if, such is accessible to the adversary. Heavier steel fencing can enclose the most vehicle-accessible areas. Raise-able concrete or steel barricades can be placed in access roads at access points. Additionally, the casks themselves, when fully closed and secured, provide barriers to nuclear material access.

C.3.2 LWR Spent Fuel Storage and Fuel Cycle Facility Staging/Washing Area

The spent fuel storage and staging/washing areas contain the next most attractive material. The assemblies have been removed from the casks, and are therefore more accessible to an adversary.

These areas will be within a PIDAS. Additionally, detection can be placed on access doors and equipment ports into the facility. Cameras and sensors can observe the internal volumes. Assembly lifting devices (cranes) can be locked out or disabled. Vault-type doors can be installed on vehicle and equipment access openings that are large enough for the assemblies. The facility walls and roof can be hardened. Pitched roofs instead of flat can be used to limit access. Rooftop barriers can be placed to prevent aircraft access.

C.3.3 Fuel Cycle Facility Air Cell (Hot Cell) and Inert Hot Cell

The fuel cycle facility part of the ESFR is essentially a large hot cell type facility that houses the electrochemical (‘pyro’) processing plant that reprocesses the spent fuel, and therefore this location contains the most attractive nuclear material. Fission products have been separated from the fissile material in the Fuel Cycle Facility and the product is formed into metal ingots before the fuel fabrication steps occur.

There are multiple security related features to address within the Fuel Cycle Facility:

- Loading equipment (cranes, hoists) can be disabled or locked out during non-facility use.
- The manipulator equipment can be installed with hard-to-remove fasteners. They may be able to be manufactured in a paired configuration, such that the opening size in the cell wall is too small to be useful for theft. The manipulators can be locked out when not in use and access controlled when in use.
- Equipment access ports can be minimized in size where possible; however, at least one must be of sufficient size to accommodate the in-cell equipment. That large equipment access port could be equipped with a vault-type door.
- Detection sensors could be placed on any large sized ports.
- Oil-filled windows represent a necessary breach in the cell wall
    - The potential may exist for strengthening one of the panes in the window.
    - Hardened “storm shutters” may be added to the exterior of windows not in use at the time and similar ones can drop down inside when the outer window is breached.
- Walls, floors, and ceilings of hot cells are normally thick reinforced concrete for shielding purposes. Additional reinforcement and smaller reinforcement spacing could be added during construction to strengthen the walls, floor, and ceiling to increase their vault-type effectiveness.
- Detection sensors can be placed within the areas around the cells, within the cells, or even within the walls.
- Portions of ventilation and HEPA filtration systems that are not enclosed within concrete can be hardened. Ventilation openings can be reduced in size, or have barriers placed to prevent access. Detectors can be added to the access barriers.

C.3.4 Radiological Sabotage Targets

The identification of equipment targets for sabotage requires a more complex and analytical process. Typically, for successful sabotage resulting in radiological release, an adversary must disable the functions of a number of different pieces of equipment. An equipment target set is defined as a minimum set of equipment that must be disabled to successfully sabotage a facility. A facility will often contain multiple possible equipment target sets. The number and diversity of equipment functions in each equipment target set provide a measure of the system's redundancy and diversity.

Radiological sabotage involves the deliberate damage of systems with the goal of generating radiological releases to harm the public or workers. The design of nuclear systems includes systematic safety assessments to identify potential initiating events and equipment and operational failures, which could also generate radiological releases. Therefore, these safety assessments provide a starting point for the identification of potential radiological sabotage targets.

To identify potential pathways for radiological sabotage, the probabilistic risk assessment for system safety is modified in two important ways. First, for sabotage, the probability of multiple, simultaneous failures of diverse and redundant components may be increased substantially. Second, for sabotage the probability of failure may increase substantially for the failure of passive components with normally high reliability (walls, fire barriers, doors, vessels, etc.) With these caveats in mind, target identification involves two steps, (1) the systematic search for sets of equipment that, if disabled, could result in the subsequent release of radionuclides (*vital equipment* identification), and (2) the definition of *vital areas* associated with these vital equipment sets to identify access paths.

For the reactor target, five main types of attack strategies should be considered. These are loss of cooling, reactivity, direct attack, fire/chemical, and other forms of attack. For example, for an attack intended to lead to loss of cooling, two methods to create this situation possible actions are: sabotage of the decay heat removal capability, or primary coolant pool drainage

C.4 Applicability to PRPP Methodology

With vital equipment sets and vital areas identified, PP pathway analysis then identifies potential pathways by which the threat could access and disable the vital equipment, evaluates the response of the physical protection system, and evaluates the PP measures to determine the attractiveness of the pathways to potential PP adversaries.

Whereas the adversary force knows which reactor to access, it presents a challenge to the Physical Protection force to determine their goal as soon as possible for effective deployment of response forces. For example, the methods of access considered are through a stand off attack on the protected area of the facility and then human entry to the restricted areas of a reactor, and inserting explosives on the heat exchanger, or theft of material from a protected area.

C.5 Conclusion

In every case, the intent is to (through first intrinsic, and second extrinsic measures) prevent the ability for theft of nuclear material or sabotage of the reactor safety systems (i.e. make openings in the hot cell too small to be used, having redundant safety systems) or to ensure timely detection of the theft/sabotage attempt (i.e. alarms around and within the protected areas). The PRPP methodology characterizes the robustness of the physical protection system by considering 1) the probability of adversary success, 2) the consequences of success, and 3) the cost of the physical protection system. All of the approaches described above reduce the probability of adversary success. Those intrinsic features identified and implemented during initial facility construction reduce the cost of the physical protection system, achieving a given level of protection with reduced operating cost.

It is important to note that without an effective set of extrinsic detectors, the value of the intrinsic barriers is minimized. Pathway evaluation shows that extrinsic detectors can be ineffectual if applied to late in the pathway. Similarly, delays early in the pathway before detection are ineffectual. The challenge is to balance the placement of detection in concert with delay in the most cost effective manner to prevent consequences at the minimum cost of the physical protection system.

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Appendix D: Representative Pathway Descriptions and Analyses

The four sets of representative pathways identified and analyzed in this Case Study were selected to cover a relatively large fraction of the total PR&PP threat space for the ESFR. They are:

- Concealed Diversion of Material
- Concealed Misuse of the Facility
- Breakout and Overt Diversion of Material and Misuse of the Facility
- Theft of Nuclear Material and Sabotage of Nuclear System Elements

D.1 Diversion

The approach to ESFR PR diversion analysis follows the GIF PR&PP Methodology standard paradigm:

CHALLENGES → **SYSTEM RESPONSE** → **OUTCOMES**

Threats ***PR & PP*** ***Assessment***

Each element of the analysis is described below. While the analysis as of this draft is primarily qualitative and high level, it attempts to be complete in the breadth of coverage. As more detail is developed in the ESFR design and operating characteristics, in target properties, and in safeguards, it is possible that new or modified pathway segments may be identified. Combined with more rigorous quantification of measures including uncertainty, our interpretation of the results may lead to altered priorities.

D.1.1 Diversion Threat Description

The threat to the ESFR can involve any of the threats outlined in the PR&PP Methodology. The Threat Description includes:

	Range of Possibility	Threat Characteristics Relevant to Diversion Analysis limited by current scope
Actor Type	**Host State**	**Host State**
Actor Capabilities	Wide range of technical skills, resources (money, workforce, U & Th), industrial capability, nuclear capability	Capabilities of industrial nation
Objectives	Wide range of nuclear weapon aspirations: number, reliability ability to stockpile, deliverability, production rate	1 SQ
Strategies	• Concealed diversion • Concealed facility misuse • Overt facility misuse • Clandestine facilities alone	Concealed or overt removal of material from the normal, monitored ESFR process

D.1.2 Diversion Target Identification

"A PR target is nuclear material that can be diverted, equipment and processes that can be misused to process undeclared nuclear materials, or equipment and technology that can be replicated in an undeclared facility."[1]

Target identification for the ESFR begins by breaking the ESFR into system elements for analysis. Figure D.1-1 shows the entire ESFR nuclear energy system. Certain elements of a complete nuclear energy system are beyond the scope of this analysis. Specifically, mining and separation facilities and sources of LWR fuel needed to feed the "inside the fence" portion of the ESFR will not be analyzed in this study. In addition, the U Parking area shown in Figure D.1-1 is also considered out of scope for the current analysis.

The system elements to be analyzed are the Material Balance Areas as defined in Figure D.1-1 and include:

- XE01 – Reactor #1 (Rx1)
- XE02 – Reactor #2 (Rx2)
- XE03 – Reactor #3 (Rx3)
- XE04 – Reactor #4 (Rx4)
- XE05 – Fuel Service Facility (FSF)
- XE06 – ESFR SF & NF Storage Cell (ESFR-fuel)
- XE07 – Fuel Cycle Facility (FCF)
- XE08 – Exceeded Recovered U Storage (XU)
- XE09 – LWR Spent Fuel Storage (LWR-SF)
- XE10 – LWR SF Casks Parking (Cask)

[1] GIF/PRPPWG-2006/005, Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, November 2006

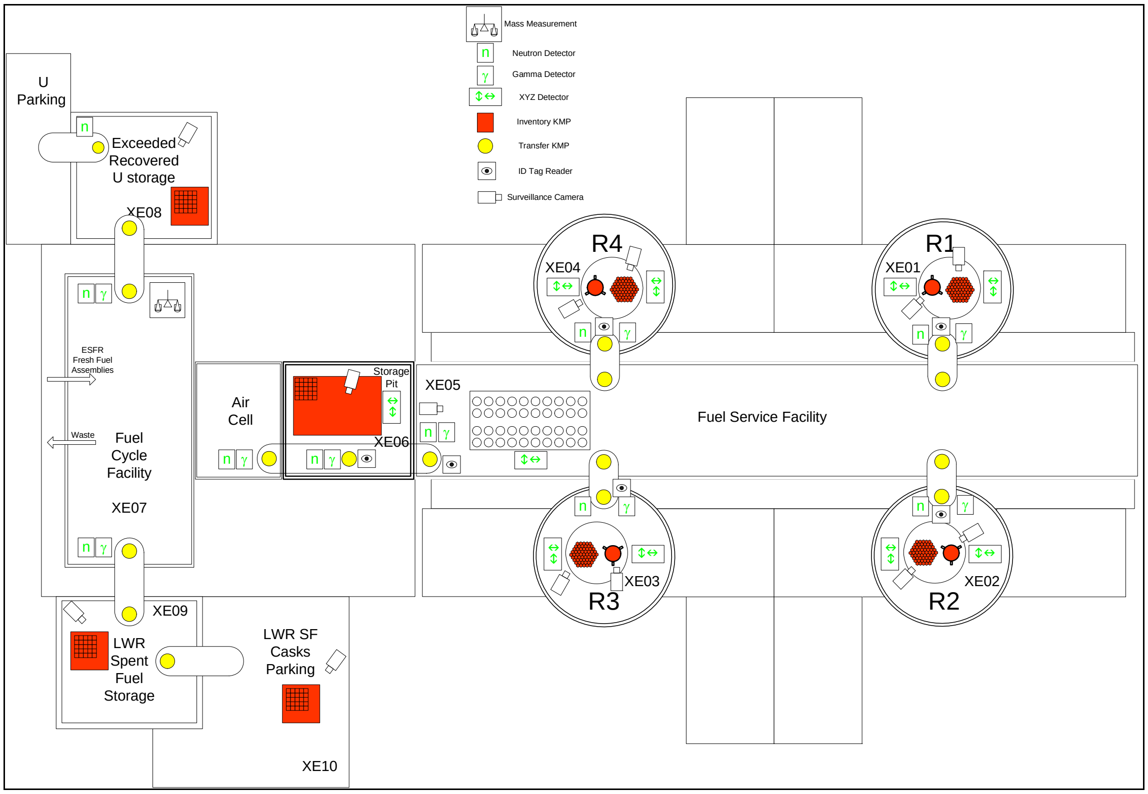

Figure D.1-1. ESFR Nuclear Energy System

A system element review looks for targets in each of the Material Balance Areas. No targets for diversion were identified in the four reactors (XE-01 to XE-04) because access during operations is not deemed viable. No targets were identified in EX-05, the Fuel Service Facility or XE-06, the ESFR NF & SF storage cell, because any material to be removed must move through system elements XE07 – XE10, where they will be picked up in the analysis.

The target analysis considered the different types of nuclear material in each system element, its location, and its configuration. The target analysis for system elements XE07 – XE10 is tabulated in Tables D.1-1 to D.1-4. Those targets displayed in the tables with a diagonal pattern are included for completeness but are not considered further in the analysis. Table D.1-5 characterizes the Targets identified. It can be seen that there are seven distinct targets. Table D.1-6 displays the system element(s) in which the targets can be found and shows that these targets have a limited number of diversion points.

Table D.1-1: Target Analysis of MBA XE-10

Diversion points (Exits)	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XE-10-1	1	Cask of LWR fuel bundles.	Irradiated U235 and TRU metal.	Casks	Parking area (outside)	Spent fuel elements	Storage	Normal storage	Cameras Inventory
XE-10-2	2	LWR Fuel bundle(s).	Irradiated U235 and TRU metal.	Casks	Transit – between XE-10 and 09	Spent fuel elements	Unloading	Cask movement	Cameras Inventory

Table D.1-2: Target Analysis of MBA XE-09

Diversion points (Exits)	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XE-09-1	1	Cask of LWR fuel bundles.	Irradiated U235 and TRU metal.	Casks	Transit via cask between XE-09 and 10	Spent fuel bundles.	Cask movement.	Normal operations.	Cameras Inventory
	2	Individual LWR Fuel bundle(s) in cask	Irradiated U235 and TRU metal.	Casks	Transit via cask between XE-09 and 10	Spent fuel bundles.	Unloading fuel form casks to fuel storage rack.	Normal operations.	Cameras Inventory
	2	Individual LWR Fuel bundle(s) in fuel storage rack	Irradiated U235 and TRU metal.	Cask/other containers	Transit – between XE-09 and 10	Spent fuel bundles.	Storage in fuel racks	Normal storage	Cameras Inventory
XE-09-2	2	LWR Fuel bundle(s).	Irradiated U235 and TRU metal.	Fuel transport container	Transit – between XE-09 and 07	Spent fuel bundles.	Transfer	Normal operation	Cameras Inventory

Table D.1-3: Target Analysis of MBA XE-08

Diversion points (Exits)	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XE-08-1	3	TRU metal from electro-refiner process.	TRU metal (80% Pu)	Recycled U transfer container.	Transit – between XE-08 and outside.	Recycled Uranium metal.	Waste material transfer off-site.	Normal Operations	Inventory. Neutron detector. Camera.
XE-08-1	7	Uranium metal	Recycled U.	Recycled U transfer container.	Transit – between XE-08 and outside.	Recycled Uranium metal.	Waste material transfer off-site.	Normal Operations	Inventory. Neutron detector. Camera.

Table D.1-4: Target Analysis of MBA XE-07

Diversion points (Exits)	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XE-07-01	3	TRU metal from electro-refiner process.	TRU metal (80% Pu)	Waste container	Transit – between XE-07 and outside	Normal operating waste.	Transfer of waste	Normal operation	Gamma detector? Neutron detector?
XE-07-01	4	Waste containing TRU metal from electro-refiner process.	TRU metal (80% Pu)	Waste container	Transit – between XE-07 and outside	Normal operating waste.	Transfer of waste	Normal operation	Gamma detector? Neutron detector?
XE-07-02	3	TRU metal from electro-refiner process.	TRU metal (80% Pu)	Fuel assembly hardware container	Transit – between XE-07 and outside.	Metal.	Raw material input	Normal operation	Gamma detector? Neutron detector?

Diversion points (Exits)	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XE-07-03 (First stage of diversion)	3	TRU metal from electro-refiner process.	TRU metal (80% Pu)	Recycled U transfer container.	Transit – between XE-07 and 08.	Recycled Uranium metal.	Waste material output	Normal Operations	Mass measurement. Inventory. Gamma detector. Neutron detector.
XE-07-04A (Misuse scenario Stage 1)	5	New ESFR fuel bundle (e.g. more U than specified)	New fuel (U and TRU)	Fuel handling container.	Transit – between XE-07 and 06.	New fuel.	Fuel transfer.	Normal Operations	Tag ID. Inventory. Gamma detector. Neutron detector. Camera.
XE-07-04B (Misuse scenario Stage 2)	6	Spent ESFR fuel bundle. (e.g. more Pu than specified)	Fuel containing U and TRU.	Fuel handling container.	Transit – between XE-06 and 07.	Spent fuel.	Fuel transfer.	Normal Operations	Tag ID. Inventory. Gamma detector. Neutron detector. Camera.

Table D.1-5: Target Description

Target ID	Target Description	Target Material Character	Misuse Possible
1	Cask of LWR fuel bundles.	Irradiated U235 and TRU (oxide).	no
2	LWR Fuel bundle(s).	Irradiated U235 and TRU (oxide).	no
3	TRU metal from electro-refiner process.	TRU metal (80% Pu)	yes
4	Waste containing TRU metal from electro-refiner cleanout process.	TRU metal (80% Pu)	Yes (more TRU in waste than specified)
5	ESFR fresh-fuel subassembly	U-TRU fuel alloyed with zirconium	yes (e.g. more U than specified)
6	ESFR spent-fuel subassembly.	Irradiated U-TRU fuel alloyed with zirconium.	Yes (e.g. more Pu than specified)
7	Uranium metal	Recycled uranium.	Yes (purer U than specified)

Table D.1-6: Targets and Related Diversion Points

Target ID	Diversion points (Exits)
1	XE-09-01
	XE-10-01
2	XE-10-02
	XE-09-02
	XE-09-03
	XE-09-03
3	XE-07-01
	XE-07-02
	XE-07-03
	XE-08-01
4	XE-07-01
5	XE-07-04A
6	XE-07-04B
7	XE-08-01

D.1.3 Diversion Qualitative Pathways Analysis

Pathways analysis for diversion begins with a consideration of every target in light of the specific threats under consideration. The analyst must systematically search for plausible scenarios that could implement the potential proliferant Host State's strategies to divert the target material. Thus the analysis proceeds along the following lines.

- Examine every potential target
- Evaluate the material type of the target (identified in Section D.1.2)
- Identify the possible physical mechanisms that could be used to remove the material
- Identify the physical and design barriers to removal
- Identify the safeguards barriers that protect each physical mechanism

- Hypothesize ways to defeat the safeguards
- Layout qualitative pathways for removal of each target
- Perform a coarse qualitative evaluation of the measures for each diversion pathway

During the analysis it is important to consider both the aspects of interest to the proliferant state and the defender (designers and inspectors). In fact, the analyst's point of view changes back and forth in this process. Care is taken to be cognizant of that point of view. Normally, both diversion and potential misuse pathways are evaluated at this time. For this test case, potential misuse scenarios are identified but not considered further.

The first result of this process is a list of diversion pathway segments as shown in Table D.1-7. As described in the GIF PR&PP Methodology, there are three stages to the PR problem:

Acquisition➔Processing➔Fabrication

Only the first stage, acquisition, is mapped out in the first stage of the analysis. Our focus here is on how the target can be moved from its normal position.

The final step in the current analysis is to evaluate the measures for the pathway. This is accomplished in Tables D.1-8. Note that in these results, an overall measure is evaluated for the Acquisition and Processing segments. No work on the fabrication segment has been accomplished.

The nomenclature for the results identifies the Target type, the system element where the diversion begins (it should be noted that the diversion may involve more than one area), and the unique pathway number.

Table D.1-7: Initial Diversion Pathways Analysis

Target ID	Target Description	Diversion Points	Potential Strategies	Proliferator Actions (Enablers)	Pathway ID	Pathway Description
T1	Cask of LWR fuel assemblies.	XE-10-1	3 - Abrupt diversion	Use heavy truck and trailer to move cask. Fool or disable the camera. Compromise the inventory measurement records.	T1-XE-10-1	Cask of LWR spent fuel assemblies is in the LWR cask parking lot. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.
		XE-09-1 XE-10-1	3 - abrupt diversion	Send back a loaded cask instead of a empty cask. Use heavy truck and trailer to move cask. Fool or disable the camera. Compromise the inventory measurement records.	T1-XE-09-1	A full cask of LWR spent fuel is sent back instead of an empty one. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
T2	LWR Fuel assembly(s).	XE-09-1 XE-10-1	1. Protracted diversion	Fuel assembly's) inserted in cask. Use heavy truck and trailer to move cask. Compromise the inventory measurement records	T2-XE-09-1a	Empty Cask of LWR Spent Fuel Facility is partially reloaded and sent back. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
		XE-10-1	1. Protracted diversion	Fuel assembly(s) left in cask. Use heavy truck and trailer to move cask. Compromise the inventory measurement records.	T2-XE-10-2	Cask of LWR Spent Fuel Facility is not unloaded completely. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.
	LWR Fuel assembly(s).	XE-09-1	1. Protracted diversion	Use special container to conceal and move fuel assembly. Fool or disable the camera. Compromise the inventory measurement records.	T2-XE-09-1b	Fuel assembly intended for XE-07 is placed in the proliferators own transport container and is removed from XE09. Camera is compromised. Proliferator takes container and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.

Target ID	Target Description	Diversion Points	Potential Strategies	Proliferator Actions (Enablers)	Pathway ID	Pathway Description
T3	TRU metal from electro-refiner process.	XE-07-01	1. Protracted diversion (abrupt?)	Put TRU metal in metal waste container. Fool or disable the neutron and gamma detectors (if they exist) Fool Cameras, material recorders	T3-XE-07-1	Proliferator put TRU material in waste container and transports out through waste portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records.
		XE-07-02	1. Protracted diversion (abrupt?)	Put TRU metal in Fuel Assembly Hardware Container Fool or disable the neutron and gamma detectors (if they exist), Fool cameras, material records.	T3-XE-07-02	Proliferator put TRU material in new fuel assembly hardware container and transports out through assembly hardware portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records (audit etc.)
		XE-07-03 XE-08-01	1. Protracted diversion (abrupt?)	Put TRU metal in Recovered Uranium Container. Move Metal to XE08 MBA for later removal from MBA. Fool or disable the neutron and gamma detectors (if they exist), Fool cameras, material records.	T3-XE-07-03	Proliferator put TRU material in Recovered U container and transports out through Recycled U portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras in transition between XE-07/08. Material will be removed from MBA-8 later. Compromise material records (audit etc.) Compromise neutron detectors in final move.
T4	Waste containing TRU metal from electro-refiner process.	XE-07-01	1. Protracted diversion (abrupt?) 4. Protracted misuse and diversion combined	Proliferator receives waste container, does not send to established and controlled waste storage location.	T4-XE-07-1	Proliferator collects normal TRU via waste container and sends to concealed facility. Misuse potential: Electro-refiner could be modified to increase TRU content of waste (misuse scenario).
T5	ESFR Fresh fuel sub-assembly	Not credible for concealed diversion				
T6	ESFR Spent fuel sub-assembly	Not credible for concealed diversion				
T7	Recycled Uranium	XE-80-01	Protracted Diversion	Proliferator transports recycled Uranium to concealed enrichment facility for processing	T7-XE-08-1	Proliferator constructs concealed enrichment facility, transports recycled U to facility for enrichment Misuse potential: proliferator could manipulate electro-refiner to produce "cleaner" uranium than specified.

Table D.1-8: Measures Evaluation for Each Pathway

	T1-XE-10-1			T1-XE-09-1		
	Cask of LWR spent fuel bundles is in the LWR cask parking lot. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.			**A full cask of LWR Spent Fuel Facility is sent back instead of an empty one. Camera is compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.**		
	Value	**Acquisition Basis**	**Processing Basis**	**Value**	**Acquisition Basis**	**Processing Basis**
Proliferation Technical Difficulty	Medium (high side, more than 50%)	Easy, hook up a trailer	Spent fuel would require a reprocessing facility such as PUREX	Medium (high side, more than 50%)	Easy, hook up a trailer	Spent fuel would require a reprocessing facility such as PUREX
Proliferation Cost	Low (but close to Medium like 25% of military budget)	Minimal expense required	This is a threat dependent measure. Assume some industrial capability so cost is relative. Dollar ranges would be better For this, assume $10M-100M	Low (but close to Medium like 25% of military budget)	Minimal expense required	This is a threat dependent measure. Assume some industrial capability so cost is relative. Dollar ranges would be better For this, assume $10M-100M
Proliferation Time	Medium (on the order of five years)	Quick, drive away	Processing time would be on the order of months, constructing a facility could take years	Medium (on the order of five years)	Quick, drive away	Processing time would be on the order of months, constructing a facility could take years
Detection Probability	High	Inventory controls must be compromised	Detection probability of processing facility not considered	High	Must fool safeguards in XE-09, Inventory controls must be compromised	Detection probability of processing facility not considered
Fissile Material Type	Medium	Spent fuel pins	Convert from spent fuel to RG-Pu	Medium	Spent fuel pins	Convert from spent fuel to RG-Pu
Detection Resource Efficiency	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

	T2-XE-09-1a			T2-XE-10-2		
	Empty Cask of LWR Spent Fuel Facility is partially reloaded and sent back. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.			**Cask of LWR Spent Fuel Facility is not unloaded completely. Camera may not need to be compromised. Proliferator takes cask and hauls away to concealed processing facility. KMP and Transfer Measuring Point (TMP) controls are compromised.**		
	Value	**Acquisition Basis**	**Processing Basis**	**Value**	**Acquisition Basis**	**Processing Basis**
Proliferation Technical Difficulty	Medium (high side, more than 50%)	Must move fuel from fuel storage rack into cask undetected	Spent fuel would require a reprocessing facility such as PUREX	Medium (high side, more than 50%)	Must leave fuel in fuel storage rack into cask undetected	Spent fuel would require a reprocessing facility such as PUREX
Proliferation Cost	Low (but close to Medium like 25% of military budget)	Little or no special equipment required	This is a threat dependent measure. Assume some industrial capability so cost is relative. Dollar ranges would be better For this, assume $10M-100M	Low (but close to Medium like 25% of military budget)	Little or no special equipment required	This is a threat dependent measure. Assume some industrial capability so cost is relative. Dollar ranges would be better For this, assume $10M-100M
Proliferation Time	Medium (on the order of five years)	Dependent on the number of fuel assessmlies taken	Processing time would be on the order of months, constructing a facility could take years	Medium (on the order of five years)	Dependent on the number of fuel assessmlies taken	Processing time would be on the order of months, constructing a facility could take years
Detection Probability	Medium	smaller quantities may be able to be moved undetected	Detection probability of processing facility not considered	Medium	smaller quantities may be able to be moved undetected	Detection probability of processing facility not considered
Fissile Material Type	Medium	Spent fuel pins	weapons usable but not optimum	Medium	Spent fuel pins	weapons usable but not optimum
Detection Resource Efficiency	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

Table D.1-8: Measures Evaluation for Each Pathway (continued)

	T2-XE-09-1b			T3-XE-07-1		
	Fuel bundle intended for XE-07 is placed in the prolifer's own transport container and is removed from XE09. Camera is compromised. Proliferator takes container and hauls away to concealed processing facility. Key Measuring Point (KMP) controls are compromised.			Proliferator puts TRU material in waste container and transports out through waste portal. Must compromise the neutron and gamma detectors (if they exist) and surveillance cameras and compromise material records.		
	Value	Acquisition Basis	Processing Basis	Value	Acquisition Basis	Processing Basis
Proliferation Technical Difficulty	Medium (high side, more than 50%)	Must develop transfer container.	Spent fuel would require a reprocessing facility such as PUREX	Low	TRU metal in waste container.	Most processing done, need only hot cell with chemical processing capability
Proliferation Cost	Low (but close to Medium like 25% of military budget)	Additional cost for developing special container	This is a threat dependent measure. Assume some industrial capability so cost is relative. Dollar ranges would be better For this, assume $10M-100M	Very low	Little or no special equipment required	Much smaller facility needed for processing TRU
Proliferation Time	Medium (on the order of five years)	Dependent on the number of fuel assessmlies taken	Processing time would be on the order of months, constructing a facility could take years	Medium (less than five years)	Dependent on the amount and of TRU taken and how often put into Waste containers	May not need as much time to construct as a reprocessing facility
Detection Probability	Medium	smaller quantities may be able to be moved undetected	Detection probability of processing facility not considered	Medium	TRU in waste container may be able to be moved undetected	Detection probability of processing facility not considered
Fissile Material Type	Medium	Spent fuel pins	weapons usable but not optimum	Medium	TRU already processed and cleaned up	weapons usable but not optimum
Detection Resource Efficiency	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

	T3-XE-07-02			T3-XE-07-03		
	Proliferator put TRU material in new fuel assembly hardware container and transports out through assembly hardware portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras. Compromise material records (audit etc.)			Proliferator put TRU material in Recovered U container and transports out through Recycled U portal. Compromise the neutron and gamma detectors (if they exist) and surveillance cameras in transition between XE-07/08. Material will be removed from MBA-8 later. Compromise material records (audit etc.) Compromise neutron detectors in final move.		
	Value	Acquisition Basis	Processing Basis	Value	Acquisition Basis	Processing Basis
Proliferation Technical Difficulty	Low	TRU metal in new fuel assembly container.	Most processing done, need only hot cell with chemical processing capability	Low	TRU metal in recovered U container.	Most processing done, need only hot cell with chemical processing capability
Proliferation Cost	Very low	Little or no special equipment required, but some kind of neutron shielding may be used	Much smaller facility needed for processing TRU	Very low	Little or no special equipment required, but some kind of neutron shielding may be used	Much smaller facility needed for processing TRU
Proliferation Time	Medium (less than five years)	Dependent on the amount and of TRU taken and how often put into fuel assembly containers	May not need as much time to construct as a reprocessing facility	Medium (less than five years)	Dependent on the amount and of TRU taken and how often put into recovered U containers	May not need as much time to construct as a reprocessing facility
Detection Probability	Medium	TRU in fuel assemly container may be able to be moved undetected	Detection probability of processing facility not considered	High	TRU in recovered U container may be able to be moved undetected, but will have to go through two MBAs	Detection probability of processing facility not considered
Fissile Material Type	Medium	TRU already processed and cleaned up	weapons usable but not optimum	Medium	TRU already processed and cleaned up	weapons usable but not optimum
Detection Resource Efficiency	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

Table D.1-8: Measures Evaluation for Each Pathway (continued)

	T4-XE-07-1			T7-XE-08-1		
	Proliferator collects normal TRU via waste container and sends to concealed facility. Misuse potential: Electro-refiner could be modified to increase TRU content of waste (misuse scenario).			Proliferator constructs concealed enrichment facility, transports recycled U to facility for enrichment Misuse potential: proliferator could manipulate electro-refiner to produce "cleaner" uranium than specified.		
		Acquisition Basis	Processing Basis	Value	Acquisition Basis	Processing Basis
Proliferation Technical Difficulty	Low	No material accountablity on waste once it exits facility	Low concentration of TRU means that processing must be efficient to extract what is there. Misuse scenario could have higher concentration	High	Easy because recycled U will be disposed of or stored and may not be under stringint safeguards	It is hard to get an enrichment facility constructed and operating
Proliferation Cost	Low	Little Cost since plans are for waste to be removed to disposal site	Hot cell and chemical processing of metal	High	Little cost because Recovered U will be removed in normal operation	An enrichment facility is expensive to build, but not to operate
Proliferation Time	Medium	Dependent on the amount of TRU in waste	construction of Chemical processing facilities is not difficult given availability of equipment	High	Acquisition time short because Recovered U will be removed	It will take more than ten years to develop an Enrichment facility
Detection Probability	Very low	Once waste is out, no safeguards. Some TRU is expected in Waste. If misuse is involved more TRU may be put into waste so may be more easily detected	Detection probability of processing facility not considered	Very low	Recycled U may have minimal Safeguards	Detection probability of processing facility not considered
Fissile Material Type	Medium	TRU is desireable but waste needs to be cleaned up	weapons usable but not optimum	Very Low	The material acquired is LEU which has a V-High PR	The material after processing is HEU which has a V-Low PR
Detection Resource Efficiency	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine	High	This is part of a multireactor facility, would have extensive safeguards	This would be a function of the cost of the international intelligence community and will be difficult to determine

D.1.4 Evaluation of Design Variations.

In order to evaluate the effect of variation in reactor design and operation, a set of fast reactor design variations was established as displayed in Table D.1-9.

The variations involved changes to, *inter alia*:

- Irradiation cycle duration
- Number of assemblies (core/blanket)
- Number of batches (core / internal / radial)
- Residence time, days (core / internal / radial)
- Pins per assembly (core / internal / radial)
- Structural pins per assembly
- Average TRU enrichment, %
- Fissile/TRU conversion ratio

A review of the ten coarse pathways identified in Table D.1-7 and quantified in Table D.1-8 was performed to determine what, if any, effect on diversion these variations would have. Although misuse scenarios could be affected in a variety of ways, no major change in diversion pathways could be identified, except for possible changes in the isotopic composition of the TRU that would be diverted.

Table D.1-9: Core Performance Parameters of Various Conversion Ratio Cores

	Baseline ESFR	Design Variation 0	Design Variation 1	Design Variation 2	Design Variation 3
	800 MW_{th} TRU CR = 0.64	Reference 1000 MW_{th} TRU CR = 0.73	1000 MW_{th} TRU CR = 0.22	1000 MW_{th} TRU CR = 1.00 No Blankets	1000 MWt TRU CR = 1.12 Radial & Internal Blankets
Nominal Electric Power, MW_e	300	350	350	350	350
Thermal Power, MW_{th}	800	1000	1000	1000	1000
Fuel composition (core / blanket)	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-20Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / U-Zr
Cycle length, months	12	12	6.6	12	12
Capacity factor	85%	90%	90%	90%	90%
Number of assemblies (core / blanket)	102 / -	180 / -	180 / -	180 / -	102 / 72
Number of batches (core / internal / radial)	3 / - / -	4 / - / -	8 / - / -	4 / - / -	4 / 4 / 6
Residence time, days (core / internal / radial)	930/ - / -	1300/ - / -	1445/ - / -	1300/ - / -	1300/1300/1970
Pins per assembly (core / internal / radial)	271 / - / -	271 / - / -	324 / - / -	271 / - / -	271 / 127 / 127
Structural pins per assembly	0	0	7	0	0
Average TRU enrichment, %	24.9	22.1	58.5	14.4	19.3
Fissile/TRU conversion ratio	0.8 / 0.64	0.84 / 0.73	0.55 / 0.22	0.99 / 1.00	1.07 / 1.12
HM/TRU inventory at BOEC, MT	9.0 / 2.2	13.2 / 2.9	6.9 / 3.9	18.5 / 2.8	20.5 / 2.5
Discharge burnup (ave/peak), MWd/kg	80 / ?	93 / 138	185 / 278	67 / 103	92 /146
TRU consumption rate, kg/year	80	81.6	241.3	-1.2 (gain)	-33.2 (gain)

D.1.5 Insights from Diversion Analysis for Further Study

Because the analysis was conducted at a coarse, qualitative level, more detailed analysis could identify specific pathway segments that offer a greater chance to avoid detection or new physical mechanisms for removal.

Measures should be determined for each pathway segment (i.e., acquisition and processing) and not rolled up to achieve one specific set of values. Note that aggregation of a measure along a pathway can obscure important insights into specific vulnerabilities that may affect overall proliferation strategies. For instance, the differences in proliferation cost, technical difficulty, and time in the acquisition phases for the different pathways is often over-shadowed by the related values in the processing phase.

Additional design, placement, and operational data on safeguards would be useful to permit thorough analysis and evaluation of measures and reduce the number of assumptions. For example, more detailed information on maintenance and repair practices would be valuable because these practices may affect access to the target material.

D.2 Concealed Misuse of the ESFR NES

Misuse threats differ in fundamental ways from diversion threats discussed in section D.1, but the primary difference is that diversion threats deal specifically with the removal of materials already in the system (and therefore subject to safeguards accountability). Misuse threats on the other hand use the facility to produce or process weapon-useable materials that are outside of safeguards, possibly to avoid detection through accountancy and other safeguards measures (Annex 0 at the end of this subchapter reports some PR resistance features to misuse of reactors).

This section describes *concealed misuse of the ESFR NES.* It summarizes firstly the threat (D.2.1), associated system elements (D.2.2) and the identification of possible targets, (D.2.3) spanning from e.g. the covert separation of weapons-usable material in the fuel cycle facility to the irradiation of ad hoc targets in one or more of the ESFR reactors to the replication of technology on clandestine sites. The target identification and categorization process is performed at qualitative analyses for the whole ESFR NES.

The Covert Pu Production in an ESFR NES is considered in the pathway identification and refinement process (D.2.4). This involves the “Irradiation of ad hoc targets” in the ESFR reactors but might also involve other targets such as the use of the fuel cycle facility for the fabrication of the irradiation targets, alternatively the irradiation targets could be fabricated outside the ESFR. Indeed the identification of targets and pathways for misuse is a complex activity involving technical expertise and creative thinking.

The pathway identification is firstly addressed at a high level, and up to 5184 theoretical possibilities, arising from a combinatorial approach, are preliminary identified. Rather than attempting an exhaustive analysis of all the reasonable pathways, a pathway looking particularly challenging for the safeguards approach is identified for showing how a qualitative analysis can generate traceable and accountable results if applied in a controlled and disciplined way. A preliminary estimation of the proliferation resistance measures for the ESFR baseline design for the selected pathway is then presented (D.2.5). Findings and considerations on the methodology on the basis of the analysis of the ESFR baseline design are also given (section D.2.6). Assumptions are reported in Annex 1 to the subchapter.

In the second part of the chapter, the ESFR design variations are recalled, then the possibility to consider the applicability of a pathway, similar to that identified for the analysis of the baseline design, to the different design options is discussed (section D.2.7). The possible design options are then considered for a pathway analysis. As discussed during the breakout session at the PR&PP Working Group meeting held at CEA Marcoule in France (January 29-30, 2008) and confirmed by a technical meeting held at JRC, in Ispra with ENEA researchers, on April 24, 2008, the selected pathway applies to design variations 0 and 1, and to a certain extent also to design variation 2, while for design variation 3, a pure diversion strategy looks more interesting (see section D.2.8). As an example, the pathways analysis for design variation 0 has been performed and is reported in section D.2.9, together with some conclusions (D.2.10). The analysis of DV1 is reported in section D.2.11 and some conclusions are presented in section D.2.12.

As a by product of the analysis process, a package summarising the main features of the DV0 and DV1 and illustrating the analysis steps were also developed. These packages could serve as the basis for having additional analyses/estimates by different analysis/experts for an expert judgment exercise. Design variations 2 and 3 (DV2, DV3) were not addressed in detail.

D.2.1 Misuse Threat Definition

There are many ways the ESFR could contribute to host state's weapons aspirations, but the most significant one is to use the ESFR for the covert production or processing of weapon-useable material. A state may choose such an approach for a number of reasons. The state may desire weapon-useable material better suited to weapons applications (for example, a higher assay of Pu-239 than that normally found in the system) or it may decide that misuse of the facility for covert production of weapon-useable material has a better chance of success than diversion of material already available.

There are other ways the ESFR can be misused, and while these will be briefly considered in this chapter, they will not be analyzed in detail. Some of these include the covert replication of the ESFR as a dedicated weapon-material production facility and the use of knowledge and expertise gained in the ESFR for weapon-material production applications.

The success of any misuse activity depends on the capabilities and objectives of the host state. These are summarized in Chapter 6, so they are not reiterated here.

Assessment of the misuse strategy requires several important assumptions:

1. It is assumed that the host state objective is to produce at least one "significant quantity[2]" of weapon-useable material (1 SQ).
2. It is assumed that the host state has ready access to all materials and expertise needed to support the described scenarios, that is, only the activities that occur within the physical confines of the ESFR facility are here assessed.
3. It is assumed that (in order to minimize the chance of detection) the host state will attempt to minimize disruption of normal facility operations during misuse of the facility.

D.2.2 Misuse System Element Identification

The process of misusing a NES for achieving weapons-usable fissile material is a complex one, typically not involving a single action on a single piece of equipment, but an integrated exploitation of various assets of the system. In the ESFR case, the system

[2] A "Significant Quantity" (SQ) is defined by the IAEA as that quantity of fissile material from which the production of a nuclear explosive device cannot be excluded. For plutonium (of any isotopic content expect plutonium containing in excess of 80% Pu-238) 1 SQ is equivalent to 8 kg Pu. For highly enriched uranium (HEU) 1 SQ is 25 kg of the U-235 isotope contained. For low enriched uranium (LEU), 1 SQ is 75 kg of the U-235 isotope. For U-233, 1 SQ is 8 kg of the U-233 isotope. Note that for uranium isotopic mixtures, the definition of the SQ counts only the 235 (or 233) isotopic mass.

elements identified as the most interesting ones for a misuse strategy are the reactors and the fuel cycle facility, the latter containing a recycling and a fabrication line.

D.2.3 Misuse Target Identification and Categorization

The PR&PP Evaluation Methodology Rev. 5 defines misuse targets as *processes and technologies* that can be effectively misused for proliferation activities (p. 21). As stated in the PR&PP Methodology report, the identification of process and equipment targets that could be involved in a misuse strategy is a complex task because a misuse strategy will likely insist on more than one process or piece of equipment (p. 23). In addition, the misuse of a nuclear energy system involves the possibility of modifying the existing structure and processes, therefore enabling the possibility to introduce additional equipment in the system. The Rev. 5 methodology report indicates the following as examples of possible misuse targets[3]:

- *Any declared equipment that is consistent with the strategies and objectives in the threat definition and that could be misused for materials processing. Targets are identified on the basis of the service the equipment provides (e.g., irradiation, plutonium separation, enrichment), without consideration of details such as capacity, technical difficulty, or cost. At this stage of the evaluation, facilities outside of the normal operating envelope must be included. Details such as how clandestine materials are inserted into the process and products extracted, including off-normal operation such as inadvertent material hold up, are considered during analysis of pathway segments. (p. 24).*

- *Technology (information and equipment) that is consistent with the strategies and objectives in the threat space and that could be misused for proliferation in clandestine facilities. This technology could include, for example, equipment that could be replicated (cloned) in a clandestine facility, information that could assist a proliferant State in designing or constructing a clandestine facility, or critical equipment that could be used in a clandestine facility after being declared lost or damaged. This step requires expert judgment to identify technology that is provided by the system elements and that would otherwise not be generally available to the proliferant State for a weapons program. Note that these targets could also be targets for theft for transfer to a proliferant State. Information theft is covered under PP pathway analysis but may use the same target identification process. (P. 25)".* [This target will not be considered here].

A possible suitable approach for identifying and screening relevant targets within a system might rely on a tailoring of Hazard and Operability (HAZOP) techniques.

Structured and Formal use of Expert Judgment techniques would also be a possible option; actually this could be applied to all the steps of the PR&PP methodology, from threat definition to systems assessment.

The ESFR NES co-locates a great fraction of its fuel cycle on a single site, and therefore the possible process targets span from fabrication of irradiation targets to fissile material

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[3] PR&PP Expert Group. 2006. *Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Revision 5*. GIF/PRPPWG/2006/005, Generation IV International Forum,. Available at: http://www.gen-4.org/Technology/horizontal

recovery, passing through irradiation in the reactor cores. On the basis of the system's description a brainstorming activity ended up in identifying the misuse targets illustrated in Figure D.2-1.

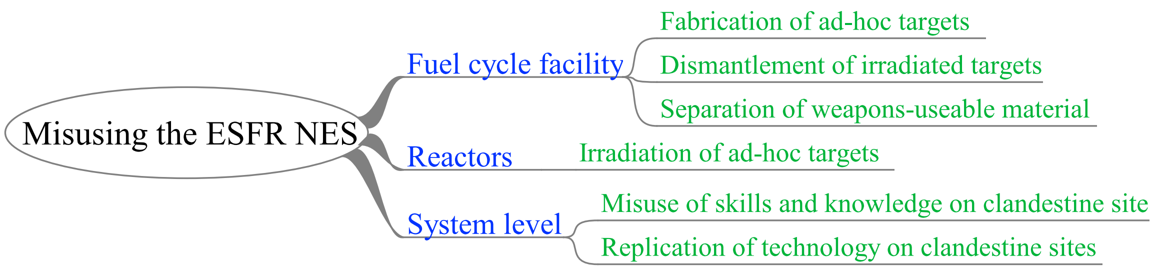


Figure D.2-1: Identified relevant ESFR system elements (in blue) and related possible misuse targets (in green).

In order to provide a preliminary characterisation of the identified possible targets, the following paragraphs will briefly analyse them with qualitative arguments.

FABRICATION AND DISMANTLEMENT OF AD-HOC TARGETS

The ESFR includes the capability to both manufacture and disassemble fuel pins and fuel assemblies. A host state might consider exploiting this capability for manufacturing fertile target assemblies to be irradiated elsewhere. This threat is not considered to be credible for three reasons.

First, the fuel for the ESFR is a specialized design not likely to be used easily in other reactor types as a target material.

Second, the fuel fabrication facilities and equipment is specially designed to fabricate and assemble the specific fuel design used in the ESFR in a remote and highly automated way. This equipment is not easily modified to produce assemblies compatible with irradiation in other reactors or reactor types, and even if such modifications were practical, they would certainly be detectable through normal safeguards.

Third, this scenario can be considered a special case of the covert irradiation threats described above. As such the proliferation resistance is at least as high as that of the target fabrication portion of those threats, and need not be considered separately.

Similarly, one might surmise a scenario where the fuel disassembly capabilities of the ESFR are exploited by the host state to disassemble targets irradiated elsewhere. Preliminary assessment indicates similar limitations to those just described, and such a scenario is essentially identical to the initial steps involved in the covert separation of plutonium threat. As such, a separate assessment of this threat variation is not warranted at this time.

SEPARATION OF WEAPONS-USEABLE MATERIAL

The ESFR NES comes with a complete commercial reprocessing facility, where LWR spent fuel assemblies and ESFR spent fuel assemblies are being recycled. The process chosen for the treatment of the fuel is a pyro-chemical one, in which the special fissile material is never found in separated form. The system is conceived to separate the mix of plutonium and minor actinides from uranium and fission products. While plutonium is never found in separate pure form and is always mixed with minor actinides, uranium is separated and treated as a waste. The process therefore could theoretically be used for separating either plutonium (even if not in pure form but mixed with minor actinides) or uranium, with a degree of purity that is to be assessed.

Covert plutonium separation

Although the possibility to separate plutonium onsite might exist, three significant issues seem to significantly limit the utility of this approach and therefore the likelihood of the host state choosing this approach is low enough that this threat can be considered to be not sufficiently viable for further assessment at this time.

First, the ESFR reprocessing plant uses an electrochemical process that does not produce a pure plutonium product. Moreover, it is not easily modified to produce a pure product, and any such modifications (even if feasible) would be readily apparent to normal safeguards. In the analysts opinion, this severely limits the benefits of such an approach to the host state so that the state is very unlikely to pursue such a course.

Second, since production of a pure plutonium product in the ESFR is unlikely, the host state must construct a separate reprocessing facility to fully separate the plutonium for weapon use. This further limits the benefit of this misuse scenario to the state.

Third, both the feed and product streams of the reprocessing system are subject to safeguards, and the introduction of out-of-safeguards feed materials (either unsafeguarded spent fuel irradiated elsewhere or target materials illicitly irradiated in the ESFR) and the subsequent removal of the excess product and associated waste streams are all very likely detectable by the planned safeguards systems.

Covert uranium separation

The pyroprocessing facility is designed in such a way that uranium is separated from the other elements and stored in ad-hoc storage areas for removal. Since the fuel cycle of the ESFR is based on plutonium and minor actinide recycle, the recovered uranium is considered to be a processing waste. Hypothetically, the existing reprocessing line could be used for separating uranium-233 covertly produced in the reactors' cores. Although this might be a scenario to be investigated, considerate is considered that this is an unlikely scenario for three reasons.

First, the possibility of covertly producing uranium-233 has already been considered to by unlikely, because the circulation of two exotic elements in the system (thorium and uranium-233) would be readily detected by the safeguards detectors in place. The possibility of separating uranium-233 produced outside the ESFR system is equally unlikely, for the fuel cycle facility is under safeguards and the insertion of exotic material compositions would be readily detected.

Second, the degree of purity of separated uranium is not clear, and since it is considered as a processing waste it is likely that no particular effort has been put in separating uranium to a high degree of purity.

Third, in order to obtain pure U-233, the routine operations of the facility would have to be altered, a batch made up only by irradiated target material would have to be processed, and the routine operations might be resumed only after having recovered the needed amount of U-233[4]

IRRADIATION OF AD-HOC TARGETS

The existence of four reactors' cores enables the host State to irradiate ad-hoc targets for producing weapon-grade nuclear material. the following paragraphs will analyse the possibility of covertly producing plutonium (Pu-239) or uranium (U-233).

Covert plutonium production

Although plutonium is readily available in the ESFR, there are two reasons a state may choose to covertly produce plutonium rather than to divert it. The state may desire better quality (so-called "weapons-grade") plutonium than that normally found in the ESFR system. It may also decide that diversion of safeguarded plutonium may more likely be detected than covert production of unsafeguarded plutonium. The processes involved in illicit plutonium production in the ESFR are the same whether the goal is achieving improved plutonium quality or simply covert production. The plutonium quality depends to a small degree on irradiation location, selection of target material, and final burn up.

In either case, the ESFR (as a fast reactor) is well-suited to plutonium production, and the scenario is essentially simple: concealed irradiation of specially prepared natural (or depleted) uranium targets inside the reactor's core.

There are three locations inside the ESFR reactor where covert irradiations might be performed: the core, the reflector or in the in-vessel fuel storage areas[5]. Preliminary assessments indicate that irradiation in the in-vessel fuel storage area is not realistic due to the negligible neutron flux in that location[6]. Similarly, preliminary assessments suggest that irradiation in the core itself is less likely to be detected than irradiation in the reflector. This is because it is very unusual to move or replace reflector elements whereas core fuel elements are frequently moved and replaced. Thus, the replacement of reflector elements with production target assemblies is more likely to be recognized as an illicit activity.

Thus, it is assessed that the most likely (i.e. least detectible) location for illicit plutonium production is in the reactor core itself. Furthermore, the outer periphery of the core seems to be preferred, mainly because the effects of reduced power generation in the

[4] If this procedure is not followed, the recovered uranium composition would mainly be U-238, and recovery of pure U-233 would not be possible.
[5] Since the baseline configuration of the ESFR core is that of a burner, no blanket is available for misuse.
[6] See Annex 1 for additional information.

target assemblies (target assemblies have less fissile material) will have less impact on overall reactor operation, and therefore is likely to be less observable and detectable.

Covert uranium-233 production

Although the ESFR is not designed to operate with a thorium-uranium fuel cycle, there are no fundamental impediments to using the ESFR to covertly produce U-233, a weapon-useable material, by irradiation of thorium targets. In fact, the only differences between the covert production of U-233 and that of plutonium are that the production of U-233 uses thorium as the fertile material, and that recovery of U-233 in the ESFR fuel cycle facility is not a viable option.

Thus, the covert production of U-233 in the ESFR is considered to be essentially identical to the covert production of plutonium. Indeed, if there is a substantive difference between the two threats, it is the fact that the U-233 production scenario, by using thorium as the fertile material, introduces a material not normally found in the system, thereby increasing the potential detectability of the scenario. This additional detectability comes both from the potential for detection of thorium compounds (via environmental sampling, in the case that the targets would be processed on site) and the unique radiation signatures associated with U-233. Because of this, this scenario has not been analyzed further. The proliferation resistance metrics of this threat are considered to be bounded by those of the covert plutonium production scenario.

MISUSE OF SKILLS AND KNOWLEDGE ON CLANDESTINE SITES

Successful design, construction and operation of any complex nuclear installation provides the host state with an array of skills, knowledge and abilities that have direct application to the production of fissile materials for weapon applications. For the ESFR this is especially true, as it involves most of the essential elements of fissile material production: fuel fabrication, reactor operation and reprocessing. The extent of these capabilities partly depends on how much of the overall effort is produced by the host state itself. For example, if the host state does not actively participate in the design of the ESFR, then that state will likely have only limited capabilities to apply to a weapons program, whether through misuse of the existing facility, replication of an ESFR (or ESFR-like) facility, or use of these capabilities for construction of other fissile material production facilities.

This threat is not unique to the ESFR, and as a result, therefore it can be seen as a cross-cutting issue that should be assessed separately.

TECHNOLOGY REPLICATION ON A CLANDESTINE SITE

Another possible scenario foresees the replication of technology and processes available in the ESFR site in a clandestine location dedicated to a military nuclear programme.

This target embeds two different possibilities: the covert replication of a complete ESFR or the covert replication of one or more of its processes.

Covert replication of an ESFR

Replication of an ESFR system at a clandestine location for production of non-safeguarded weapons material is feasible, but not the most likely scenario for a number of reasons.

First, the ESFR is a large facility and produces a significant amount of power. Both of these features produce substantial observable signatures. Even if the covert facility is limited to a single reactor there are many observables. A single ESFR reactor produces nominally 300 MW of electricity and a huge quantity of waste heat, both of which are observable and not readily explained by the host state. Moreover, if the covert system is not connected to the electric grid, then the income from electricity generation is lost and the effective cost to the host state increases dramatically.

Second, considerable infrastructure, capabilities, and resources are needed to construct an ESFR, all requirements that are unlikely met in most states today. As a result, covert construction of even a scaled-down ESFR will likely involve acquisition of components, equipment, supplies and other resources that will be detectable through existing export controls and non-proliferation arrangements with nuclear suppliers.

Third, even if such a covert plant were successfully constructed, the host state must provide sufficient unsafeguarded fissile material (either HEU or plutonium in spent fuel) to start-up the reactor. Even if this is accomplished, additional unsafeguarded fissile material must be provided for continued operation of the plant, or the reactor core must be redesigned to operate on natural (or depleted) uranium and a continued unsafeguarded supply of that material must be provided.

Covert replication of one or more processes available in the ESFR

The possibility of partially replicating the processes available in the ESFR is more realistic than replicating the entire system, and the two most attractive facilities that could be replicated are the reactor's core for irradiating uranium targets and the reprocessing facility for separating the produced plutonium. The clandestine replication of these two parts is considered to be highly unlikely for a number of reasons.

First, the original reactor core is by far too big for the intended purpose, and down-scaling even a single ESFR reactor to a size more appropriate to a state's nuclear weapons aspirations and financial capabilities is not a straightforward proposition, and one that is not assured of success.

Second, the ESFR reprocessing plant does not produce a pure plutonium target. As such either that portion of the plant requires significant modification or redesign, or additional processing steps must be added to the plant to produce the required product. This increases the cost and expertise needed to successfully accomplish this scenario.

SUMMARY OF THE MISUSE TARGET IDENTIFICATION PROCESS

Given the above considerations, a coarse analysis of the identified targets seems to consider the concealed production (breeding) of a better-than-available quality of plutonium by irradiation of uranium targets as the most attractive alternative to be analysed.

D.2.4 Misuse Pathway Identification and Refinement

Pathways represent the detailed description of the activities that the proliferator has to carry out for achieving his objectives given the choice of the selected target. Since there are many alternative ways in which he can perform the needed activities, it is generally possible to identify more than one pathway associated to a given target. A Pathway is defined as made up by three distinct stages: *Acquisition*, *Processing* and *Fabrication*. The Fabrication Stage was beyond the scope of our analysis, which will end at the processing of the material in a suitable way for the fabrication of a weapon.

Given an objective, the activity of pathways identification for misuse is not straightforward. Since a misuse strategy might involve the use of more than one target within the same system, the rigid application of the PR&PP methodology steps is here less useful than with other strategies. For a misuse analysis, the pathways cannot be mechanistically derived from the identified targets considering only one target at a time, but a more creative and iterative process is needed. For this reason, also the issue of comprehensiveness of the identified set of targets and related pathways is here more serious than in the analysis of other strategies. For this exercise, comprehensiveness will not be pursued, and the analysis will focus only on the identified target covert production of plutonium.

The high level pathway considered for the analysis consists of the concealed irradiation of uranium targets in the ESFR reactor cores (*Acquisition Stage*) and Pu recovery in a clandestine reprocessing facility (*Processing Stage*).

To implement it, the proliferator will have to perform the following activities:

1) Acquire U feed;
2) Fabricate U Pins;
3) Assemble final targets;
4) Irradiate targets in reactor core/s;
5) Disassemble targets;
6) Separate plutonium.

Each of these actives may:

a) Be further split into more elementary activities;
b) Be carried out in different ways.

This enumeration of six main activities was suitable to capture the main decisions that the proliferator has to make. The first layer of Figure D.2-2 illustrates these six activities, together with, on the other layers, possible alternatives for implementing them.

Several techniques could be used for identifying a comprehensive set of pathways on the basis of the information illustrated so far. A representation by an Event Tree, (actually a decision tree as all splits would represent choices), would have shown the links among choices and their possible dependencies. A representation with a logic tree, (a Success Tree in this case), can be derived from Figure D.2-2 simply by linking the activities of the first layer with an AND gate. For each of these activities an OR gate could represent the possible choices.

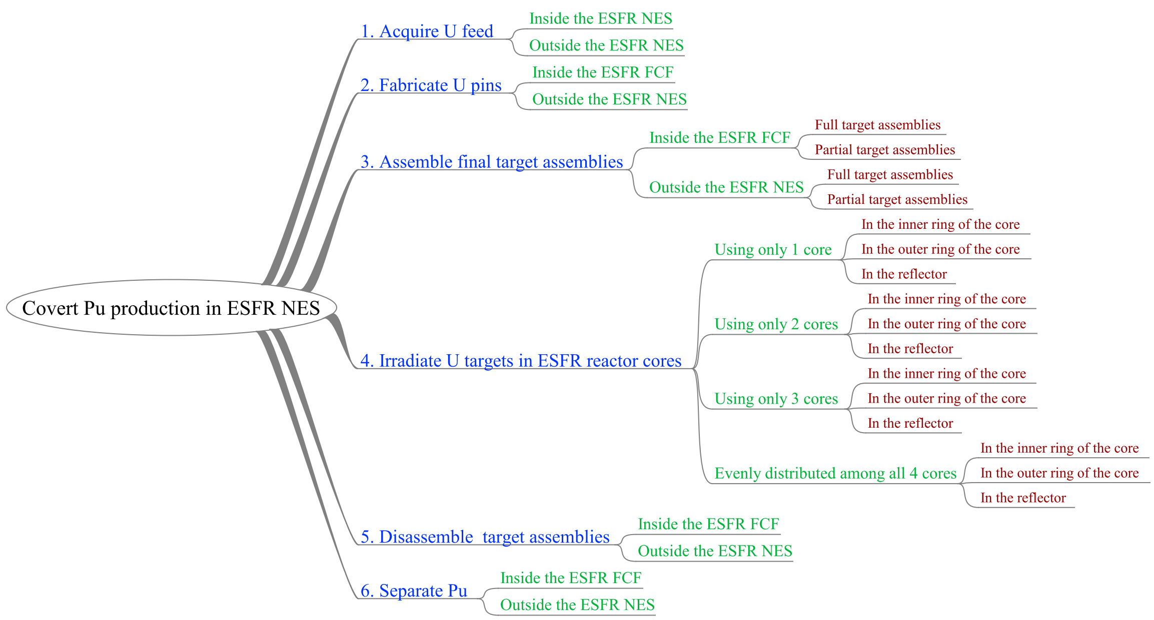


Figure D.2-2: Covert Pu production in ESFR NES: Pathway identification.

By mechanistically combing possible alternatives, Figure D.2-2 embeds up to 5184 pathways. This is too large a number of pathways for a detailed analysis even of qualitative type. At least in principle, all these pathways could be mechanistically generated and then ranked, using some criterion, in order to identify a reduced number of them for a subsequent analysis. A possible ranking criterion can be the probability of non-detection of the pathways, as the overall non-detection probability of each pathway can be computed, and is simply the product of the non-detection probabilities of the different segments, given that these probabilities can all be reasonably estimated.

Alternatively the potential pathways can be qualitatively screened with some considerations on the possible alternatives, represented by the second and third layers of figure D.2-2. The subgroup analyzing the misuse threat adopted this qualitative screening option and then selected one representative pathway that appears both feasible (from the proliferator's perspective) and sufficiently challenging (from the PR&PP methodology perspective).

For selecting this challenging pathway, the following assumptions have been made:

a) All transfers/movements inside the facility follow standard procedures and schedules for minimising the perturbation of normal operations and therefore for minimising the likelihood of detection. Irradiation time is hence fixed to 12 months.
b) For introducing nuclear material inside the ESFR site and diverting it, the proliferator will use the existing openings, e.g., maintenance access hatches.

c) The uranium pins are fabricated outside the ESFR site in order to minimise the activities performed in a safeguarded area, and therefore minimise the likelihood of detection.
d) According to data provided by Argonne National Laboratory (see Annex 1), in order to get one significant quantity of Pu in a twelve month irradiation period, between 5.2 and 11.5 full target assemblies are needed. Since there are 271 pins in each assembly, at a minimum, a total of 271 x 5.2 =1410 to 271 x 11.5 =3117 target pins are needed. Conservatively, taking the lower value of 1400 pins, these target pins are assumed to be inserted into 10 assemblies made up by standard and target pins in order to minimize the detection capability of the radiation monitors and the disturbances in the design neutron flux. Weapons Grade Pu could be obtained.
e) The target assemblies are evenly distributed among the four reactor cores available onsite to minimize the number of suspicious movements within the same core.
f) The location for irradiation has been identified in the outer ring of the core to match overall core flux, without causing safety problems or arousing suspicion.

As a result, the selected high-level pathway can be refined to the following one:

1. Host state acquires outside natural uranium (or depleted uranium (DU) if available).
2. Host state prepares target uranium pins outside the ESFR site.
3. (Host state introduces target pins into the ESFR site and then into the FCF).
4. Host state assembles ESFR final target fresh fuel assemblies made up of uranium target pins and standard ESFR fresh fuels pins using the FCF.
5. (Host state transfers target assemblies from FCF to in vessel storage baskets).
6. (Host state loads target assemblies into outer-ring of the 4 reactors cores during refuelling).
7. Host State irradiates target assemblies for 12 months in the outer ring of the core.
8. (Host state unloads target assemblies out of reactor cores into in-vessel storage baskets, during subsequent refuelling, and leaves them there for cooling).
9. (Host state transfers target assemblies out of in vessel storage baskets to FCF).
10. Host state disassembles target assemblies and recovers target pins at the FCF (then transfers target pins out of ESFR FCF to clandestine facility).
11. Host state separates Pu at a clandestine facility.

Segments, 1, 2, 4, 7, 10 and 11 correspond to the first layer of Figure D.2-2. Segments in parenthesis correspond to activities linked to the routine operation of the NES (transfers etc.).

An additional characterization of the above segments is given below in Table D.2-1.

Table D.2-1: Further characterisation of pathway segments in terms of related concealment actions and target material type.

Segment	Concealment actions	Target material type
1. Host state acquires outside natural uranium (or depleted uranium (DU) if available)	Purchase through black market	Natural Uranium
2. Host state prepares dummy uranium pins outside the ESFR site	Clandestine fabrication in undeclared facilities at undeclared sites	Natural Uranium pins
3. Host state introduces dummy pins into the ESFR site and then into the FCF	Use maintenance accesses	Natural uranium pins
4. Host state assembles ESFR final target fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins using the FCF.	Tampering with cameras in pin fabrication areas Substitution of real pins with dummy ones and hiding real pins in order to maintain global inventory	Natural Uranium pins contained in Dummy assemblies
5. Host state transfers target assemblies from FCF to in vessel storage baskets	None	Natural Uranium target pins contained in Dummy assemblies
6. Host state loads target assemblies into outer-ring of the 4 reactors cores during refuelling	None	Natural Uranium target pins contained in Dummy assemblies
7 Host State irradiates target assemblies for 12 months in the outer ring of the core	None	Natural Uranium target pins contained in Dummy assemblies
8. Host state unloads target assemblies out of reactor cores into in-vessel storage baskets, during subsequent refuelling, and leaves them there for cooling	Report modifications allowing the discharge of the dummy assemblies: a) Reports modification stating that dummy assemblies already underwent 36 months of standard irradiation period b) Reports modification for keeping other assemblies to remain 48 months in the core instead of the standard 36 months	Pu formed by the irradiation of Natural uranium target pins in dummy assemblies
9. Host state transfers target assemblies out of in vessel storage baskets to FCF	None	Pu formed by the irradiation of Natural uranium target pins in dummy assemblies
10. Host state disassembles target assemblies and recovers target pins at the FCF (then transfers target pins out of ESFR FCF to clandestine facility)	Substitution of with dummy pins with the real ones previously hidden in order to maintain global inventory Tampering with cameras in FCF	Pu formed by the irradiation of Natural uranium target pins in dummy assemblies
11. Host state separates Pu at a clandestine facility	Clandestine separation in undeclared facilities at undeclared sites	Separated Pu in metal form

D.2.5 Estimation of Measures

A possibility for estimating the PR measures would be to set up a panel of experts and to ask for their judgments, documenting their rationale. For the estimation of the pathway's PR measures a qualitative but rigorous and traceable approach has been adopted:

a) The pathway segmentation and description has been developed up to the level needed to generate meaningful measures estimates.
b) For each of the segments, questions supporting the measures estimation have been developed.
c) On the basis of the replies to the questions, estimates for each of the segment measures are derived.
d) An attempt to aggregate the estimates for each measure over the whole pathway is done.

Table D.2-2 reports most of the questions developed. Questions related to MT (Which is MT at the end of processing step?) and DE (How much does it cost to cover the segment?) were omitted from the table because they don't change through the segments. Moreover, according to PR&PP Rev. 5 methodology, MT is to be estimated at pathway level. The measures estimation for the pathway segments, in terms of replies to the above-identified questions, is shown below (Tables D.2-3 to D.2-7). The replies to questions related to MT are not reported, because it must be evaluated on the whole pathway and is set by the objectives of this analysis to weapons-grade plutonium. The PR&PP methodology suggests example quantitative metrics and scales for the estimation of the measures and on this basis a judgment of the proliferation resistance is made. Uncertainties should be also indicated both on the metrics estimates and on the derived PR judgments. On the basis of the replies reported in Tables D.2-3 to D.2-7 the PR of the segments is estimated. The respective judgments including the uncertainties are reported in Table D.2-8.[7]

[7] Part of the analysis of the baseline ESFR design for the misuse threats has been published in: G.G.M. Cojazzi, G. Renda, J-S. Choi, Applying the GIF PR&PP Methodology for a qualitative analysis of a misuse scenario in a notional Gen IV Example Sodium Fast Reactor, *INMM-49th Annual Meeting*, July 13-17, 2008, Nashville, Tennessee, USA. Table D.2-8 differs slightly from the corresponding table there reported. In table D.2-8 the PR qualifiers were derived in a normative way from the bins of Annex 2.

Table D.2-2: questions to be answered for estimating measures.

Seg	TD	PT	PC	DP
1	a) How difficult to find the necessary amount of uranium without being detected? b) How much is it difficult to perform the shipment?	a) How long does it take to organize procurement? b) How long does it take to import all necessary material?	a) How much does the material cost? b) How much does the shipment cost?	a) Is AP in place? Can AP be effectively enforced? b) Are AP measures able to detect the segment? c) Can export control and trade analysis help? d) Which is the likelihood that those measures detect the illicit action?
2	How difficult: a) to build a clandestine facility b) to train the people and to run it c) to deliver the expected output at a sufficient quality?	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to produce all the pins?	How much does it cost to set up all the needed infrastructure?	Is AP in place? Can AP be effectively enforced? Are AP measures able to detect the segment? Can export control and trade analysis help? Which is the likelihood that those measures detect the illicit action?
3	a) How difficult to introduce the pins via the maintenance routes? b) How much is it difficult to conceal the action?	How long does it take to transfer in the necessary pins?	How much does it cost to transfer in the necessary pins?	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the illicit action?
4	a) How difficult to assemble the dummy assemblies? b) How much is it difficult to conceal the action?	a) How long does it take to assemble the dummy assemblies? b) How long does it take to conceal the action?	a) How much does it cost to assemble the dummy assemblies? b) How much does it cost to conceal the action?	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the dummy assemblies?
5	How difficult to transfer dummy assemblies	How long does it take?	How much does it cost?	Same as 4
6	How difficult to insert “out-of-spec” assemblies?	How long does it take? How long does it take compared to normal operation?	How much does it cost to overcome technical difficulties?	Same as 4
7	How difficult to irradiate the dummy assemblies without compromising safety and operability?	How long does it take?	a)How much does it cost to overcome technical difficulties? b)How much does it cost e.g. in terms of variation of electricity production	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the irradiation of the dummy assemblies?
8	a) How difficult to withdraw “out-of-spec” spent assemblies? b) How difficult to perform the identified concealment?	How long does it take? How long does it take compared to normal operation?	How much does it cost to overcome technical difficulties?	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the unloading of the dummy assemblies?
9	How difficult to transfer?	How long does it take?	How much does it cost?	Same as 4
10	How difficult: a) to tamper with the camera b) to recover the dummy pins c) substitute them with the “original” ones d) transfers dummy pins out of ESFR FCF through maintenance channels e) to transfer dummy pins to clandestine facility	How long does it take to perform the actions described for TD?:	How much does it cost?	a) Which are the safeguards measures that could cover the segment? b) Which is the likelihood that those measures detect diversion or tampering?
11	Same as 2	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to process all the pins?	Same as 2	Same as 1

Table D.2-3: Measures estimation for Technical Difficulty (TD).

Seg.	Segment Description	TD Questions	TD Answers	TD Assessment
1	Host state acquires outside natural uranium (or depleted uranium (DU) if available)	How difficult is it to: a) find the necessary amount of uranium without being detected? b) perform the shipment?	a) In order to be able to import clandestinely the necessary amount of uranium, an importer not adhering to the NSG is to be found. b) The amount of needed material (500 kg) should not pose particular problems in terms of shipment	Very Low to Low
2	Host state prepares dummy uranium pins outside the ESFR site	How difficult is it to: a) build a clandestine facility b) train the people and to run it c) deliver the expected output at a sufficient quality?	a) Not enough information on the details of the equipment needed is available. Assuming a technically advanced State, the replication of the needed technology should not pose particular problems b) Since similar equipments are running in the State, training of personnel should not be a problem c) Since similar operations are routinely carried out in the declared facility, this shouldn't pose particular problems	Very Low to Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) How difficult to introduce the pins via the maintenance routes? b) How much is it difficult to conceal the action?	a) Host state controls all access to the FCF, it would not be difficult to introduce dummy elements into the ESFR and FCF. b) Once inside the FCF, the dummy elements are bag-into the assembly station as tool sets (i.e., several bag-in operations may be required)	Very Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How difficult to assemble the dummy assemblies? b) How much is it difficult to conceal the action?	a) The action involves substitution of radioactive pins with the dummy ones. The level of radioactivity will pose serious health hazards to the personnel performing the action. 154 pins per day are transferred in for fabrication. Substitution of pins at such a frequency without perturbing the overall process is not easy. Accessibility of the site for personnel is not completely clear. b) The difficulty of tampering with the camera depends on the logic with which the camera works. Might span form a simple in front of the lens tampering to more complicate action.	Medium
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How difficult to transfer dummy assemblies	Normal operation, no particular difficulty is expected	Very Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How difficult to insert "out-of-spec" assemblies?	The assembly is a regular assembly in terms of dimensions, and should not pose problems of insertions No concealment is considered to be needed.	Very Low
7	Host State irradiates dummy assemblies for 12 months	How difficult to irradiate the dummy assemblies without compromising safety and operability?	Normal operation, no particular difficulty is expected	Very Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	a) How difficult to withdraw "out-of-spec" spent assemblies ? b) How difficult to perform the identified concealment ?	a) The assembly is a regular assembly in terms of dimensions, and should not pose problems of insertions b) No sufficient information is available on the reporting system to assess the difficulty of altering reports.	Very low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How difficult to transfer?	Normal operation, no technical difficulty is expected	Very Low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How difficult is it to: a) tamper with the camera b) recover the dummy pins c) substitute them with the "original" ones d) transfers dummy pins out of ESFR FCF through maintenance channels e) transfer dummy pins to clandestine facility	a) The action involves substitution of dummy pins with the "original" ones. The level of radioactivity will pose serious health hazards to the personnel performing the action b-c) The recovery of the irradiated dummy pins and their substitution will pose serious radiological hazards to the personnel performing the action. Frequency at which substitution will have to be performed for avoiding perturbation of normal flux is high and will represent a serious challenge The accessibility to the area is not entirely clear d) Transferring the pins outside the FCF would not pose difficulties other than the radiological hazards e) Transferring the pins to the clandestine facility would not pose particular difficulties	Medium
11	Host state recovers Pu at a clandestine facility	Same as 2	a-b-c) This step is within the host state's technical capability, but would be more difficult than the pin fabrication segment	Low

Table D.2-4: Measures estimation for Proliferation Time (PT).

Seg	Segment Description	PT Questions	PT Answers	PT Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How long does it take to organize procurement? b) How long does it take to import all necessary material?	a-b) There is not much time constraint on this step. The acquisition can either be made over the years or, if needed within months	Very Low to Medium
2	Host state prepares dummy uranium pins outside the ESFR site	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to produce all the pins?	a) No sufficient information of the details of the needed equipments is available, but it is reasonable to assume that the construction might take less than a year. b) Since a similar facility is already in operation in the State, additional training of personnel is not needed c) The time needed for producing the pins depends on the dimensions of the facility. It is expected to be around few weeks	Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How long does it take to transfer in the necessary pins?	Since it is expected to introduce 1355 pins it will take time and procedure to bag-in dummy elements.	Very Low to Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How long does it take to assemble the dummy assemblies? b) How long does it take to conceal the action?	a) Assembling the ESFR assemblies will take few days b) Tampering with the camera will take a negligible amount of time	Very Low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How long does it take?	Normal operation, therefore from few months to one year.	Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How long does it take? How long does it take compared to normal operation?	The time needed for the operation is negligible and doesn't differ from regular operation	Very low
7	Host State irradiates dummy assemblies for 6.6 months	How long does it take?	The irradiation time is around the standard 12 months cycle	Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How long does it take? How long does it take compared to normal operation?	The time needed for the withdrawal is negligible and doesn't differ from regular operation. Cooling time is expected to be around 12 months	Medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How long does it take?	Normal operation, therefore from 2 to 3 years	Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How long does it take to perform the actions described for TD?:	1355 pins have to be carried away, this might take few weeks.	Very low
11	Host state recovers Pu at a clandestine facility	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to process all the pins?	a) The time to build the necessary facility is uncertain, depending on the availability of indigenous specialized equipment Even already existing hot cells might be used. From negligible to few years b) Training of personnel depends on the type of separation adopted. In case of acqueous separation, ad hoc training is needed, and several months are expected to be needed. It can be performed in parallel to the eventual building of the facility c)The time needed to process all the pins depends on the capabilities of the facility. The time to recover the WG-Pu might be as short as few weeks.	Very low to medium

Table D.2-5: Measures estimation for Proliferation Cost (PC).

Seg	Segment Description	PC Questions	PC Answers	PC Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How much does the material cost? b) How much does the shipment cost?	a-b) The acquisition and shipments cost for U should be minimal	Very Low
2	Host state prepares dummy uranium pins outside the ESFR site	How much does it cost to set up all the needed infrastructure?	The costs involved to replicate the equipment and manufacturing the fuel elements should be minimal	Very Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How much does it cost to transfer in the necessary pins?	The cost of transferring the pins should be negligible	Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How much does it cost to assemble the dummy assemblies? b) How much does it cost to conceal the action?	a-b) The cost of the segment should be negligible	Very low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How much does it cost?	Normal operation, cost is negligible	Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How much does it cost to overcome technical difficulties?	No additional cost is foreseen	Very low
7	Host State irradiates dummy assemblies for 6.6 months	How much does it cost: a) to overcome technical difficulties? b) due to potential variation of electricity production	a-b) Unless major modifications to core neutronics (and therefore e.g. electricity production) is made, no additional cost is foreseen	Very low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How much does it cost to overcome technical difficulties?	No additional cost is foreseen for the transfer. No sufficient information is available on the reporting system to assess the cost of altering reports.	Very low
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How much does it cost?	Normal operation, cost is expected to be negligible	Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How much does it cost?	The absolute cost of the segment strongly depends on the technique adopted for tampering with the camera. In any case it is supposed to be negligible in relative terms.	Very low
11	Host state recovers Pu at a clandestine facility	Same as 2	The cost of recovering the WG-Pu is mainly the cost for building and run the facility.	Very low

Table D.2-6: Measures estimation for Detection Probability (DP).

Seg	Segment Description	DP Questions	DP Answers	DP Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) Is AP in place? Can AP be effectively enforced? b) Are AP measures able to detect the segment? c) Can export control and trade analysis help? d) Which is the likelihood that those measures detect the illicit action?	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State could give the inspectorate the possibility to detect the clandestine material d) The likelihood of detecting this segment is assumed to be very low	Very low
2	Host state prepares dummy uranium pins outside the ESFR site	Is AP in place? Can AP be effectively enforced? Are AP measures able to detect the segment? Can export control and trade analysis help? Which is the likelihood that those measures detect the illicit action?	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State could give the inspectorate the possibility to detect the clandestine material d) The likelihood of detecting this segment is assumed to be on the low side	Very low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the illicit action?	a-b) The foreseen safeguards measures doesn't consider to control maintenance accesses, therefore no means to detect introduction of pins seem to exist	Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the dummy assemblies?	a) Cameras and (maybe) weighting of pins is foreseen just prior of assemblies fabrication. Cameras are supposed to be tampered with, either with in front of the lens tampering or via more sophisticated approaches. b)weighting shouldn't be able to detect anything, same thing for tampered cameras. The likelihood of detecting the tampering might be low if in front of the lens tampering is considered to be effective, high otherwise.	Low to high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 4	a) n-gamma detectors are in place in several places of the transfer route, together with xy(z) monitoring systems in the storage pit, in the washing staging area and in the reactor building. In addition, there are three different sets of cameras. b) Since the "fingerprint" of the assemblies has been taken on the dummy, detectors are unable to detect that the assembly is illegal. xyz monitoring systems and cameras do not have the possibility to spot that the segment is illicit.	Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 4	a) x-y-z positioning systems and cameras are in place. b) The measures don't seem to be able to detect that the assemblies to be loaded are dummy assemblies	Very low
7	Host State irradiates dummy assemblies for 6.6 months	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the irradiation of the dummy assemblies?	a-b) No measures are in place able to cover this segment	Very low

Seg	Segment Description	DP Questions	DP Answers	DP Assessment
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the unloading of the dummy assemblies?	a) Reports review, x-y-z positioning system and cameras are in place b) If reports are altered, x-y-z positioning system and cameras don't seem to be able to detect that the action is illegal. No sufficient information is available on the reporting system to assess the probability of detecting altered reports.	Low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 4	a) n-gamma detectors are in place in several places of the transfer route, together with xy(z) monitoring systems in the storage pit, in the washing staging area and in the reactor building. In addition, there are three different sets of cameras. b) Since the "fingerprint" of the assemblies has been Taken on the dummy, detectors are unable to detect that the assembly is illegal. xyz monitoring systems and cameras do not have the possibility to spot that the segment is illicit.	Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	a) Which are the safeguards measures that could cover the segment? b) Which is the likelihood that those measures detect diversion or tampering?	a) Cameras, neutron counters and weighting of pins is foreseen just prior of assemblies fabrication. Cameras are supposed to be tampered with, either with in front of the lens tampering or via more sophisticated approaches. b)Neutron detectors will Probably have difficulty in detecting anything weighting shouldn't be able to detect anything, same thing for tampered cameras. The likelihood of detecting the tampering might be low if in front of the lens tampering is considered to be effective, high otherwise.	Low to high
11	Host state recovers Pu at a clandestine facility	Same as 1	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State would give the inspectorate the possibility to detect the clandestine facility. c) If specialized equipments are imported from abroad, trade analysis might be of some help d) The likelihood of detecting this segment is assumed to be very low	Very low to low

Table D.2-7: Measures estimation for Detection Resources Efficiency (DE).

Seg	Segment Description	DE Questions	DE Answers	DE Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	How much does it cost to cover the segment?	Cost of covering this segment are uncertain, but could be on the high side	Low
2	Host state prepares dummy uranium pins outside the ESFR site	Same as 1	Cost of covering this segment are uncertain, but could be on the high side	Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Same as 1	Since no measures to cover the segment are in place, cost is negligible	Very high
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Same as 1	The cost of weighting sensors and cameras is very low. Man power for review is not high, therefore cost is low	Very high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 1	The segment is covered by four n-gamma detectors, three xyz monitoring systems and two different sets of cameras. These are a substantial part of the equipments in place inside the facility, and actually cover four different MBAs. Reviewing the data connected to the equipments in place will be time consuming. Cost is considered to be not irrelevant.	Medium
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 1	The segment is covered by a xyz monitoring system and by a set of cameras. The review of the data captured should not be too resources intensive.	Very High
7	Host State irradiates dummy assemblies for 6.6 months	Same as 1	The set of cameras are relatively inexpensive, but are not able to cover the segment.	Very High
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Same as 1	xyz monitoring system and cameras are relative inexpensive. No sufficient information is available on the reporting system to assess the the cost of their review	High to very high
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 1	The segment is covered by four n-gamma detectors, three xyz monitoring systems and two different sets of cameras. These are a substantial part of the equipments in place inside the facility, and actually cover four different MBAs. Reviewing the data connected to the equipments in place will be time consuming. Cost is considered to be not irrelevant.	Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	Same as 1	The segment is covered by cameras, weighting sensors and neutron detectors. The overall cost is not high	High to very high
11	Host state recovers Pu at a clandestine facility	Same as 1	Cost of covering this segment are uncertain, but could be on the high side	Low

Table D.2-8: Overall view of the qualitative estimates of the selected pathway on the baseline design.

Segment	PR(TD)	PR(PT)	PR(PC)	PR(MT)	PR(DP)	PR(DE)
1 Host state acquires natural uranium (or depleted uranium (DU) if available)	Very low to low	Very low to medium	Very low	N/A	Very low	Low
2 Host state prepares dummy uranium pins outside the ESFR site	Very low to low	Low	Very low	N/A	Very low	Low
3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Very low	Very low to low	Very low	N/A	Very low	Very high
4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Medium	Very low	Very low	N/A	Low to high	Very high
5 Host state transfers dummy assemblies from FCF to in vessel storage baskets	Very low	Low	Very low	N/A	Very low	Medium
6 Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Very low	Very low	Very low	N/A	Very low	Very High
7 Host State irradiates dummy assemblies for 12 months	Very low	Low	Very low	N/A	Very low	Very High
8 Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Very low to medium	Medium	Very low	N/A	Low to medium	High to very high
9 Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Very low	Medium	Very low	N/A	Very low	Medium
10 Host state recovers dummy pins at the FCF and transfers dummy pins out of ESFR FCF to clandestine facility	Medium	Very low	Very low	N/A	Low to high	High to very high
11 Host state recovers Pu at a clandestine facility	Low	Very low to medium	Very low	Low (WG Pu)	Very low to low	Low
Global	Medium	Medium	Very low	Low (WG Pu)	Low to high	Low to high

D.2.6 Findings on the ESFR baseline design and on the methodology

The baseline ESFR qualitative analysis highlighted that 1 SQ of WG Pu (MT) might be covertly produced in the standard irradiation period of 12 months, however such an attempt would involve challenges difficult to overcome.

TD is mainly driven by boundary conditions imposed by safeguards, especially in FCF (Segments 4 and 10), and PT is dominated by the choice of following standard operation schedule. Both measures are strongly influenced by the choice of a covert strategy, imposing all reasonable efforts to minimize detection by the international community. If the actor breaks out, PT would be greatly reduced, and it is likely that also TD would be influenced, since concealment accounts for a substantial share of the pathway difficulty.

Due to the considered Safeguards approach, DP is dominated by FCF segments, in particular by segments 4 and 10.

In view of the analysis outcomes, it has been possible to notice that the postulated safeguards approach could be improved in terms of coverage and robustness with inexpensive modifications, e.g. more control on maintenance accesses (segment 3) and foreseeing comparison of finger prints of different assemblies (5, 6, 9).

The application of the methodology to the baseline design analysis confirmed that the high-level framework illustrated in the Rev.5 methodology report is a good and robust one.

The exercise investigated a practical way of applying the PR&PP evaluation methodology at a qualitative level in a traceable way, leading to accountable and dependable results. The analysis of a misuse strategy showed how in such scenarios proliferation pathways are likely to involve more than one misuse target at a time, making their identification not entirely straightforward.

Some aspects are still open in the description of the methodology as in the rev.5 report: practical use of some measures and metrics needs further investigation (it is still unclear how to make the best use of MT and DE), and the example metrics illustrated in the report might need some additional investigations (especially those of PC and DE). Moreover, given a proliferation strategy some measures are likely to dominate over the others, and within a measure some segments will, in their turn, dominate the overall estimate.

D.2.7 Discussion on design variations

As possible design variations for the baseline design, four distinct options were proposed and considered. Of these options, one exhibits a standard burner configuration (design variation 0), the second exhibits a deep burner configuration (design variation 1), one is a self sustaining reactor with a TRU conversion factor of 1 (design variation 2) and the latter is a breeder configuration (design variation 3). The basic core characteristics of the four designs are recalled in Table D.2-9.

Table D.2-9: basic core characteristics of the baseline design and the design variations.

	Baseline ESFR	Design Variation 0	Design Variation 1	Design Variation 2	Design Variation 3
	800 MW_{th} TRU CR = 0.64	Reference 1000 MW_{th} TRU CR = 0.73	1000 MW_{th} TRU CR = 0.22	1000 MW_{th} TRU CR = 1.00 No Blankets	1000 MW_{th} TRU CR = 1.12 Radial & Internal Blankets
Nominal Electric Power, MW_e	300	350	350	350	350
Thermal Power, MW_{th}	800	1000	1000	1000	1000
Fuel composition (core / blanket)	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-20Zr / -	Metallic U-TRU-10Zr / -	Metallic U-TRU-10Zr / U-Zr
Cycle length, months	12	12	6.6	12	12
Capacity factor	85%	90%	90%	90%	90%
Number of assemblies (core / blanket)	102 / -	180 / -	180 / -	180 / -	108 / 72
Number of batches (core / internal / radial)	3 / - / -	4 / - / -	8 / - / -	4 / - / -	4 / 4 / 6
Residence time, days (core / internal / radial)	930/ - / -	1300/ - / -	1445/ - / -	1300/ - / -	1300/1300/1970
Pins per assembly (core / internal / radial)	271 / - / -	271 / - / -	324 / - / -	271 / - / -	271 / 127 / 127
Structural pins per assembly	0	0	7	0	0
Average TRU enrichment, %	24.9	22.1	58.5	14.4	19.3
Fissile/TRU conversion ratio	0.8 / 0.64	0.84 / 0.73	0.55 / 0.22	0.99 / 1.00	1.07 / 1.12
HM/TRU inventory at BOEC, MT	9.0 / 2.2	13.2 / 2.9	6.9 / 3.9	18.5 / 2.8	20.5 / 2.5
Discharge burnup (ave/peak), MWd/kg	80 / ?	93 / 138	185 / 278	67 / 103	92 /146
TRU consumption rate, kg/year	80	81.6	241.3	-1.2 (gain)	-33.2 (gain)

In the following paragraphs the proposed design variations will be briefly analyzed to understand whether a misuse strategy would still make sense or not. In particular the focus will be on the misuse of the reactor core for producing undeclared plutonium, and on whether the detailed pathway analysed in the baseline design still applies to the design variations or not. Finally, for each design variation a very high level analysis of how the measures estimates could vary in comparison to the baseline design will be proposed.

<u>DESIGN VARIATION 0</u>

The first design variation is in line with the original baseline design: it is a burner configuration (TRU conversion ratio of 0.73), and it foresees a TRU feed made from

LWR spent fuel elements. A choice of one design over the other would not have a particular impact on the overall fuel cycle strategy. The core configuration differs in the number of assemblies (180 vs. 102, with the same number of pins per assembly), their composition (22.1 vs. 24.9 % of average TRU enrichment still arranged in two zones), and their overall residence time (1300 vs. 930 days). The cycle length is the same (12 months). Preliminary ANL calculations show that to produce 1SQ of undeclared Pu from U-238 target assemblies, in a 12-month irradiation period, between 6.3 and 13.9 full target assemblies would be needed, depending on the assumptions (See Annex 1, par A.1.2).

Since the two configurations are quite similar, the pathway analysed for the baseline design is applicable also to design variation 0, and it is worthwhile to investigate how the core design's variations influence the estimates of the measures on the selected scenario. Assumptions made for the baseline design might need some adjustment, e.g., the number of partial target assemblies needed for producing 1SQ of Pu.

Due to the different core geometry and fuel recharging strategy, it is expected that the measure that would be mostly influenced by this design variation is detection probability.

DESIGN VARIATION 1

The second design variation considers a reactor in deep burner configuration, with a TRU conversion ratio of 0.22. This configuration implies a substantial variation in the overall fuel cycle strategy, deeply committed to burning transuranic elements, and this leads to a shorter cycle length (6.6 months instead of 12 months) and to a different fuel composition (in particular, the average enrichment in TRU is 58.5%, arranged in two zones, instead of ca. 22% for design variation 0). A larger number of LWR spent fuel elements per year are needed in input.

The number of assemblies within the core is the same as that foreseen for design variation 0 (but the number of pins per assembly is larger 324 vs. 271), and the overall residence time is longer (1445 days). The configuration foresees 8 batches instead of 3 (baseline) and 4 (design variation 0). This leads to an augmented number of operations aimed at shuffling around the fuel elements within the core before actual discharge.

Preliminary calculations by Argonne National Laboratory show that to produce 1SQ of undeclared Pu from U-238 target assemblies, in a 12-month irradiation period, a proliferator would need to irradiate between 12.1 and 26.6 full target assemblies, depending on the assumptions. This calculation is compatible with the irradiation of the target assemblies for two cycle lengths (13.2 months). In case of using a single fuel cycle length irradiation period, the needed number of assemblies would increase.

Also in this case, the pathway selected for the baseline study is applicable, possibly with minor differences in the original assumptions (e.g. two irradiation cycles instead of one or in the higher number of partial target assemblies needed to produce 1 SQ of Pu). Detection probability would seem to be the most influenced measure.

In case a single cycle length irradiation time is chosen, proliferation time would be reduced, although this might not end up in a significant variation on the final pathway's PT estimate.

DESIGN VARIATION 2

Design variation 2 foresees a reactor core with a TRU conversion ratio equal to unity, i.e. with the reactor producing the same amount of fissile material that it consumes. Ideally this reactor would not require additional feed in terms of TRU, however a uranium feed would be necessary.

This objective is achieved without the use of blankets, and therefore the overall core configuration doesn't differ substantially from design variations 0 and 1. The cycle length is equal to that of both the baseline system and design variation 0 (12 months) and the overall residence time is 1300 days. The number of foreseen batches is equal to that of design variation 0 (i.e. 4 batches for a complete turnover). This configuration responds to a different strategic fuel cycle picture when compared to the configurations seen so far, and this has an impact on the feed material reaching the ESFR site, which is likely to be only natural or depleted uranium instead of LWR spent fuel assemblies. The fuel composition foresees an average enrichment in TRU of 14.4%, i.e. much lower than that of the other configurations seen so far.

Although the variations within the fuel cycle facility might enable additional pathways to the ones available for the baseline design (e.g. the presence of U not only in the waste stream but also in the feed stream, with the possibility to use part of this U in order to directly fabricate target pins inside the FCF), the pathway analysed before still applies, and no particular variations in the assumptions are foreseen.

As in design variation 0, it is expected that the main difference in the measures estimation will be related to DP.

DESIGN VARIATION 3

This scenario represents a major change to the reactor design and to the fuel cycle strategy. The system core has a TRU conversion ratio greater than unity (1.12) and the design foresees the presence of both internal and radial blanket assemblies. In addition to 108 fuel assemblies (containing 271 pins each) loaded in the inner (42) and outer core (66), another 72 assemblies (containing 127 pins each) are loaded in the inner and radial blanket. The cycle length is still 12 months, and the overall residence time varies depending on the type of assembly and its location (1300 days for driver assemblies in the core, 1300 days for internal blanket assemblies, and 1970 days for radial blanket assemblies). Producing more fissile material than it consumes, this design variation foresees a net export of fissile material. This overall change will have a big impact not only on the core geometry and design, but also on the fuel cycle facility that will have to process and fabricate both core and blanket assemblies, and on the material transported into (ideally only U is needed) and out of the ESFR site (fresh ESFR fuel elements, feed for fresh fuel to be fabricated elsewhere?). In addition, a new area in the facility is to be foreseen for storage of fissile material to be shipped away.

In principle, the pathway analysed for the baseline design is applicable also with this configuration, without substantial modifications to the original assumptions. It has to be noticed that the availability of additional types of assemblies in the system and of additional zones in which targets might be irradiated (both the inner and outer blanket region), design variation 3 enables additional targets and pathways to be considered relative to design variations 0, 1 and 2. In particular, the possibility of taking advantage of the blanket region might be attractive for a would-be proliferator. It must also be noticed that the routine breeding of fissile material inside the reactor blankets already produces a nuclear fissile material that at some point in time will be of weapon-grade quality and should be considered for a pure diversion strategy. In this case, although an irradiation misuse pathway is technically feasible, the main driver for misusing the system instead of directly diverting material (producing a better than available Pu) might not exist anymore, and the only possible driver for a misuse strategy could be the consideration that it might be less detectable to produce undeclared fissile material than diverting the already available (and safeguarded) one. Even considering the latter scenario, it would seem that a misuse strategy would require many illicit actions (e.g. modifying the fuel assemblies, removing fertile pins into the assembly, removing the fertile pins from the facility) and for each of them a concealment action is needed. A pure diversion strategy would eliminate some steps and consequently also concealment would be easier and eventually the probability of detection would be lower.

D.2.8 Possible options for a detailed analysis

In principle, all the above design variations represent interesting aspects that make them candidates for a detailed pathway analysis. In general, the misuse pathways for each of these design variations are very similar to that of the baseline design. Primary differences among them are mainly in the number of pins needing irradiation and the time needed to accumulate 1 SQ.

- Design variation 0 is very similar to the baseline design, and represents a real design alternative to the same strategic need (electricity production via a fast reactor in a burner configuration) for which the baseline design has been conceived. The estimation of the detailed pathway already analysed for the baseline design would give the opportunity to test the ability of the PR&PP methodology to discriminate between very similar design options, and eventually to show how it could support designers' choices within the same "context".
- Design variation 1 is mainly an actinide burner; actinide burners are particularly attractive for the overall sustainability of the nuclear fuel cycle, and are a promising option to cope with the issue of long-living nuclear wastes. In this case, the estimation of the detailed pathway already analysed for the baseline design would give the opportunity to analyse how such a configuration affects PR when compared to a "traditional" burner, and might be useful to show how the methodology could support strategic fuel cycle decisions at policy making level.
- Design variations 2 and 3 are different forms of "self-sustaining" systems, where the input material is no more made by fissile and fertile material but by fertile material only (U-238). On the long term the strategy beneath these options is likely to be the dominant one, and the estimation of the detailed pathway already analysed for the baseline design would give the opportunity not only to compare the PR of breeding options against the PR of burner configurations, but also to analyse the impact of the presence of the blanket on the PR of self-sustaining reactors.
- Design variation 3 includes a breeding blanket, and thus is capable of producing high-quality plutonium during routine operations. Because of this, it is likely that an illicit production scenario as described here would be more complex (and therefore more likely detected) than a simple diversion of blanket material. Therefore interpretation of the PR of a misuse scenario for design variation 3 should be made in careful comparison with the PR of the related diversion pathway.

D.2.9 Qualitative analysis of a misuse pathway for design variation 0

On the basis of the consideration expressed in the previous paragraph, design variation 0 was chosen for a detailed analysis of one proliferation pathway. The main objective of the analysis is to investigate the capability of the qualitative application of the methodology to resolve differences in PR between two very similar designs. To this aim, the pathway already estimated for the baseline design has been adapted and analysed in terms of differences with the baseline analysis, which served as a reference.

In order to characterize the pathway to be estimated, the following assumptions have been made:

a) All transfers/movements inside the facility follow standard procedures and schedules for minimizing the perturbation of normal operations and therefore for minimizing the likelihood of detection. Irradiation time is hence fixed in 12 months.
b) For introducing nuclear material inside the ESFR site and diverting it, the proliferator will use the existing openings, as e.g. maintenance accesses.
c) The uranium pins are fabricated outside the ESFR site for minimizing the activities performed in a safeguarded area, and therefore minimizing the likelihood of detection.
d) Preliminary ANL calculations show that to produce 1SQ, in a year time, of undeclared Pu from U-238 target assemblies, between 6.3 and 13.9 full target assemblies would be needed, depending on the assumed U-238 capture rate. To maximize the difficulty of detecting the action, it is assumed that 6 full target assemblies are sufficient to acquire 1 SQ of Pu in a single irradiation cycle. The needed number of pins (6 assemblies x 271 pins/assembly = 1626 U target pins) are supposed to be inserted in 12 assemblies made up by standard and target pins in order to minimize the detection capability of the radiation monitors and the disturbances in the design neutron flux. Weapons Grade Pu could be obtained.
e) The target assemblies are evenly distributed among the four reactor cores available onsite to minimize the number of suspicious movements within the same core.
f) The location for irradiation has been identified in the outer ring of the core to match overall core flux, without causing safety problem or arousing suspicion.

As a result, the selected high-level pathway can be refined in the following one:

1. Host state acquires outside natural uranium (or depleted uranium (DU) if available).
2. Host state prepares target uranium pins outside the ESFR site.
3. (Host state introduces target pins into the ESFR site and then into the FCF).
4. Host state assembles ESFR final target fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins using the FCF.
5. (Host state transfers target assemblies from FCF to in vessel storage baskets).
6. (Host state loads target assemblies into outer-ring of the 4 reactors cores during refueling).
7. Host State irradiates target assemblies for 12 months in the outer ring of the core.
8. (Host state unloads target assemblies out of reactor cores into in-vessel storage baskets, during subsequent refueling, and leaves them there for cooling).
9. (Host state transfers target assemblies out of in vessel storage baskets to FCF).

10. Host state disassembles target assemblies and recovers target pins at the FCF (then transfers target pins out of ESFR FCF to clandestine facility).
11. Host state separates Pu at a clandestine facility.

Segments in parenthesis correspond to activities linked to the routine operation of the NES (transfers etc.).
For estimating the PR measures on the above pathway, the same approach illustrated for the baseline design analysis has been adopted, and since the two design options are very similar, replies to the questions illustrated in Table D.2-2 were formulated. Although these questions were originally formulated for the baseline design, they were assessed to be still fitted for the purpose. Tables D.2-10 to D.2-14 report the replies emerged during the analysis, and Table D.2-15 reports the final estimates for the six PR measures on the basis of the Rev.5 methodology report's illustrative scales. As for the baseline design, MT is set to weapons-grade plutonium.

Table D.2-10: Measures estimation for Technical Difficulty (TD).

Seg.	Segment Description	TD Questions	TD Answers	TD Assessment
1	Host state acquires outside natural uranium (or depleted uranium (DU) if available)	How difficult is it to: a) find the necessary amount of uranium without being detected? b) perform the shipment?	The needed amount of Uranium is greater than that needed by the baseline design, because the number of needed pins is greater (6 full target assemblies instead of 5). The difference is considered to be not sufficient for adding difficulty to the implementation of the segment	Very Low to Low
2	Host state prepares dummy uranium pins outside the ESFR site	How difficult is it to: a) build a clandestine facility b) train the people and to run it c) deliver the expected output at a sufficient quality?	No expected differences are foreseen compared to the baseline design	Very Low to Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) How difficult to introduce the pins via the maintenance routes? b) How much is it difficult to conceal the action?	Since the amount of pins is greater than that considered for the baseline design, it is expected that the segment might be more difficult for the introduction of pins (especially storing them waiting for the substitution). The difficulty of concealing the action might be higher due to the greater number of pins to be disguised.	Very Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How difficult to assemble the dummy assemblies? b) How much is it difficult to conceal the action?	The only difference compared to the baseline design is the greater number of assemblies to be modified. As a consequence, it is expected that the difficulty for assembling the assemblies would be substantially comparable. Since the safeguards measures are unchanged and a concealment strategy is considered, the difficulty of concealing the action is not related to the number of assemblies to be modified, therefore no substantial difference form the baseline design are foreseen.	Medium
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How difficult to transfer dummy assemblies	No expected differences are foreseen compared to the baseline design	Very Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How difficult to insert “out-of-spec” assemblies?	No expected differences are foreseen compared to the baseline design	Very Low
7	Host State irradiates dummy assemblies for 12 months	How difficult to irradiate the dummy assemblies without compromising safety and operability?	No expected differences are foreseen compared to the baseline design	Very Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	a) How difficult to withdraw “out-of-spec” spent assemblies ? b) How difficult to perform the identified concealment ?	No expected differences are foreseen compared to the baseline design	Very low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How difficult to transfer?	No expected differences are foreseen compared to the baseline design	Very Low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How difficult is it to: a) tamper with the camera b) recover the dummy pins c) substitute them with the “original” ones d) transfers dummy pins out of ESFR FCF through maintenance channels e) transfer dummy pins to clandestine facility	No expected differences are foreseen compared to the baseline design	Medium
11	Host state recovers Pu at a clandestine facility	Same as 2	No expected differences are foreseen compared to the baseline design	Low

Table D.2-11: Measures estimation for Proliferation Time (PT).

Seg	Segment Description	PT Questions	PT Answers	PT Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How long does it take to organize procurement? b) How long does it take to import all necessary material?	No expected differences are foreseen compared to the baseline design	Very Low to Medium
2	Host state prepares dummy uranium pins outside the ESFR site	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to produce all the pins?	No expected differences are foreseen compared to the baseline design	Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How long does it take to transfer in the necessary pins?	The time needed to introduce the pins would be higher due to the greater number of material to be introduced. The difference is not relevant on the overall pathway duration	Very Low to Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How long does it take to assemble the dummy assemblies? b) How long does it take to conceal the action?	The time needed for assembling 12 target assemblies will be greater than that required by the baseline design. The difference will not influence the duration of the whole pathways. The time needed for the concealment action is unchanged.	Very Low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How long does it take?	No expected differences are foreseen compared to the baseline design	Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How long does it take? How long does it take compared to normal operation?	No expected differences are foreseen compared to the baseline design	Very low
7	Host State irradiates dummy assemblies for 6.6 months	How long does it take?	No expected differences are foreseen compared to the baseline design	Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How long does it take? How long does it take compared to normal operation?	No expected differences are foreseen compared to the baseline design	Medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How long does it take?	No expected differences are foreseen compared to the baseline design	Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How long does it take to perform the actions described for TD?:	The time needed is considered to be greater due to the greater number of pins to be processed. The order of magnitude would not change and the overall impact on the pathway's duration would be irrelevant or extremely low.	Very low
11	Host state recovers Pu at a clandestine facility	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to process all the pins?	No expected differences are foreseen compared to the baseline design	Very low to medium

Table D.2-12: Replies Measures estimation for Proliferation Cost (PC).

Seg	Segment Description	PC Questions	PC Answers	PC Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How much does the material cost? b) How much does the shipment cost?	No expected differences are foreseen compared to the baseline design	Very Low
2	Host state prepares dummy uranium pins outside the ESFR site	How much does it cost to set up all the needed infrastructure?	No expected differences are foreseen compared to the baseline design	Very Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How much does it cost to transfer in the necessary pins?	No expected differences are foreseen compared to the baseline design	Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How much does it cost to assemble the dummy assemblies? b) How much does it cost to conceal the action?	Costs for assembling 12 assemblies instead of 10 would be higher, but the difference wouldn't have any impact on the costs of the overall pathway. Concealment costs are unchanged.	Very low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How much does it cost?	No expected differences are foreseen compared to the baseline design	Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How much does it cost to overcome technical difficulties?	No expected differences are foreseen compared to the baseline design	Very low
7	Host State irradiates dummy assemblies for 6.6 months	How much does it cost: a) to overcome technical difficulties? b) due to potential variation of electricity production	No expected differences are foreseen compared to the baseline design	Very low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How much does it cost to overcome technical difficulties?	No expected differences are foreseen compared to the baseline design	Very low
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How much does it cost?	No expected differences are foreseen compared to the baseline design	Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How much does it cost?	Minor costs variations compared to the baseline design might be present due to the greater number of pins to be transferred out, but these variations would be irrelevant for the overall pathway.	Very low
11	Host state recovers Pu at a clandestine facility	Same as 2	No expected differences are foreseen compared to the baseline design	Very low

Table D.2-13: Measures estimation for Detection Probability (DP).

Seg	Segment Description	DP Questions	DP Answers	DP Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) Is AP in place? Can AP be effectively enforced? b) Are AP measures able to detect the segment? c) Can export control and trade analysis help? d) Which is the likelihood that those measures detect the illicit action?	No expected differences are foreseen compared to the baseline design	Very low
2	Host state prepares dummy uranium pins outside the ESFR site	Is AP in place? Can AP be effectively enforced? Are AP measures able to detect the segment? Can export control and trade analysis help? Which is the likelihood that those measures detect the illicit action?	No expected differences are foreseen compared to the baseline design	Very low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the illicit action?	The safeguards measures are unchanged. The possibility of detection is (at least in a first approximation) dependent on the possibility to detect the tampering with the safeguards equipment and only to a lesser extent to the number of pins to be introduced. As a consequence, no expected differences are foreseen compared to the baseline design. Anyhow, the fraction of modified assemblies over the standard ones is smaller here than in the baseline design.	Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the dummy assemblies?	No expected differences are foreseen compared to the baseline design	Low to high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 4	No expected differences are foreseen compared to the baseline design	Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 4	No expected differences are foreseen compared to the baseline design	Very low
7	Host State irradiates dummy assemblies for 6.6 months	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the irradiation of the dummy assemblies?	No expected differences are foreseen compared to the baseline design	Very low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the unloading of the dummy assemblies?	No expected differences are foreseen compared to the baseline design	Low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 4	No expected differences are foreseen compared to the baseline design	Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	a) Which are the safeguards measures that could cover the segment? b) Which is the likelihood that those measures detect diversion or tampering?	The same considerations made for the baseline design are valid also here. Anyhow, the fraction of modified assemblies over the standard ones is smaller here (0.016) than in the baseline design (0.024).	Low to high
11	Host state recovers Pu at a clandestine facility	Same as 1	No expected differences are foreseen compared to the baseline design	Very low to low

Table D.2-14: Measures estimation for Detection Resources Efficiency (DE).

Seg	Segment Description	DE Questions	DE Answers	DE Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	How much does it cost to cover the segment?	No expected differences are foreseen compared to the baseline design	Identical to base case. Low
2	Host state prepares dummy uranium pins outside the ESFR site	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Very high
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Very high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Medium
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Very High
7	Host State irradiates dummy assemblies for 6.6 months	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Very High
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. High to very high
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. High to very high
11	Host state recovers Pu at a clandestine facility	Same as 1	No expected differences are foreseen compared to the baseline design	Identical to base case. Low

Table D.2-15. Overall view of the example qualitative estimates on the design variation 0.

Segment	PR(TD)	PR(PT)	PR(PC)	PR(MT)	PR(DP)	PR(DE)
1 Host state acquires natural uranium (or depleted uranium (DU) if available)	Very low to low	Very low to medium	Very low	N/A	Very low	Low
2 Host state prepares dummy uranium pins outside the ESFR site	Very low to low	Low	Very low	N/A	Very low	Low
3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Very low	Very low to low	Very low	N/A	Very low	Very high
4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Medium	Very low	Very low	N/A	Low to high	Very high
5 Host state transfers dummy assemblies from FCF to in vessel storage baskets	Very low	Low	Very low	N/A	Very low	Medium
6 Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Very low	Very low	Very low	N/A	Very low	Very High
7 Host State irradiates dummy assemblies for 12 months	Very low	Low	Very low	N/A	Very low	Very High
8 Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Very low to medium	Medium	Very low	N/A	Low to medium	High to very high
9 Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Very low	Medium	Very low	N/A	Very low	Medium
10 Host state recovers dummy pins at the FCF and transfers dummy pins out of ESFR FCF to clandestine facility	Medium	Very low	Very low	N/A	Low to high	High to very high
11 Host state recovers Pu at a clandestine facility	Low	Very low to medium	Very low	Low (WG Pu)	Very low to low	Low
Global	Medium	Medium	Very low	Low (WG Pu)	Low to high	Low to high

D.2.10 Conclusions for design variation 0 pathway analysis

Although there are major differences in the overall size and scale of the system, DV0's proliferation resistance is substantially the same of that of the baseline design. The greater number of assemblies to be modified might increase the technical difficulty and the time needed for completing some segments, but the impacts on the overall pathway's difficulty and time would be irrelevant. If standard scales are considered, even at the level of single segments the difference is not recordable.

The greater number of assemblies to be modified could lead to a greater detection probability, however:

a) The greater number of target assemblies (12 vs 10) are merged in a greater number of regular assemblies (180 vs 102);

b) When a concealment action is performed, the detection of the illicit action has more to do with the quality of the concealment than the variation on the number of assemblies considered.

The qualitative application of the methodology proposed in this exercise is able to spot even small differences in the overall scenario (the experts can pinpoint also variations that would not influence the final estimates), but the scales adopted are not suited for capturing these subtle differences.

The need of a set of scales better suited for discriminating very similar designs should be investigated. In this case, however, we think that the proliferation resistance of the two designs is comparable, and therefore a more discriminating set of scales wouldn't have made any difference.

D.2.11 Qualitative analysis of a misuse pathway for design variation 1

Similarly for what was done for the analysis of Design variation 0 a package was prepared with enough in formation inside of it and with a set of tables for allowing for a guided analysis of the pathway. This package is a by-product of the analysis and would allow for more analysis of the same pathway by additional experts if a panel of experts is settled. Hereafter the summary of the findings and the results of the analysis are reported.

Design variation 1 is based on a reactor configured for deep burn, with a TRU conversion ratio of 0.22. In particular, this configuration features a shorter cycle length (6.6 months instead of 12) and a different fuel composition (in particular, the average TRU enrichment is 58.5%, arranged in two zones, instead of approximately 25% as in the baseline design and 22% in design variation 0). See Figures 2.5 and 2.14 in Chapter 2 of this report. The higher TRU loading also means that more LWR spent fuel is necessary to fuel the reactor. Actually the burning of TRU coming from the processing of LWR spent fuel can be seen as the primary objective of this design variation.

The number of assemblies within the core is the same of that foreseen for design variation 0, but the number of pins per assembly is larger (324 vs. 271). Although the cycle length for Variation 1 is shorter than for Variation 0, the overall residence time is longer at 1435 days (vs. 1300 days in Variation 0) due to the larger number of batches foreseen in Variation 0 (8 as opposed to 3 in the Baseline and 4 in Variation 0, see Table D.2-7). The larger number of batches also means that each fuel element is handled many more times prior to discharge than in either the baseline or Variation 0 designs.

Although the design details of Variation 1 differ from those of the Baseline, the overall operations and plant layout remain similar. As such, the proliferation pathway selected for both the Baseline and Variation 0 assessments is applicable also to Variation 1. The main difference is due to the different cycle length in this variation, and leads to differing timelines and numbers of assemblies and fuel pins that must be manufactured, inserted, irradiated and removed.

The analysts used the ANL estimates for the number of target assemblies necessary to produce 1 SQ in a 12-month cycle for the baseline design to extrapolate the number of assemblies needed to do so in Design Variation 1 assuming a single 6.6 month irradiation cycle. This estimate shows that between 22 and 48 target assemblies would be needed to produce 1 SQ in a single cycle. It has to be noted that fewer (approximately half) assemblies would need to be irradiated if left in the reactor for two cycles.

Since the basic pathway is the same, the estimate of most measures is expected to be similar for this variation as in both the Baseline and Variation 0. The increased number of target pins and assemblies needed to generate 1 SQ and the increased number of operations needed to handle the increased target assemblies suggest that both technical difficulty and detection probability estimates may be increased slightly compared to the Baseline and Variation 0 cases. If irradiation during a single cycle is chosen, then proliferation time will be slightly decreased (relative to the Baseline and Variation 0) and slightly better-quality plutonium produced. Conversely, if irradiation over two cycles is selected, then detection probability may be less affected, but proliferation time slightly increases and plutonium quality slightly decreases.

In order to characterize the pathway to be estimated, the following assumptions have been made:

a) All transfers/movements inside the facility follow standard procedures and schedules for minimizing the perturbation of normal operations and therefore for minimizing the likelihood of detection. Irradiation time is hence fixed at 6.6 months.
b) The proliferator will use the existing openings (such as maintenance accesses) for introducing nuclear material into and removing material from the ESFR site.
c) The uranium pins are fabricated outside the ESFR site for minimizing the activities performed in a safeguarded area, and therefore minimizing the likelihood of detection.
d) Extrapolations from preliminary ANL calculations show between 22 and 48 U-238 target assemblies need to be irradiated in a single 6.6-month cycle to produce 1SQ, depending on the assumed U-238 capture rate. For purposes of this assessment, it is assumed that 22 full target assemblies are sufficient to acquire 1 SQ of Pu in a single irradiation cycle. The needed number of pins (22 assemblies x 324 pins/assembly = 7128 U target pins) are assumed inserted in 44 assemblies made up of both standard and target pins in order to minimize the detection capability of the radiation monitors and the disturbances in the design neutron flux. Weapons Grade Pu could be obtained.
e) The target assemblies are evenly distributed among the four reactor cores available onsite to minimize the number of suspicious movements within the same core.
f) The location for irradiation has been identified in the outer ring of the core to match overall core flux, without causing safety problem or arousing suspicion.

As a result, the selected high-level pathway can be refined in the following one:

12. Host state acquires outside natural uranium (or depleted uranium (DU) if available).
13. Host state prepares target uranium pins outside the ESFR site.
14. (Host state introduces target pins into the ESFR site and then into the FCF).
15. Host state assembles ESFR final target fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins using the FCF.
16. (Host state transfers target assemblies from FCF to in vessel storage baskets).
17. (Host state loads target assemblies into outer-ring of the 4 reactors cores during refueling).
18. Host State irradiates target assemblies for a single 6.6-month irradiation cycle in the outer ring of the core.
19. (Host state unloads target assemblies out of reactor cores into in-vessel storage baskets, during subsequent refueling, and leaves them there for cooling).
20. (Host state transfers target assemblies out of in vessel storage baskets to FCF).
21. Host state disassembles target assemblies and recovers target pins at the FCF (then transfers target pins out of ESFR FCF to clandestine facility).
22. Host state separates Pu at a clandestine facility.

Segments in parenthesis correspond to activities linked to the routine operation of the NES (transfers etc.).

A possibility for estimating the measures would be to set up a panel of experts and to ask for their judgments, documenting their rationale. For the estimation of the pathway's PR measures we adopted a qualitative but rigorous and traceable approach. a) The pathway segmentation and description has been developed up to the level needed to generate meaningful measures estimates. b) For each of the segments, questions supporting the measures estimation have been developed. c) On the basis of the replies to the questions, estimates for each of the segment measures are derived. d) An attempt to aggregate the estimates for each measure over the whole pathway is done. Table D.2-16 reports the questions developed for the estimation of the TD, measure for each segment, together with the answers and the corresponding PR judgment. Tables D.2-17 to D.2-20 illustrate the same information for the other PR measures (PT, PC, DP, DE). Finally Table D.2-21 summarizes the PR judgments of the six measures for all the segments. A notional aggregated value for the whole pathway is also given.[8]

It can the noticed that the both questions and replies highlight some differences in the measures estimation of the pathways but these differences do not result in different PR judgments neither for the segments nor for the whole pathway. In this case this can be considered as an index of not sufficient discriminating power of the binning proposed by the rev.5 methodology report, which should be considered as illustrative and tailored for each practical application.

[8] Part of the analysis of the ESFR design variations for the misuse threats has been published in: G. G. M. Cojazzi, J. Hassberger, G. Renda, Applying the PR&PP Methodology for a qualitative assessment of a misuse scenario in a notional Generation IV Example Sodium Fast Reactor. Assessing design variations, *Proceedings of Global 2009*, Paris, France, September 6-11, 2009. Tables D.2-15 and table D.2-21. differ slightly from the corresponding table there reported. In tables D.2-15 and in table D.2-21 the PR qualifiers were derived in a normative way from the bins of Annex 2.

Table D.2-16. Measures estimation for Technical Difficulty (TD).

Seg.	Segment Description	TD Questions	TD Answers	TD Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	How difficult is it to: a) find the necessary amount of uranium without being detected? b) perform the shipment?	a) In order to be able to import clandestinely the necessary amount of uranium, an importer not adhering to the NSG is to be found. However, if the state routinely imports NU or DU in sufficiently large quantities, addition of the small amount of additional material (500 kg) may go unnoticed, even if obtained through NSG-compliant sources. b) The amount of needed material (500 kg) should not pose particular problems in terms of shipment	Identical to the base case. Very Low to Low
2	Host state prepares dummy uranium pins outside the ESFR site	How difficult is it to: a) build a clandestine facility b) train the people and to run it c) deliver the expected output at a sufficient quality?	a) Not enough information on the details of the equipment needed is available. Assuming a technically advanced State, the replication of the needed technology should not pose particular problems b) Since similar equipment is running in the State, training of personnel should not be a problem c) Since similar operations are routinely carried out in the declared facility, this shouldn't pose particular problems	Identical to the base case. Very Low to Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) How difficult to introduce the pins via the maintenance routes? b) How much is it difficult to conceal the action?	a) Since the host state controls all access to the FCF, it should not be difficult to introduce dummy elements into the ESFR and FCF. b) Once inside the FCF, some effort may be required to camouflage the dummy elements to introduce them into the assembly station (perhaps as maintenance tooling.) Several bag-in operations may be required.	Identical to the base case. Very Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How difficult to assemble the dummy assemblies? b) How much is it difficult to conceal the action?	a) The action involves substitution of radioactive pins with the dummy ones. The level of radioactivity will pose serious health hazards to the personnel performing the action. The individual operations involved are identical to those of the base case. b) The difficulty of tampering with the camera depends on the logic with which the camera works. Might span form a simple in front of the lens tampering to more complicate action. However, since twice as many dummy pins are needed as compared with the base case (7128 pins vs 3117 pins) it may be somewhat more difficult to conceal the operation.	Very slightly more difficult than the base case due to the greater number of individual dummy pins operations required. Medium
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How difficult to transfer dummy assemblies	Normal operation, no particular difficulty is expected	Identical to the base case. Very Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How difficult to insert "out-of-spec" assemblies?	The assembly is a regular assembly in terms of dimensions, and should not pose problems of insertions No concealment is considered to be needed.	Identical to the base case. Very Low
7	Host State irradiates dummy assemblies for 6.6 months	How difficult to irradiate the dummy assemblies without compromising safety and operability?	Normal operation, no particular difficulty is expected	Essentially identical to the base case, although the increased number of dummy pins may increase TD very slightly. Very Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	a) How difficult to withdraw "out-of-spec" spent assemblies ? b) How difficult to perform the identified concealment ?	a) The assembly is a regular assembly in terms of dimensions, and should not pose problems of insertions b) No sufficient information is available on the reporting system to assess the difficulty of altering reports.	Essentially identical to the base case, although the increased number of dummy pins may increase TD very slightly. Very low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How difficult to transfer?	Normal operation, no particular difficulty is expected	Essentially identical to the base case, although the increased

Seg.	Segment Description	TD Questions	TD Answers	TD Assessment
				number of dummy pins may increase TD very slightly. Very Low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How difficult is it to: a) tamper with the camera b) recover the dummy pins c) substitute them with the "original" ones d) transfers dummy pins out of ESFR FCF through maintenance channels e) transfer dummy pins to clandestine facility	a) The action involves substitution of dummy pins with the "original" ones. The level of radioactivity will pose serious health hazards to the personnel performing the action b-c) The recovery of the irradiated dummy pins and their substitution will pose serious radiological hazards to the personnel performing the action. Frequency at which substitution will have to be performed for avoiding perturbation of normal flux is high and will represent a serious challenge The accessibility to the area is not entirely clear d) Transferring the pins outside the FCF would not pose difficulties other than the radiological hazards e) Transferring the pins to the clandestine facility would not pose particular difficulties	Essentially identical to the base case, although the increased number of dummy pins may increase TD very slightly. Medium
11	Host state recovers Pu at a clandestine facility	Same as 2	a-b-c) This step is within the host state's technical capability, but would be more difficult than the pin fabrication segment	Identical to the base case. Low

Note: On the basis of ANL estimates WG Pu can be obtained at the end of the pathway. Hence the measure is not included in the evaluation tables. The PR estimate for MT is already filled in Table D.2-19.

Table D.2-17. Measures estimation for Proliferation Time (PT).

Seg	Segment Description	PT Questions	PT Answers	PT Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How long does it take to organize procurement? b) How long does it take to import all necessary material?	a-b) There no significant time constraints on this step. The acquisition can be made over months or years .	Identical to the base case. Very Low to Medium
2	Host state prepares dummy uranium pins outside the ESFR site	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to produce all the pins?	a) Insufficient information of the details of the needed equipments is available, but it is reasonable to assume that the construction might take less than a year. b) Since a similar facility is already in operation in the State, additional training of personnel is not needed c) The time needed for producing the pins depends on the dimensions of the facility. It is expected to be around few weeks.	Identical to the base case. Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How long does it take to transfer in the necessary pins?	Since it is expected to introduce 1728 pins it will take time and procedure to bag-in dummy elements.	Essentially identical to the base case, although the increased number of dummy pins may increase PT very slightly. Very Low to Low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How long does it take to assemble the dummy assemblies? b) How long does it take to conceal the action?	a) Assembling the ESFR assemblies will take few days b) Tampering with the camera will take a negligible amount of time	Very Low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How long does it take?	Normal operation, therefore from few months to one year.	Identical to the base case. Low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How long does it take? How long does it take compared to normal operation?	The time needed for the operation is negligible and doesn't differ from regular operation	Identical to the base case. Very low
7	Host State irradiates dummy assemblies for 6.6 months	How long does it take?	The irradiation time is around the standard 6.6 months cycle	Same than the base case due to available binning Low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How long does it take? How long does it take compared to normal operation?	The time needed for the withdrawal is negligible and doesn't differ from regular operation. Cooling time is expected to be around 12 months	Identical to the base case. Medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How long does it take?	Normal operation, therefore from 2 to 3 years	Identical to the base case. Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How long does it take to perform the actions described for TD?:	1728 pins have to be carried away, this might take few weeks.	Essentially identical to the base case, although the increased number of dummy pins may increase PT very slightly. Very low
11	Host state recovers Pu at a clandestine facility	How long does it take: a) to build the clandestine facility? b) to train the needed personnel? c) to process all the pins?	a) The time to build the necessary facility is uncertain, depending on the availability of indigenous specialized equipment Even already existing hot cells might be used. From negligible to few years b) Training of personnel depends on the type of separation adopted. In case of aqueous separation, ad hoc training is needed, and several months are expected to be needed. It can be performed in parallel to the eventual building of the facility c) The time needed to process all the pins depends on the capabilities of the facility. The time to recover the WG-Pu might be as short as few weeks.	Identical to the base case. Very low to medium

Table D.2-18. Measures estimation for Proliferation Cost (PC).

Seg	Segment Description	PC Questions	PC Answers	PC Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) How much does the material cost? b) How much does the shipment cost?	a-b) The acquisition and shipments cost for U should be minimal	Identical to base case. Very Low
2	Host state prepares dummy uranium pins outside the ESFR site	How much does it cost to set up all the needed infrastructure?	The costs involved to replicate the equipment and manufacturing the fuel elements should be minimal,	Very slightly higher due to increased number of dummy pins involved. Very Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	How much does it cost to transfer in the necessary pins?	The cost of transferring the pins should be negligible	Very slightly higher due to increased number of dummy pins involved. Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) How much does it cost to assemble the dummy assemblies? b) How much does it cost to conceal the action?	a-b) The cost of the segment should be negligible	Identical to base case. Very low
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	How much does it cost?	Normal operation, cost is negligible	Identical to base case. Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	How much does it cost to overcome technical difficulties?	No additional cost is foreseen	Identical to base case. Very low
7	Host State irradiates dummy assemblies for 6.6 months	How much does it cost: a) to overcome technical difficulties? b) due to potential variation of electricity production	a-b) Unless major modifications to core neutronics (and therefore e.g. electricity production) is made, no additional cost is foreseen	Identical to base case. Very low
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	How much does it cost to overcome technical difficulties?	No additional cost is foreseen for the transfer. No sufficient information is available on the reporting system to assess the cost of altering reports.	Identical to base case. Very low
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	How much does it cost?	Normal operation, cost is expected to be negligible	Identical to base case. Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	How much does it cost?	The absolute cost of the segment strongly depends on the technique adopted for tampering with the camera. In any case it is supposed to be negligible in relative terms.	Identical to base case. Very low
11	Host state recovers Pu at a clandestine facility	Same as 2	The cost of recovering the WG-Pu is mainly the cost for building and run the facility.	Identical to base case. Very low

Table D.2-19. Measures estimation for Detection Probability (DP).

Seg	Segment Description	DP Questions	DP Answers	DP Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	a) Is AP in place? Can AP be effectively enforced? b) Are AP measures able to detect the segment? c) Can export control and trade analysis help? d) Which is the likelihood that those measures detect the illicit action?	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State could give the inspectorate the possibility to detect the clandestine material d) The likelihood of detecting this segment is assumed to be very low	Identical to base case. Very low
2	Host state prepares dummy uranium pins outside the ESFR site	Is AP in place? Can AP be effectively enforced? Are AP measures able to detect the segment? Can export control and trade analysis help? Which is the likelihood that those measures detect the illicit action?	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State could give the inspectorate the possibility to detect the clandestine material d) The likelihood of detecting this segment is assumed to be on the low side	Identical to base case. Very low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the illicit action?	a-b) The foreseen safeguards measures doesn't consider to control maintenance accesses, therefore no means to detect introduction of pins seem to exist.	Identical to base case. Very low
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	a) Which are the safeguards measures in place for this segment? b) Which is the likelihood that those measures detect the dummy assemblies?	a) Cameras and (maybe) weighting of pins is foreseen just prior of assemblies fabrication. Cameras are supposed to be tampered with, either with in front of the lens tampering or via more sophisticated approaches. b)weighting shouldn't be able to detect anything, same thing for tampered cameras. The likelihood of detecting the tampering might be low if in front of the lens tampering is considered to be effective, high otherwise.	Identical to base case. Low to high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 4	a) n-gamma detectors are in place in several places of the transfer route, together with xy(z) monitoring systems in the storage pit, in the washing staging area and in the reactor building. In addition, there are three different sets of cameras. b) Since the "fingerprint" of the assemblies has been taken on the dummy, detectors are unable to detect that the assembly is illegal. xyz monitoring systems and cameras do not have the possibility to spot that the segment is illicit.	Identical to base case. Very low
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 4	a) x-y-z positioning systems and cameras are in place. b) The measures don't seem to be able to detect that the assemblies to be loaded are dummy assemblies	Identical to base case. Very low
7	Host State irradiates dummy assemblies for 6.6 months	a) Which are the safeguards measures able to detect the segment? b) Which is the likelihood that those measures detect the irradiation of the dummy assemblies?	a-b) No measures are in place able to cover this segment	Identical to base case. Very low
8	Host state unloads dummy assemblies out	a) Which are the safeguards	a) Reports review, x-y-z positioning system and cameras are in place	Identical to base case.

Seg	Segment Description	DP Questions	DP Answers	DP Assessment
	of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	measures able to detect the segment? b) Which is the likelihood that those measures detect the unloading of the dummy assemblies?	b) If reports are altered, x-y-z positioning system and cameras don't seem to be able to detect that the action is illegal. No sufficient information is available on the reporting system to assess the probability of detecting altered reports.	Low to medium
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 4	a) n-gamma detectors are in place in several places of the transfer route, together with xy(z) monitoring systems in the storage pit, in the washing staging area and in the reactor building. In addition, there are three different sets of cameras. b) Since the "fingerprint" of the assemblies has been Taken on the dummy, detectors are unable to detect that the assembly is illegal. xyz monitoring systems and cameras do not have the possibility to spot that the segment is illicit.	Identical to base case. Very low
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	a) Which are the safeguards measures that could cover the segment? b) Which is the likelihood that those measures detect diversion or tampering?	a) Cameras, neutron counters and weighting of pins is foreseen just prior of assemblies fabrication. Cameras are supposed to be tampered with, either with in front of the lens tampering or via more sophisticated approaches. b)Neutron detectors will Probably have difficulty in detecting anything weighting shouldn't be able to detect anything, same thing for tampered cameras. The likelihood of detecting the tampering might be low if in front of the lens tampering is considered to be effective, high otherwise.	Identical to base case. Low to high
11	Host state recovers Pu at a clandestine facility	Same as 1	a) AP is in place and no obstacle to enforcement are identified b) Theoretically, access to all sites of the State would give the inspectorate the possibility to detect the clandestine facility. c) If specialized equipments are imported from abroad, trade analysis might be of some help d) The likelihood of detecting this segment is assumed to be very low	Identical to base case. Very low to low

Table D.2-20. Measures estimation for Detection Efficiency (DE).

Seg	Segment Description	DE Questions	DE Answers	DE Assessment
1	Host state acquires natural uranium (or depleted uranium (DU) if available)	How much does it cost to cover the segment?	Cost of covering this segment are uncertain, but could be on the high side	Identical to base case. Low
2	Host state prepares dummy uranium pins outside the ESFR site	Same as 1	Cost of covering this segment are uncertain, but could be on the high side	Identical to base case. Low
3	Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Same as 1	Since no measures to cover the segment are in place, cost is negligible	Identical to base case. Very high
4	Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Same as 1	The cost of weighting sensors and cameras is very low. Man power for review is not high, therefore cost is low	Identical to base case. Very high
5	Host state transfers dummy assemblies from FCF to in vessel storage baskets	Same as 1	The segment is covered by four n-gamma detectors, three xyz monitoring systems and two different sets of cameras. These are a substantial part of the equipments in place inside the facility, and actually cover four different MBAs. Reviewing the data connected to the equipments in place will be time consuming. Cost is considered to be not irrelevant.	Identical to base case. Medium
6	Host state loads dummy assemblies into outer-ring of reactors core (during refueling)	Same as 1	The segment is covered by a xyz monitoring system and by a set of cameras. The review of the data captured should not be too resources intensive.	Identical to base case. Very High
7	Host State irradiates dummy assemblies for 6.6 months	Same as 1	The set of cameras are relatively inexpensive, but are not able to cover the segment.	Identical to base case. Very High
8	Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Same as 1	xyz monitoring system and cameras are relative inexpensive. Insufficient information is available on the reporting system to assess the the cost of their review	Identical to base case. High to very high
9	Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Same as 1	The segment is covered by four n-gamma detectors, three xyz monitoring systems and two different sets of cameras. These are a substantial part of the equipments in place inside the facility, and actually cover four different MBAs. Reviewing the data connected to the equipments in place will be time consuming. Cost is considered to be not irrelevant.	Identical to base case. Medium
10	Host state recovers dummy pins at the FCF and transfers dummy elements out of ESFR FCF to clandestine facility	Same as 1	The segment is covered by cameras, weighting sensors and neutron detectors. The overall cost is not high.	Identical to base case. High to very high
11	Host state recovers Pu at a clandestine facility	Same as 1	Cost of covering this segment are uncertain, but could be on the high side	Identical to base case. Low

Table D.2-21. Overall view of the example qualitative estimates of the selected pathway.

Segment	PR(TD)	PR(PT)	PR(PC)	PR(MT)	PR(DP)	PR(DE)
1 Host state acquires natural uranium (or depleted uranium (DU) if available)	Very Low to Low	Very Low to Medium	Very Low	NA	Very low	Low
2 Host state prepares dummy uranium pins outside the ESFR site	Very Low to Low	Low	Very Low	NA	Very low	Low
3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF	Very Low	Very Low to Low	Very low	NA	Very low	Very high
4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins	Medium	Very Low	Very low	NA	Low to high	Very high
5 Host state transfers dummy assemblies from FCF to in vessel storage baskets	Very Low	Low	Very low	NA	Very low	Medium
6 Host state loads dummy assemblies into outer-ring of reactors core (during refuelling)	Very Low	Very low	Very low	NA	Very low	Very High
7 Host State irradiates dummy assemblies for 6.6 months	Very Low	Low	Very low	NA	Very low	Very High
8 Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refueling) and leaves them there for cooling	Very low to medium	Medium	Very low	NA	Low to medium	High to very high
9 Host state transfers dummy assemblies out of in vessel storage baskets to FCF	Very Low	Medium	Very low	NA	Very low	Medium
10 Host state recovers dummy pins at the FCF and transfers dummy pins out of ESFR FCF to clandestine facility	Medium	Very low	Very low	NA	Low to high	High to very high
11 Host state recovers Pu at a clandestine facility	Low	Very low to medium	Very low	Low (WG Pu)	Very low to low	Low
Global	Medium	Medium	Very low	Low (WG Pu)	Low to high	Low to high

D.2.12 Conclusions from the study on the Concealed Misuse of the ESFR NES

- The process of misusing a NES for achieving weapons-usable fissile material is a complex one, typically not involving a single action on a single piece of equipment, but an integrated exploitation of various assets and system elements.
- The target identification and categorization steps allow to identify different ways in which the ESFR could be misused and this can lead to a variety of pathways. This process allowed to identify an high level misuse pathway that was considered both challenging for the baseline design of the system and of potential interest for the other design variation options.
- The pathway can then be refined up to a level which allowed a rigorous and traceable estimation of the measures for the baseline design.
- The concealed aspect of the considered strategy strongly influenced the measures estimates, highlighting the role of Safeguards for this threat.

- Given a proliferation strategy some measures are likely to dominate over the others, and within a measure some segments will, in their turn, result to dominate the overall pathway estimate.

All different design options where briefly considered during the evaluation of the misuse threat and the applicability to them of the same pathway considered for the baseline design has been investigated. The same qualitative process was then preliminary applied to design variations 0 and 1 (DV0 and DV1) and confirmed these overall conclusions. As a by product of the analysis process, a packages summarizing the main features of the DV0 and DV1 and illustrating the analysis steps were also developed. These packages could serve as the basis for performing additional analyses/estimates by different analysis/experts. Design variations 2 and 3 (DV2, DV3) were not addressed in detail. Preliminary considerations suggest that a similar misuse pathway could be challenging also for DV2, while for DV3 a pure theft strategy could be more interesting from a proliferator point of view.

- The assessments of DV0 and DV1 demonstrated that the qualitative application of the methodology to a misuse scenario is capable of identifying small differences in the rationale and in measure estimates. Due to the binning process, the PR judgments for the two pathways that were analyzed were essentially the same.

It was demonstrated that the methodology was able to:

- Analyze the system proliferation resistance via a qualitative approach, providing useful results to feed back to system designers even in conditions where detailed information is largely missing.
- Provide traceability of the analysis outcomes, via the explicit recording of the evidence upon which the estimates and judgments were made. This enables the possibility of a thorough review of the analysis results, building confidence on the dependability and accountability of the outcomes.

The following improvements to the methodology were indicated by the study:

Contribution to the methodology:

- The exercise illustrated a practical way of applying the PR&PP Evaluation Methodology at qualitative level in a traceable way, leading to accountable and dependable results.

Identified weaknesses to be addressed:

- The practical use of some measures needs further investigation (it is still unclear how to make the best use of MT and DE).
- The example metrics illustrated in the Rev.5 report might need some additional investigations (especially those of PC and DE).

Annex 0. Literature on PR resistance features to misuse of reactors.

In the document IAEA-STR-332 there is a list of PR features for facilities including PR features affecting the possibility to misuse a reactor. The list is quite comprehensive and is hereafter reported. (Item 22, a-e).

"22. An intrinsic proliferation resistance feature could be a technical feature of a nuclear energy system that prevents or inhibits the undeclared production of direct-use material. Examples of such features might be:

a. no locations in or near the core of a reactor where undeclared "target" materials (i.e., source materials that can be transformed by neutron irradiation into direct-use materials) could be placed;
b. cores with characteristics that prevent operation of the reactor with undeclared "target" materials, such as cores with small reactivity margins;
c. facilities that are difficult to modify for undeclared production of nuclear material;
d. cores that are not accessible during reactor operation (so that "target" materials could only be introduced during refueling); and
e. uranium enrichment plants that cannot be used to produce high enriched uranium (i.e., uranium enriched to greater that 20% in the isotope U-235)."

There is not very much about misuse in IAEA INPRO TECDOC-1434.

In the new INPRO PR implementation manual (IAEA-TECDOC-CD-1575) misuse is explicitly considered, by three criteria (CR3.4, CR3.5, CR3.6) affecting User Requirement 3 (UR3): "the diversion of nuclear material should be reasonably difficult and detectable."

Criterion 3.4 refers to "facility process" and is related to indicator "IN3.4: Difficulty to modify process", which depends on three Evaluation Parameters (EP):

EP3.4.1: Extent of automation. (Illustrative Scale).
EP3.4.2: Availability of data for inspectors. (Illustrative Scale).
EP3.4.3: Transparency of process. (Yes/No Scale).
EP3.4.4: Accessibility of material to inspectors (Yes/No Scale).

Criterion 3.5 refers to "facility design" and is related to indicator "IN3.5: Difficulty to modify the facility design", which depends on one evaluation parameter:
EP3.5.1: Verifiability of facility design by inspectors. (Yes/No Scale).

Criterion 3.6 refers to "facility misuse" and is related to indicator "IN3.6: Detectability to misuse technology or facilities", which depends on one evaluation parameter:
EP3.6.1: Possibility to detect misuse of the technologies and the INS facilities for processing of undeclared nuclear materials. (Yes/No Scale).

Misuse is also indirectly relevant to other indicators.

Annex 1. List of questions for misuse of ESFR and replies from ANL

A.1.1 Baseline Design

a) About the neutron flux level in the in-vessel storage basket and the possibility to irradiate fertile material there.

Questions and replies from ANL:

1. What is the level of neutron flux in the in-vessel storage basket?

The neutron flux in the in-vessel storage basket is expected to be very low. The ESFR is based on the major successful design features of the EBR-II. Experience with EBR-II indicated a low neutron flux outside the core.

2. Is there shielding between the in-vessel storage basket and the core?

The core barrel design includes neutron shielding around the outside of the core barrel.

3. Can material in the in-vessel storage basket be irradiated to produce WG-Pu? E.g., if U-238 blankets are stored in the in-vessel storage basket, can the U-238 capture neutrons to produce Pu-239?

Very little activation occurs in the in-vessel storage basket. So Pu-239 production would be minimal and it would take extremely long to accumulate.

4. Is on-load refueling operation at all technically possible?

No. To remove fuel from the core, the core cover needs to be raised. The reactor can not operate with the core cover in the raised position.

5. Can the reactor be modified to allow on-load refueling to produce WG-Pu?

This would be a major modification. It would require reactor shutdown and draining of the sodium, followed by a complete re-design of the system.

b) About the number of pins to be irradiated in an assembly of the outer ring of core for obtaining one significant quantity of Pu in a year.

ANL insight:

..Without doing detailed calculations we would not be able to provide precise answers to your questions about the number of pins or assemblies that would need to be modified with DU in order to produce 1 SQ of Pu in one year.

In response to your other question about the magnitude of the flux in the ESFR, I spoke with a colleague here at Argonne and he informed me that a peak fast flux (central core region) of ~$1x10^{15}$ would be a good estimate. Also, he said that this fast flux component represents ~65% of the total flux (i.e., fast flux plus thermal flux). So this would suggest that the peak total flux in the central core region is ~$1.54x10^{15}$.

Furthermore, assuming that the peak-to-average flux ratio is similar to, but slightly more than, the peak-to-average power ratio, which is ~1.6, say ~1.7 - 1.75 for the flux ratio, then the average total flux in the core would be ~9x10^{14}.

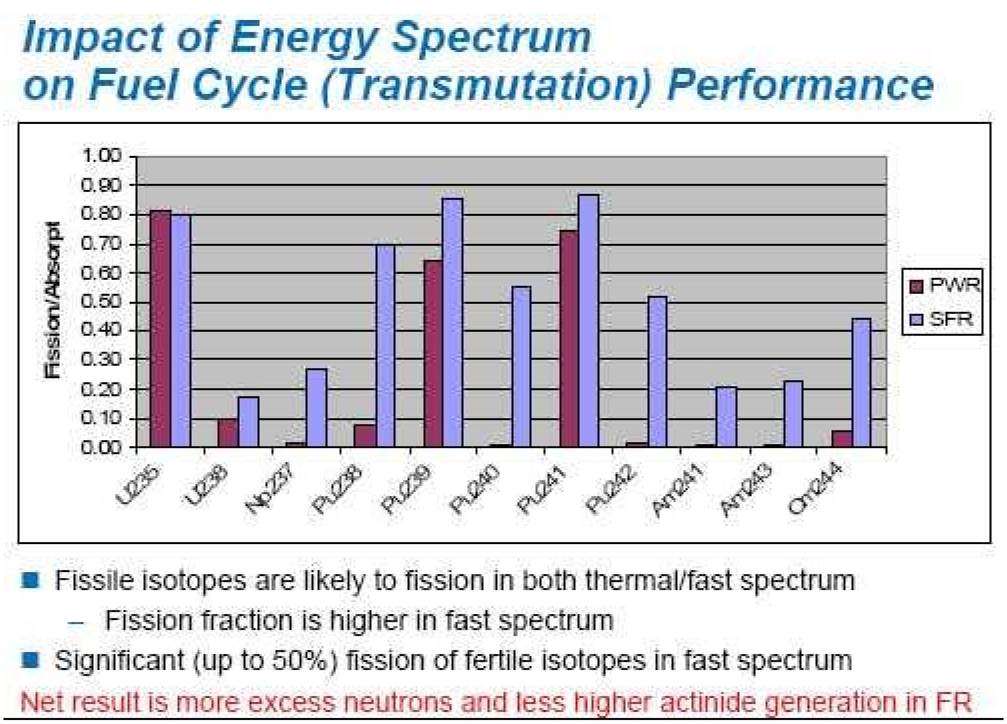
ANL Quick estimate

We made a quick calculation for outer core fuel with a U-238 microscopic capture rate ("cross-section") range of 0.25 to 0.55, and we estimated that a single 88 kg assembly of U-238 fuel pins would produce only ~700 g Pu/yr (using the 0.25 cross section) to ~1500 g Pu/yr (using the 0.55 cross-section). So, in the outer core region, as many as 11.5 entire assemblies to a minimum of 5.2 entire assemblies are required to produce 8 kg Pu in one year.

<u>c) About quality of Pu which can be produced in FR and in LWR.</u>

ANL insight:

One reason fast reactors are "better" at producing more pure Pu-239 than thermal reactors is that fast reactors also fission a proportion of the actinides as they accumulate. In thermal reactors, the actinides produced (other than Pu-239 and Pu-241) merely accumulate, thus, degrading the Pu-239 with other isotopes of Pu and other actinides. See graphic below.



<u>d) About quality of Pu which can be produced in ESFR by irradiating uranium targets in the outer ring of the core</u>

In order to understand better and to justify a misuse scenario with respect to a pure diversion scenario, it would be good to have an idea of the isotopic composition that one can get in the Pu obtained by irradiation of a dummy fuel assembly composed of pure U in the outer ring of the core for a period of 12 months.

We should be able then to compare the obtained Pu isotopic composition with the bests standard Pu of the ESFR a regime which should be that which can be obtained form the ESFR prefabricated fresh fuel. A preliminary and qualitative fast reply would be enough.

ANL Insight

In reply to your question concerning the isotopic composition of the Pu produced in a dummy assembly of depleted or natural U placed in the outer core region of the ESFR, it seems reasonable to assume that the Pu content after one year would be close to Pu-239 = ~ 97-98 %, Pu-240 = ~ 1-2 %, and all other Pu isotopes < 1 %.

<u>e) About the Detectability of dummy assemblies with partial defects</u>

Assuming a substitution of a certain number of pins (partial defect) in a fresh re-fabricated fuel assembly, what would be the detectability of such a dummy assembly?
Trivial question corresponds to the cases of the substitution of 0 pins and to the substitution of all the pins. In these cases, the detectability would be almost perfect.
What about e.g. the detectabilty of a dummy assembly with the substitution of 50 % of the pins?

As an expert judgment estimate, it can be assumed that the identification of such an assembly might be difficult.

A.1.2 Design Variations

<u>a1) About the number of pins to be irradiated in an assembly of the outer ring of the core for obtaining one signification quantity of Pu in one year in DV0 and DV1:</u>

ANL insight:

Using the following (condensed) formula, I calculated the # grams Pu generated per assembly per year for DV0 and DV1, assuming the same range for the U-238 capture rate (0.25 - 0.55):

Y (g Pu/assembly/yr) **=**

X (g HM/assembly) **** 0.0316*** (g Pu * n / g HM * barn * yr) **** capture rate*** (barn/n)

***DV0**: (1000* MW_{th}*, TRU CR = 0.73)*
X = 73000 g HM/assembly

> ***Capture rate = 0.25**, Y = 577 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 577 = **13.9 assemblies/SQ***
>
> ***Capture rate = 0.55**, Y = 1270 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 1270 = **6.3 assemblies/SQ***

***DV1**: (1000* MW_{th}*, TRU CR = 0.22)*
X = 38000 g HM/assembly

> ***Capture rate = 0.25**, Y = 301 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 301 = **26.6 assemblies/SQ***
>
> ***Capture rate = 0.55**, Y = 661 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 661 = **12.1 assemblies/SQ***

Here's how the 0.0316 term was calculated:

$$(1 \text{ mole} / 238 \text{ g HM}) * (1\text{e-}24 \text{ cm}^2 / \text{barn}) * (1\text{e}15 /n/ / \text{cm}^2 \text{ s}) * (3.15\text{e}7 \text{ s/yr}) * (239 \text{ g Pu} / \text{mole})$$

$$= 0.0316 \text{ (g Pu} * /n/ / \text{g HM} * \text{barn} * \text{yr)}$$

<u>a2) About the number of pins to be irradiated in an assembly of the outer ring of the core for obtaining one significant quantity of Pu in a year in DV2</u>

ANL insight:

The following are rough calculations for DV2, just like the ones for DV0 and DV1. Again, this is assuming an average neutron flux of 1e15 (n / cm^2 *s) and a U238 capture rate range as before.*

***DV2**: (1000* MW_{th}*, TRU CR = 1.00)*
X = 103000 g HM/assembly

> ***Capture rate = 0.25**, Y = 812 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 812 = **9.9 assemblies/SQ Pu***
>
> ***Capture rate = 0.55**, Y = 1790 g Pu/assembly per year, (8000 g Pu/SQ/yr)*
> *8000 / 1790 = **4.5 assemblies/SQ Pu***

<u>b) About the composition of the pins in the DV2 assemblies: given an assembly of a certain core zone, is the fertile material mixed in all the pins or concentrated in dedicated pins?</u>

ANL insight:

The fertile material is distributed throughout all the pins in the assemblies.
DV2 is the break-even core with no blanket assemblies. All the fuel assemblies are driver assemblies. The fuel composition is metallic U-TRU-10Zr. The average TRU enrichment is given as 14.4%. Inner core driver assemblies will have slightly lower TRU enrichment and outer core driver assemblies will have slightly higher TRU enrichment.

Annex 2: Illustrative PR measures' metrics and scales as in Rev.5 methodology report

Here below the definition of the six PR measures as in the Rev.5 Methodology report are reported:

Proliferation Technical Difficulty – The inherent difficulty arising from the need for technical sophistication, including material-handling capabilities, required to overcome the multiple barriers to proliferation

Proliferation Cost – The economic and staffing investment required to overcome the multiple technical barriers to proliferation, including the use of existing or new facilities

Proliferation Time – The minimum time required to overcome the multiple barriers to proliferation (i.e., the total time planned by the Host State for the project)

Fissile Material Type – A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives

Detection Probability – The cumulative probability of detecting the action described by a segment or pathway

Detection Resource Efficiency – The staffing, equipment, and funding required to apply international safeguards to the NES.

Measures and Metrics	Metric Scales Bins (Median)	Proliferation Resistance
Proliferation Resistance Measures Determined by Intrinsic Features		
Proliferation Technical Difficulty (TD) Example metric: Probability of pathway failure from inherent technical difficulty considering threat capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Proliferation Cost (PC) Example metric: Fraction of national resources for military capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-100% (90%)	High
	>100% (>100%)	Very High
Proliferation Time (PT) Example metric: Total time to complete pathway	0-3 mon (2 mon)	Very Low
	3 mon-1 yr (8 mon)	Low
	1-10 yr (5 yr)	Medium
	10 yr-30 yr (20 yr)	High
	>30 yr (>30 yr)	Very High
Fissile Material Type (MT) Example metric: Dimensionless ranked categories (HEU, WG-Pu, RG-Pu, DB-Pu, LEU); interpolation based on material attributes	HEU	Very Low
	WG-Pu	Low
	RG-Pu	Medium
	DB-Pu	High
	LEU	Very High

Measures and Metrics	Metric Scales Bins (Median)	Proliferation Resistance
Proliferation Resistance Measures Determined by Extrinsic Measures and Intrinsic Features		
Detection Probability (DP) Example metric: Cumulative detection probability	a	Very Low
	b	Low
	c	Medium
	d	High
	e	Very High
Detection Resource Efficiency (DE) Example metric: GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)	<0.01 (0.005 GWyr/PDI)	Very Low
	0.01-0.04 (0.02 GWyr/PDI)	Low
	0.04-0.1 (0.07 GWyr/PDI)	Medium
	0.1-0.3 (0.2 GWyr/PDI)	High
	>0.3 (1.0 GWyr/PDI)	Very High

NOTES: HEU = high-enriched uranium, nominally 95% ^{235}U; WG-Pu = weapons-grade plutonium, nominally 94% fissile Pu isotopes; RG-Pu = reactor-grade plutonium, nominally 70% fissile Pu isotopes; DB-Pu = deep burn plutonium, nominally 43% fissile Pu isotopes; LEU = low-enriched uranium, nominally 5% ^{235}U.

- a Significantly lower cumulative detection probability than the IAEA detection probability and timeliness goal for depleted, natural, and LEU uranium.
- b 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of depleted, natural, and LEU uranium).
- c 20% in 3 months, 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of spent fuel/irradiated material).
- d 50% in 1 month, 90% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity HEU/separated Pu).
- e Significantly greater cumulative detection probability than the IAEA detection probability and timeliness goal for HEU/separated Pu.

D.3 Breakout

This section analyses the third PR threat strategy considered in the Case Study, connected with breakout and the *diversion of material and/or misuse of the ESFR to produce fissile material*. It summarizes the threat strategy and discusses the associated system elements and targets identification, and pathway identification and preliminary qualitative PR analysis. Note: the breakout threat was formerly referred to as "abrogation" in PRPP literature; it was decided that "breakout" is a less restrictive term for this scenario, as a State may or may not include formal abrogation in its strategy.

D.3.1 Breakout Threat Description

Chapter 6 summarizes the assumed capabilities and objectives of the host State. This section considers the strategy of breakout. As a strategy, breakout does not exist unto itself but exists as a 'strategy modifier': ultimately every successful proliferant state necessarily breaks out if/when it decides to use or announce possession of its nuclear weapon. The nature of the breakout determines much of the nature of the threat (both the time available to the proliferant state – before and after breakout, and ultimately the complexity of weapon made possible).

Since misuse and diversion are treated explicitly in sections D.1 and D.2, including target and pathway identification, the interesting aspect of breakout will be the scenario that minimizes the time from breakout to weapons readiness, which is effectively a subset of the Proliferation Time measure: i.e., answering the question, "what is the fastest a proliferant state can prepare a weapon using ESFR technology, once international controls are moot?"

The goal of analyzing the breakout scenario is therefore to complement the concealed misuse/diversion scenarios by exploring the minimum post-breakout time to weapons readiness.

D.3.2 Breakout Target Identification

Since the breakout scenario is assumed to seek a minimum time from breakout to weapons readiness, a number of potential targets will be chosen as candidates. These targets were chosen from the following:

Diversion targets:

- stockpiled ESFR fresh fuel – Pu separation in ESFR facility;
- stockpiled ESFR fresh fuel – Pu separation in a clandestinely developed PUREX facility;
- stockpiled LWR spent fuel – Pu separation in ESFR facility;
- stockpiled LWR spent fuel – Pu separation in a clandestinely developed PUREX facility;

Misuse targets:

- o undeclared irradiation of targets & separation in ESFR fuel facility;
- o low-burnup irradiation of ESFR fuel & separation in ESFR fuel facility;
- o low-burnup irradiation of depleted uranium targets (for an ESFR breeder) & separation in ESFR fuel facility;
- o irradiation of various materials in the ESFR and separation in a clandestinely developed PUREX facility;
- o misuse of ESFR fuel facility to extract high Pu-purity TRU;

The targets chosen for further analysis were:

1. Diversion of stockpiled ESFR fresh fuel – Pu separation from spent LEU in a clandestinely developed PUREX facility (utilizing either the full pin length or just the lower-burnup ends of the pins);

2. Misuse of facility to irradiate fertile material in-core;

3. Misuse of facility to irradiate fertile material in storage basket;

4. Misuse of facility to extract high Pu-purity TRU in FCF.

D.3.3 Breakout Strategies

As described above, a unique feature of the breakout threat strategy is its coexistence with other threat strategies, affecting them primarily through the Proliferation Time measure. With this in mind, the investigation has thus far identified several general sub-categories, or strategies (perhaps “sub-strategies”), of breakout. The strategy chosen by a proliferant state will affect both the time available and potential complexity for proliferation activities, as outlined below and illustrated (qualitatively only) in Figure D.3-1.

- Immediate, absolute breakout (proliferant state decides to break out and immediately acts upon decision): minimum time, minimum complexity available to proliferation activities.
- Immediate, *ad hoc* breakout (proliferant state “effectively” breaks out through actions, without explicitly breaking out): medium time, medium complexity available to proliferation activities.
- Delayed, optional breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and intention to break out if/when detection occurs): medium time, medium complexity available to proliferation activities.
- Delayed, intended breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and a predetermined schedule for breakout and overt activity – the “load the gun” scenario): maximum time, maximum complexity available to proliferation activities.

The category of breakout chosen by a proliferant state is significantly affected by political factors (foreign relations agenda of state, probability [timing and extent] of external intervention after breakout, external dependence of proliferant state’s supply chain, etc.). These factors, although of interest, must be excluded from ESFR technology case study.

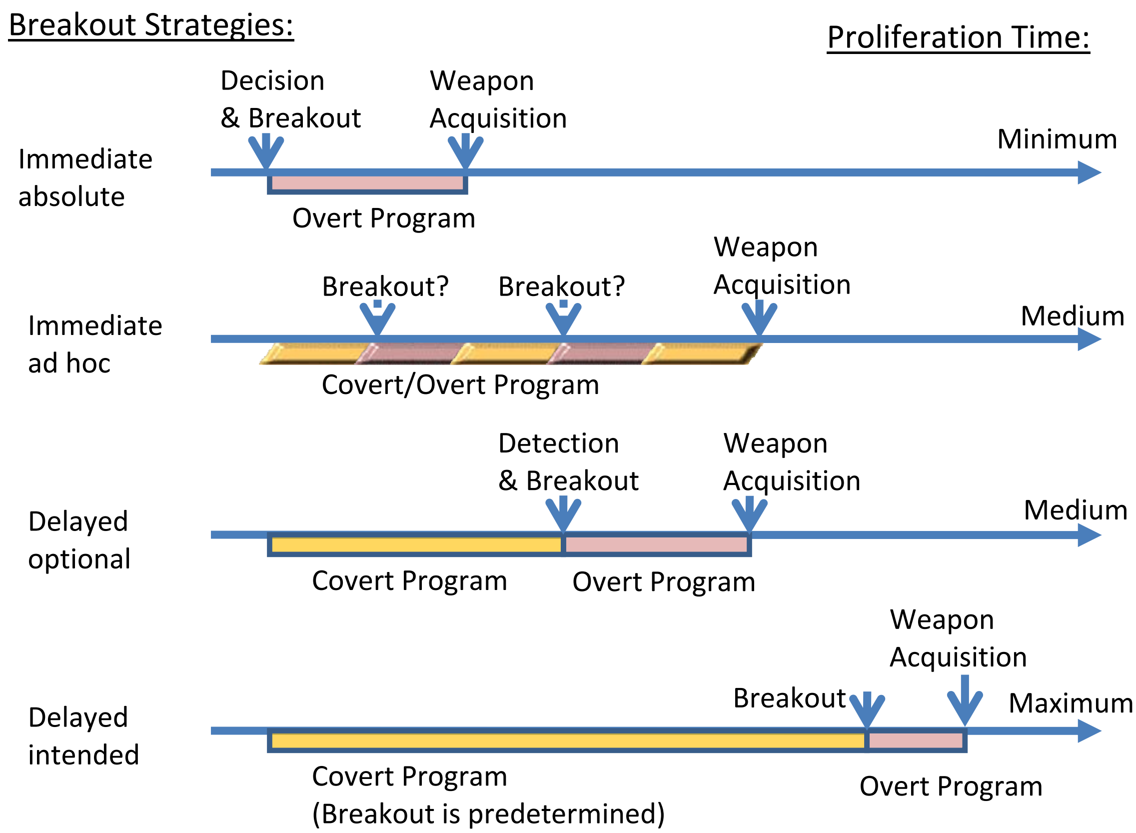


Figure D.3-1. Qualitative Depiction of Breakout Strategies

D.3.4 Breakout Qualitative Pathways Analysis

A qualitative pathways analysis is conducted in the case of each candidate target to determine relative ranking of the "proliferation time" measure, specifically as it applies to the post-breakout period. Preliminary results of this analysis are listed in Table D.3-1.

Table D.3-1. Dependence on Breakout Strategy of Target Attractiveness as Determined by the Proliferation Time Measure

Target [2]	Breakout Strategy [4] (decreasing Proliferation Time, and thus available complexity) →			
	Delayed intended[1]	Delayed optional[1]	Immediate *ad hoc*[3]	Immediate absolute
Diversion: U-TRU from LEU • full pin length	Medium	Medium	High	High
Diversion: U-TRU from LEU • top & bottom sections	High	High	High	High
Misuse: U-TRU from undeclared irradiation of targets in core	High	High	Medium	Very low
Misuse: U-TRU from undeclared irradiation of targets in storage baskets	High	High	Low	Very low
Misuse: FCF to produce high Pu-purity U-TRU	High	Medium	Low	Very low
Design Variation: breeder, *Diversion* – inner blanket	High	Medium	Low	Very low

Notes:
1. If detected – select least time path between continuing at max rate or taking TRU directly from TRU extraction
2. Requires PUREX processing, assumed in a clandestine off-site location
3. Plan is to continue, assuming "acceptable" international reaction
4. Breakout pathways would take all SQs possible; usually more than 1

D.3.5 Insights from Breakout Analysis for Further Study

Until the point of breakout is reached, safeguards, supplier-group controls, national intelligence agencies, and technical means will play a role in detecting the intent to break out. Detection probability and efficiency are important measures during this period, but play no role after breakout.

Intuitively it is not clear which, if any, of the above breakout strategy leads to a minimum post-breakout time, or if generalizations of this sort can be made. For example, “delayed, intended breakout” allows the maximum total time, but since the “gun is fully loaded” at the time of breakout it may lead to a minimum post-breakout time to weapons readiness. On the other hand this may not be the case if the proliferant state’s strategy includes overt weapons-grade material production following breakout. In this case a simpler end-product intended by a less-premeditated breakout scenario may lead to a shorter post-breakout period, and thus be more attractive. Among other things, the value of the Material Type measure is brought into question with such considerations, as strategies based upon specific political gains (for example) may be satisfied with lower-grade weapons.

Determining measures: A key issue in assessing the breakout pathways is the definition of the proliferant state’s strategy around detection, and how the state’s aversion to detection risk changes as it progresses closer to the end of the pathway. Such “dynamic strategy” considerations add another level of complexity to the analysis.

It will be informative to explore how/if pre-breakout measures can significantly affect the post-breakout time to weapons readiness (see Table D.3-2), at least on the context of the ESFR case study. It will also be interesting to make comparisons with alternate acquisition strategies, such as enrichment.

Finally, the close connection of the Breakout strategy with the Diversion and Misuse threat strategies suggests that performing a parallel pathway analysis with one of those groups, but from the point of view of a Breakout threat strategy, will potentially offer insight into how the change in threat strategy influences measures. This will be investigated using a specific baseline pathway analysis from the Misuse analysis.

Table D.3-2. Factors Benefiting Breakout and Measures that Address These

Phase	Breakout Factor	PRPP Measure
Pre-Breakout	Low probability of detection of diversion/misuse	• Detection probability • Detection resource efficiency
	Low scrutiny of collateral clandestine activities to reduce time for subsequent overt activities	• Detection probability (Additional Protocol) • Detection resource efficiency • Proliferation time • Technical difficulty (need to start technical development in pre-breakout phase)
	Low scrutiny/interference of supply chain to acquire needed equipment and materials	• Detection probability (Additional Protocol?) • Technical difficulty (need to import equipment, vs. domestic development) • Proliferation cost
Post-Breakout	Available time/speed of development	• Technical difficulty • Proliferation time • Material type
	Available inventory and material type	• Detection probability (addresses build-up of NM inventory during pre-breakout stage) • Material type
	Technology for weaponization	• Technical difficulty • Material type • Detection probability (addresses build-up of necessary technology during pre-breakout phase)
	Knowledge for weaponization	• Technical difficulty • Material type • Detection probability (addresses build-up of necessary expertise during pre-breakout phase)
	Physical barriers to external intervention	• Transparency of facilities * • Robustness of facilities *
	Political barriers to external intervention	• Foreign relations (will and ability to intervene) * • Response time and capability *

* These measures not included in PRPP methodology

D.4 Theft of Fissile Material and Sabotage of System Elements

This section analyzes the PP threat objective considered in the Case Study, connected with the *theft of fissile material from the ESFR* and *sabotage of select ESFR system elements*. It summarizes the threat description and discusses the associated system elements and target identification, and pathway identification and preliminary qualitative PP analysis.

D.4.1 Theft/Sabotage Threat Description

Using the methodology developed by the Generation IV Proliferation Resistance and Physical Protection (PRPP) Expert Group to analyze the proliferation resistance and physical protection robustness of future Generation IV nuclear energy systems, a theft scenario and sabotage scenario will be analyzed. Scenarios will be developed using the ESFR as our case study.

D.4.2 Generic Site Boundary Identification

In order to establish a baseline definition for physical protection areas within a facility; the following diagram represents the generic site layout.

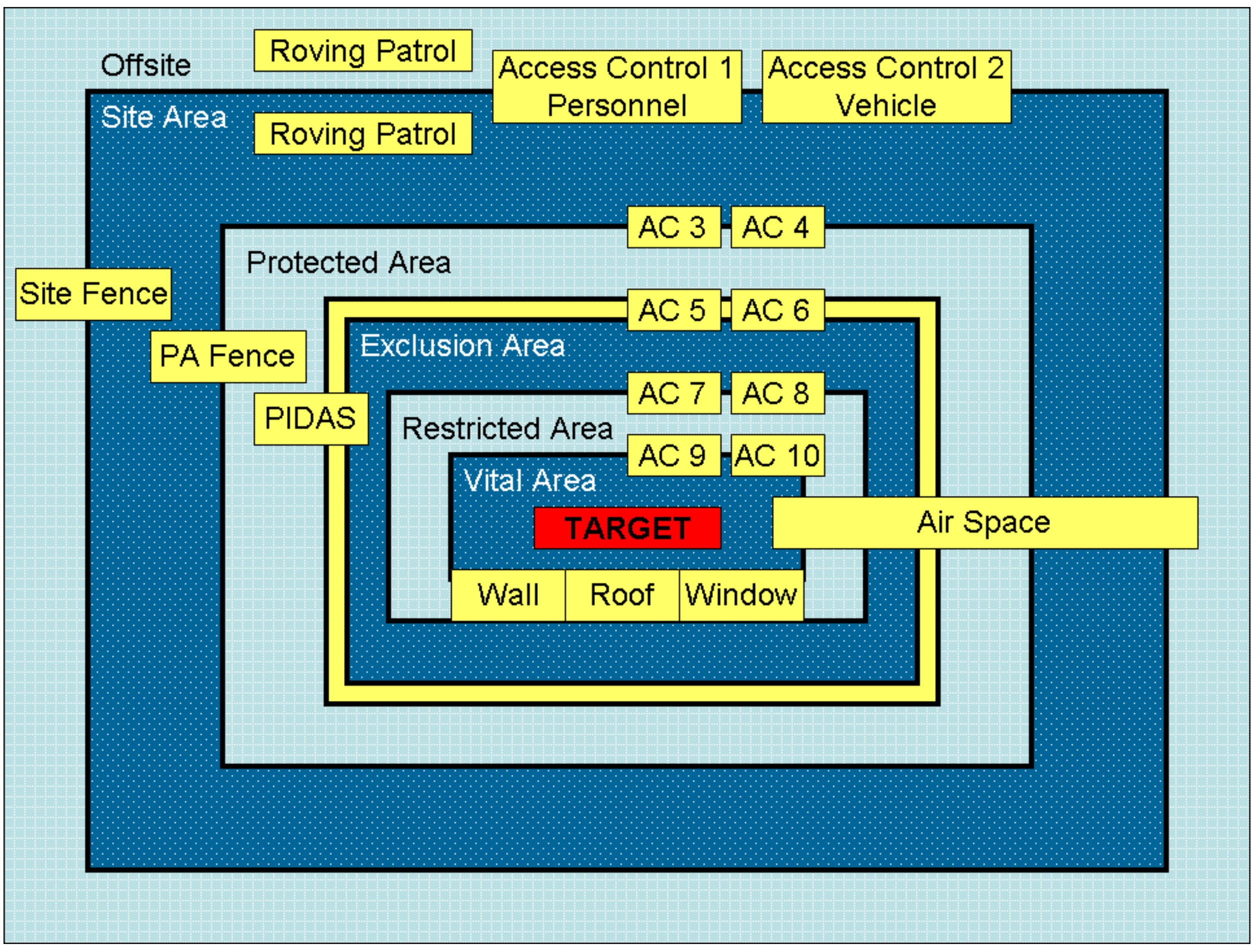


Figure D.4-1. Generic Site Layout

The outermost layer of the site layout is referred to as the offsite area. This is the surrounding area not owned by the host facility. This can be public or private lands.

The next layer is the site area. This area is the outermost boundary of the facility. Typically a site fence is constructed around the entire site perimeter providing the first layer of protection. Access to the site area is limited to access control points. Two types of access control points are identified in the generic site layout. Access Control (AC) 1 Personnel is an access point for individuals on foot, where as AC 2 Vehicle are areas that are designed to accommodate vehicles that must enter and exit the facility. (For consistency, all even numbered ACs are access points for vehicles, and odd numbered ACs are access points for personnel.) The site area is typically where office buildings, parking, and non-plant structures are located.

The next layer is the protected area (PA). A PA fence establishes the boundary between the protected area and the site area. Again access control points are established to allow control entry into the PA. The PA is traditionally where maintenance facilities are located, dry cask storage, plant auxiliary buildings and occasionally the cooling tower.

The next layer in the generic site layout is the exclusion area. The exclusion area is surrounded by PIDAS (Perimeter Intrusion Detection and Assessment System). The boundary around the exclusion area is no longer a simple chain link fence, but is now an enhanced barricade to delay, deter and detect an adversary. This area typically consists of non-safety related components and emergency backup equipment (i.e. emergency diesel generators).

The next layer is the restricted area. This area typically consists of safety related components.

Within the restricted area is the vital area; which with regards to most PP designs contains the primary target material. The entire PP system is designed to enhance protection around the target area. While access to the vital area is controlled by ACs; other means of entry are reflected on the diagram as potential entry points for adversaries.

In addition, Air Space is reflected on the diagram to indicate that all areas are accessible via air craft.

The layered site layout provides increased security, detection and deterrence factors as one moves from the outer to the inner most layer. However, it should be noted that although the PP system is designed to protect the primary target other target areas exist that are contained within the other areas of the facility, for example spent fuel in dry storage.

D.4.3 Theft/Sabotage Actor Definition

The importance of a specific PP threat depends on facility characteristics and the level of design detail available. However, each threat specified in the sections below should be reviewed as a part of the evaluation process. As presented in Table D.4-1, the definition of a PP threat has two components: a description of the actor (which includes type, objectives, and capabilities); and a description of the actor's strategy. The threat space is defined by considering an appropriate range of combinations of actors and strategies. For this study, one threat will be specified to exercise the methodology.

Three types of actors must be considered to define the PP threat space:

- Outsiders
- Outsiders in collusion with insiders
- Insiders alone.

Outsiders can include armed terrorist groups, agents of proliferant states, advocacy group, organized criminal gangs, and lone individuals. Insiders can be sympathetic with outsiders but may also include disaffected, anti-social, mentally unstable, or suborned employees or contract staff.

The PP assessment should consider a mixture of non-host state and sub-national threats. This mixture can lead to complicated analyses but is necessary to consider the synergism between categories. The level of detail to which the actor is defined should be appropriate to the assessment goals. For system assessments where operations would start decades in the future, the definition of the actor types will be qualitative and stylized. Where operations would occur in the present or near future, the actor definitions will likely be specific and detailed.

Five categories of actor capabilities must be considered to define the PP threat space:

- Knowledge (including outsider access to insider knowledge)
- Skills
- Weapons and tools (commercial, military, or improvised)
- Number of actors
- Commitment and dedication (risk tolerance up to self-sacrifice).

Five categories of actor objectives must be considered to define the PP threat space:

- Sabotage intended to disrupt normal operations
- Sabotage intended to cause radiological release
- Theft for production of nuclear explosives
- Theft for production of RDDs
- Theft of technical information.

Table D.4-1. Summary of the PP Threat Dimensions

Actor Type	• Outsider • Outsider with insider • Insider alone • Above and non-Host State
Actor Capabilities	• Knowledge • Skills • Weapons and tools • Number of actors • Dedication
Objectives (relevant to the nuclear fuel cycle)	• Disruption of operations • Radiological release • Nuclear explosives • Radiation Dispersal Device • Information theft
Strategies	• Various modes of attack • Various tactics

For this study we define the following specific threat:

Actor Type: Military trained assault force
Actor Capabilities:

- ***Knowledge*** – knowledge of plant layout and PP basic design, sufficient knowledge of plant processes to understand targets of opportunity
- ***Skills*** – ability to design assault equipment to penetrate barriers, training in using assault weapons,
- ***Weapons and tools*** – assault weapons, specialized explosive ordinance, armored vehicles
- ***Numbers of actors*** – 12 outsiders and 1 insider
- ***Dedication*** – Military Objective oriented

Objective: Theft of items from the ESFR facility in sufficient quantity to obtain 1 SQ of nuclear weapon material.
Strategy: Surprise assault on ESFR facility directed at material storage areas.

D.4.4 Theft Scenario Example Analysis

The following section will out line the target identification for the ESFR and potential pathways with regard to potential theft scenarios. In addition, both qualitative and quantitative examples will be presented to demonstrate the methodology.

D.4.4.1 Theft Target Identification

The section identifies areas of the ESFR that could be the target for theft of nuclear materials (modified from *PR&PP Evaluation Methodology Development Case Insights Report*, Rev. 3a, January 14, 2005).

ESFR Nuclear System Elements

The ESFR layout is shown in Figure D.4-2, taken from "Safeguarding the ESFR Nuclear Energy System". The plant boundary is not shown on this figure, but is assumed to be several hundred acres.

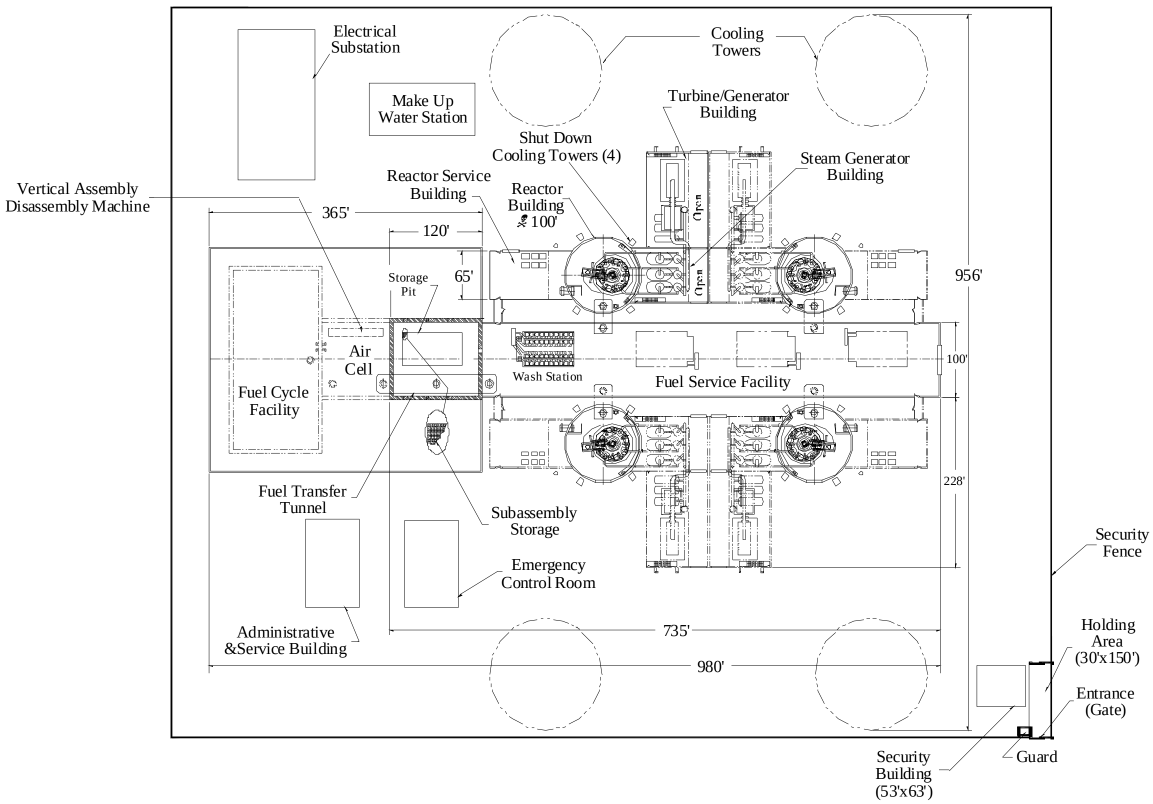


Figure D.4-2. ESFR Nuclear Energy System Site Layout

Within the plant boundary, as in "Safeguarding the ESFR Nuclear Energy System" (*ESFR-Safeguards-rev3.92*) material balance areas were identified that would incorporate accessible or removable targets for the theft of nuclear materials. These include:

- LWR Spent Fuel Casks Parking
- LWR Spent Fuel Storage
- Fuel Cycle Facility
    - Air Cell (Hot Cell)
    - Inert Hot Cell
    - Staging/Washing Area

These target areas are shown in Figure D.4-3 below, taken from "Safeguarding the ESFR Nuclear Energy System".

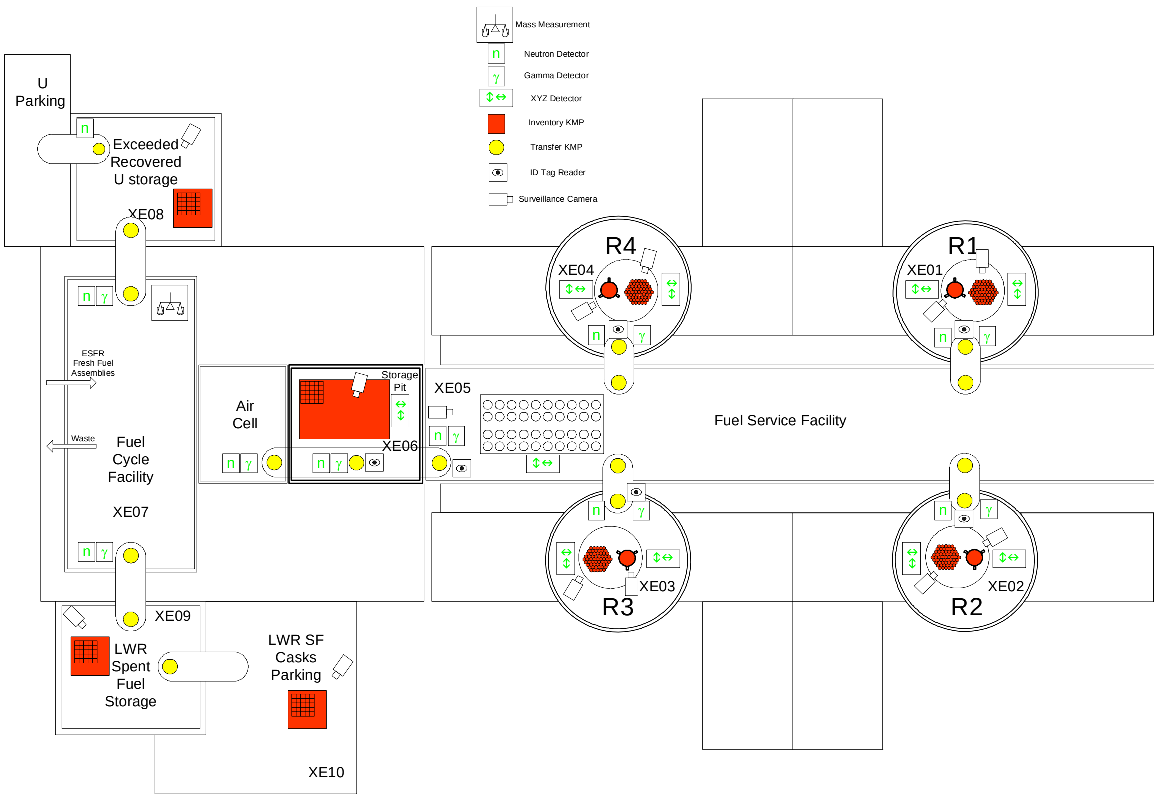


Figure D.4-3. ESFR Safeguards Approach

Note that the reactor itself is not included, in this paper, since fuel inside the core is not accessible, without very time-consuming measures, as compared to that in other facility locations and is not transportable for any distance without a shielded vehicle. Rather, item storage areas are considered more attractive due to the mobility of the materials as items.

LWR Spent Fuel Cask Parking:

The target material in the LWR Spent Fuel Cask Parking area is the full spent fuel assemblies of LWR fuel that have arrived on site, and have not yet been unloaded from the shipping cask. This may not include sufficient nuclear material quantity to be an attractive target, so one or more additional assemblies that have been unloaded may be needed to obtain a sufficient quantity. Depending on the shipment mode, a cask can contain 4 to 9 PWR spent fuel assemblies. There is sufficient nuclear material in a full cask shipment to acquire several SQ of Pu. Each PWR spent fuel assembly contains ~ 4-6 kg Pu, depending upon the burnup. A typical 110-tonne Type B cask can hold up to 6 tonnes of spent fuel, which is equivalent to 9 PWR spent fuel assemblies containing ~ 36-54 kg Pu. Even larger casks are often used in the U.S. These are robust 125-tonne Type B casks carried by rail, each containing up to 20 tonnes of spent fuel (equivalent to 30 spent PWR fuel assemblies). Assumption 10 on p.23 of the Development Study Insights Report states that a standard PWR transportation cask houses 21 PWR spent fuel assemblies. This is equivalent to 84-126 kg Pu.

LWR Spent Fuel Storage

The target in the LWR Spent Fuel Storage area is full spent fuel assemblies that have been unloaded from the shipping cask and are inside the LWR Spent Fuel Storage building. This building is assumed to be a metal shed or concrete block style building with a spent fuel pool inside. Two PWR spent fuel assemblies contain more than 1 SQ of Pu.

Fuel Cycle Facility
Air Cell (Hot Cell)

Target material consists of full assemblies waiting to have the fuel rods removed from the assembly and fuel rods that have been removed from a fuel assembly. In both cases, these are full length fuel rods. A typical SFR-L2 spent fuel assembly from the ESFR is made up of 271 fuel pins and contains 17.6 kg Pu. A half of an assembly would provide the adversary with a significant quantity of material; however, stealing an entire assembly would be more efficient and less time consuming. (See Appendix 2.A by J.S. Choi in the Development Study Insights Report.)

Fuel Cycle Facility
Inert Hot Cell

Most of the fuel reprocessing occurs in the argon inerted hot cell. Full length, intact fuel elements are in the cell, as well as the elements that have been chopped into shorter lengths.

Chopped elements are electro-refined, but this material would be “in-process” in a batch sized melt chamber, with batch sizes small enough to prevent criticality. This makes this in-process material an unlikely target, both from a quantity and access to molten material in a melt chamber.

Uranium product and transuranic-uranium material would likely be in batch sized slugs or pucks. The make-up U from PWR spent fuel would typically be enriched only very slightly above natural uranium, to approximately 0.8% ^{235}U. The U from SFR-L2 spent fuel would not be appreciably enriched in ^{235}U. The initial loading of a fast reactor is ~20% enriched in U-235. Once a recycle system is in full swing, the U-235 content will be replaced with Pu/TRU fissile material. The enrichment of PWR SNF will be quite low, but the facility, at least at the start, will have large quantities of enriched U available.

Fissile makeup material is also available as a target in this cell (and outside the cell where it is staged to enter).

The uranium, TRU-U product and fissile makeup materials are combined to form fuel slugs. While each batch is in process, it is in a furnace and not a ready target. The resulting fuel slugs are a target.

The fuel slugs are assembled into fuel pins and then into fuel elements, which are also a target.

Around the entire cell, targets include: full length intact fuel elements (both entering and leaving), chopped fuel elements, pucks of TRU-U material, fissile makeup material, fuel slugs, and fuel pins. There is sufficient material around the entire cell to obtain 1 SQ of Pu.

Fuel Cycle Facility

Staging/Washing Area

Spent full length fuel assemblies are in the staging and washing area, for removal of external excess sodium after removal from the adjoining reactors. Re-fabricated assemblies are wetted with sodium, heated and staged in this area for the next core load. So, full assemblies, both spent and newly-refabricated are targets. Each assembly is stored in a special crucible for containment and atmosphere control. A typical PWR spent fuel assembly weighs ~ 650 kg. It will be necessary for the adversary to steal two assemblies.

D.4.4.2 Theft Pathway Identification

Once the targets are identified, then pathways to those targets can be identified, as in the following figures. The pathways are outlined in terms of Adversary Sequence Diagrams for Theft as described in Figures D.4-4 through D.4-13.

This report only addresses theft with removal of the target to the site boundary, and does not address activities beyond the site boundary.

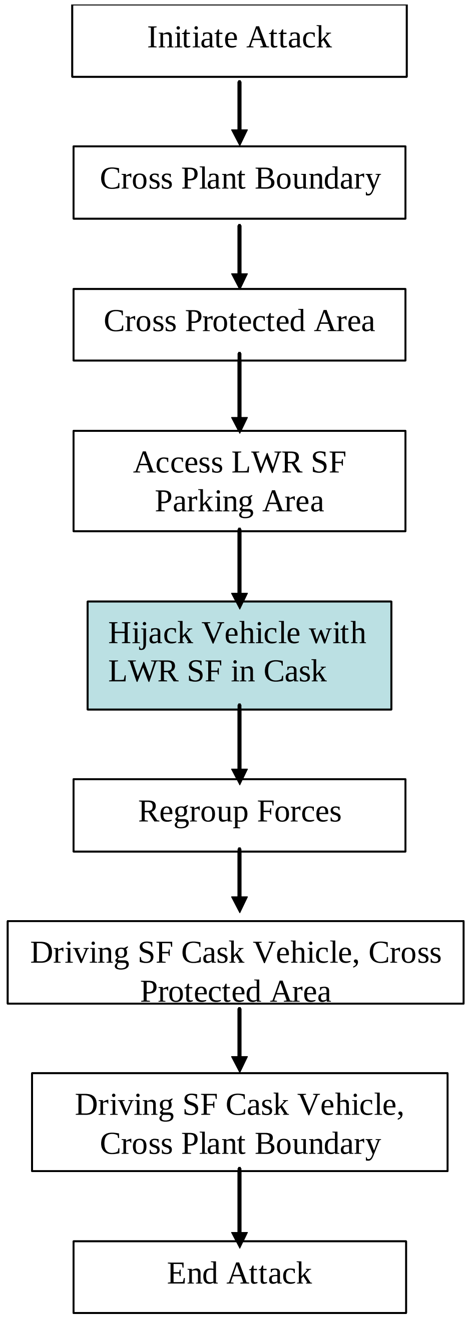


Figure D.4-4. Adversary Sequence Diagram for Theft of LWR Spent Fuel in Spent Fuel Cask on Vehicle in LWR SF Storage Parking/Loading/Unloading Area

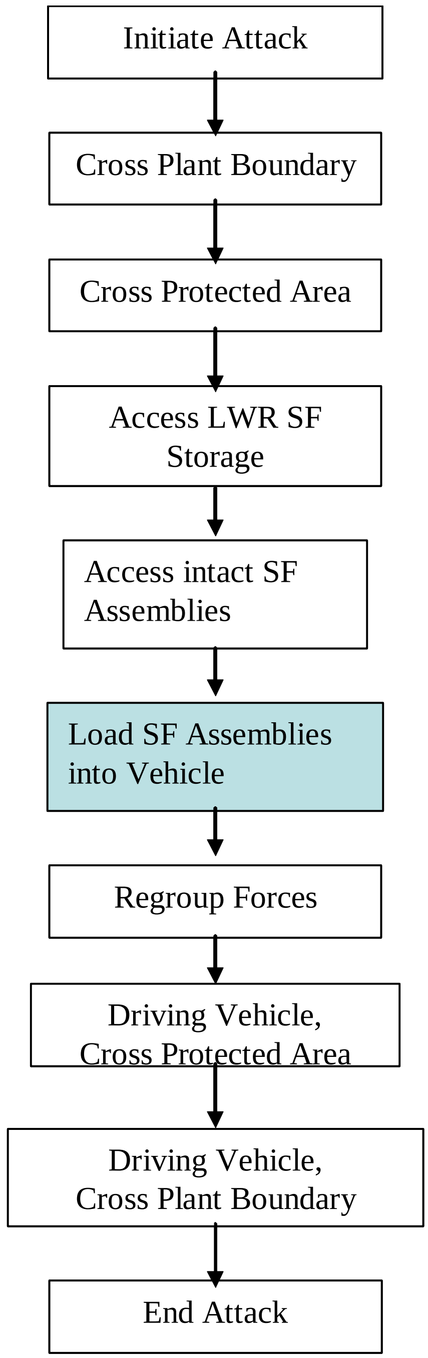


Figure D.4-5. Adversary Sequence Diagram for Theft of LWR Spent Fuel in LWR SF Storage Area

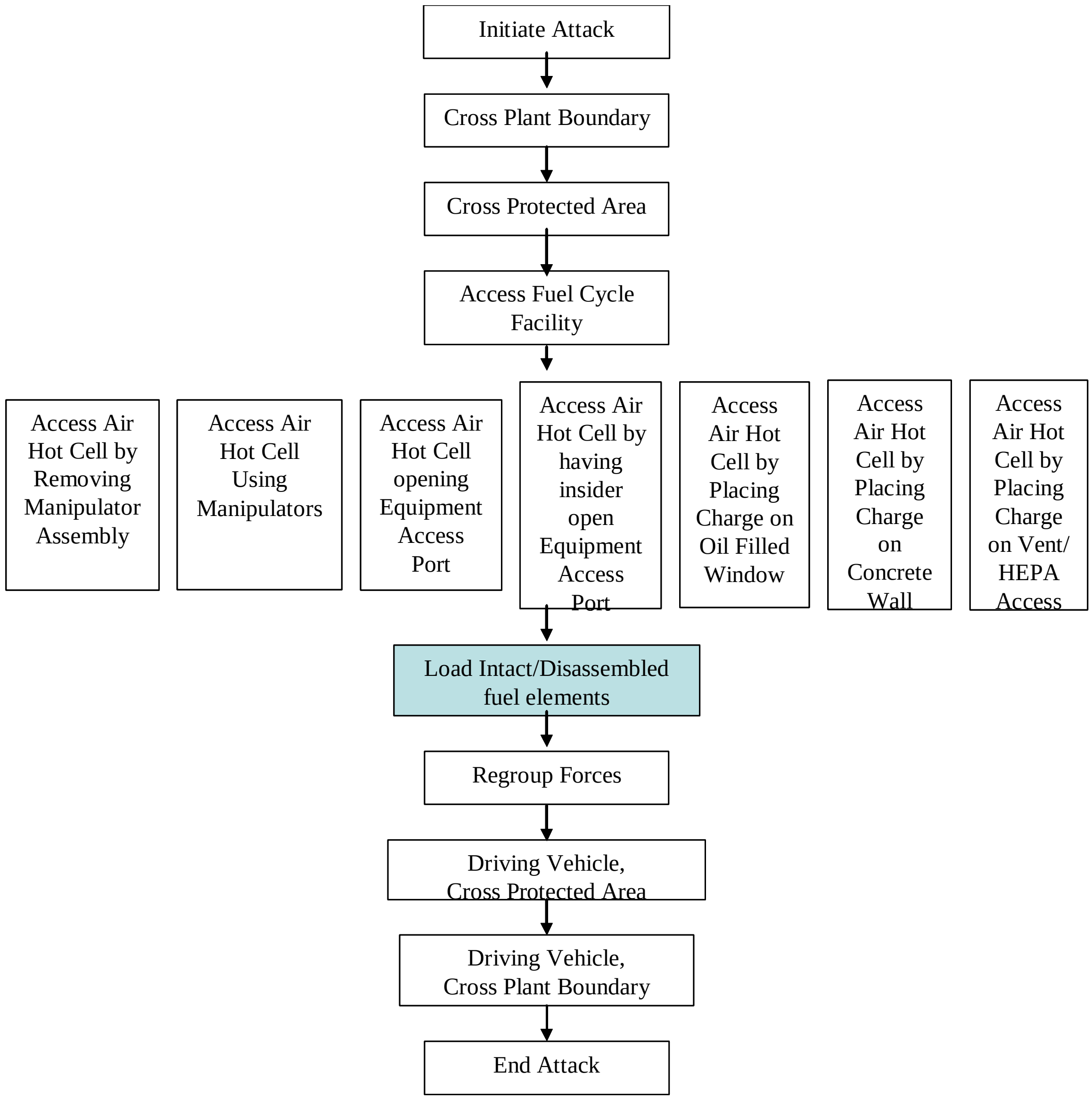


Figure D.4-6. Adversary Sequence Diagram for Theft of Intact/Disassembled Fuel Rods (in Receiving/Shipping Cell)

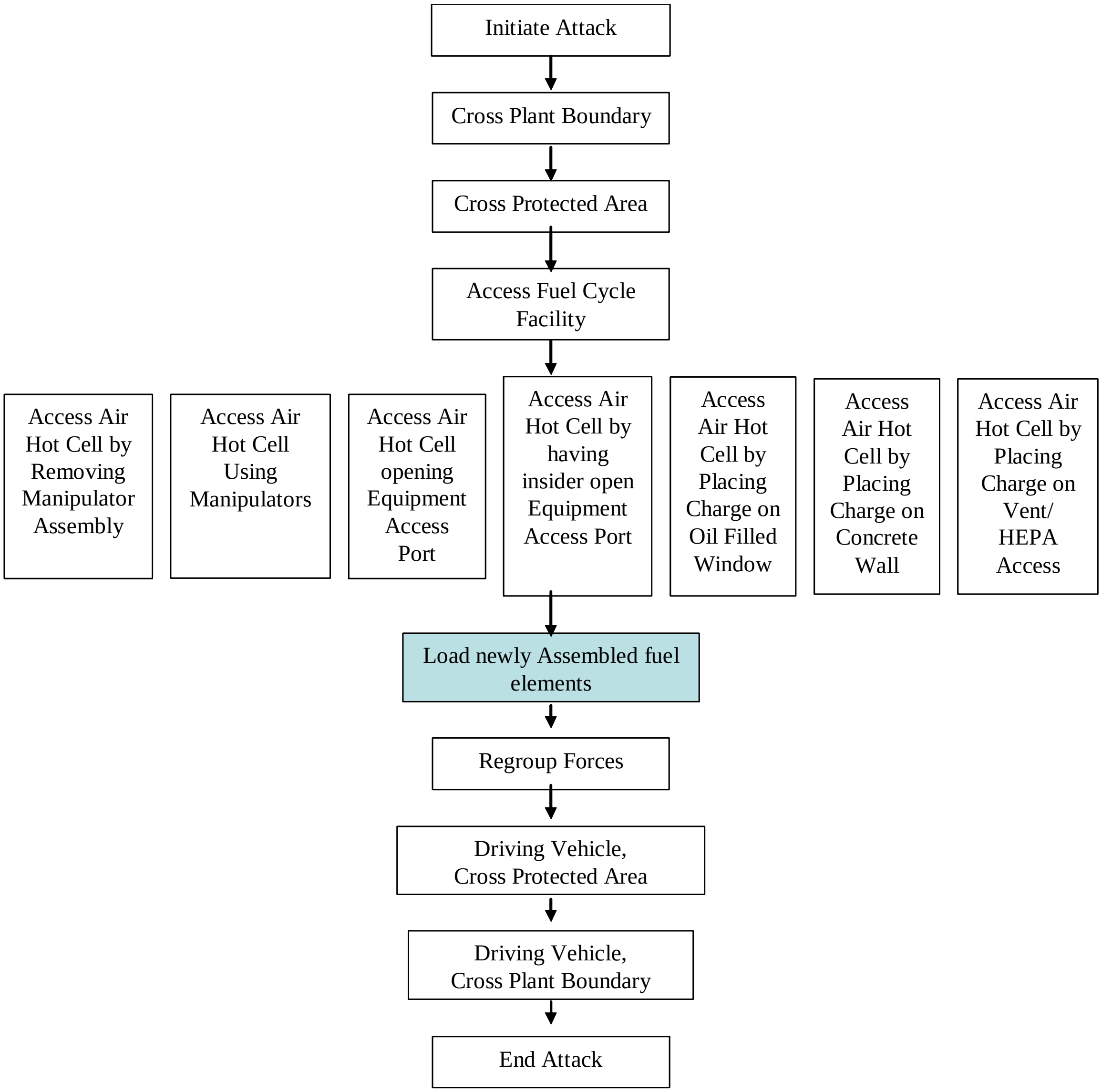


Figure D.4-7. Adversary Sequence Diagram for Theft of newly Assembled Fuel Rods (in Receiving/Shipping Cell)

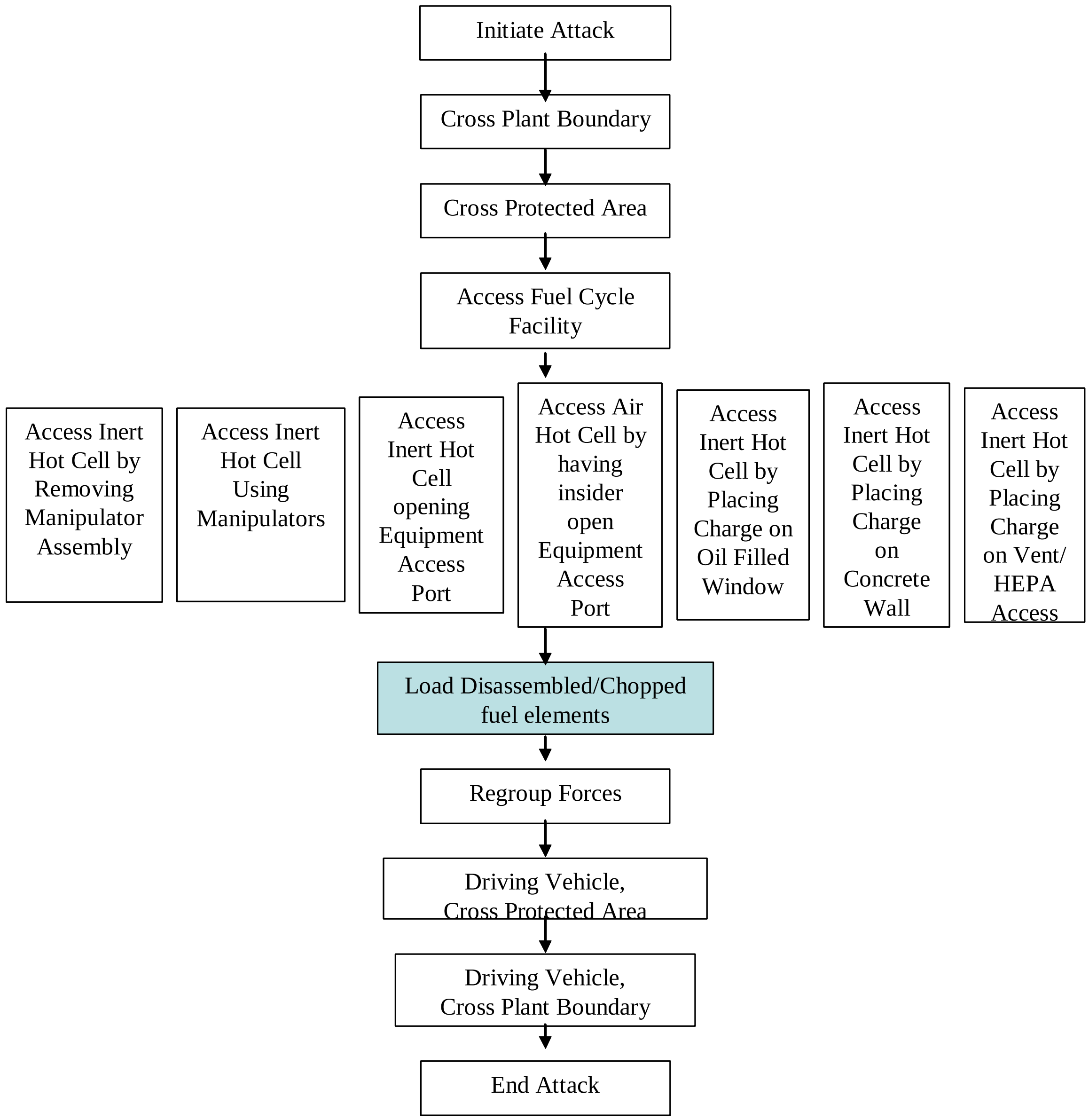


Figure D.4-8. Adversary Sequence Diagram for Theft of Disassembled/Chopped Fuel Rods (in Process Cell)

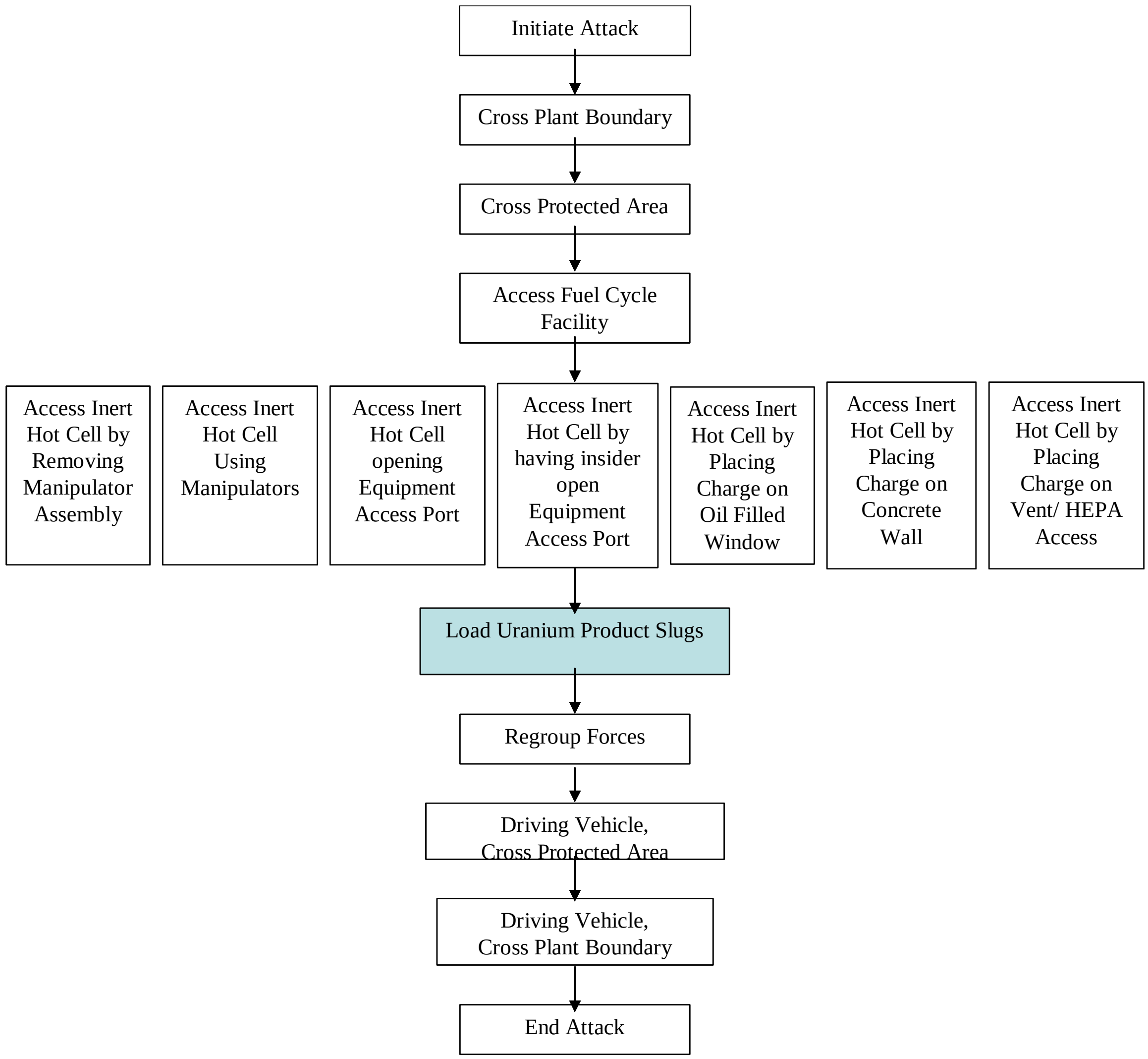


Figure D.4-9. Adversary Sequence Diagram for Theft of Uranium Product (in Process Cell)

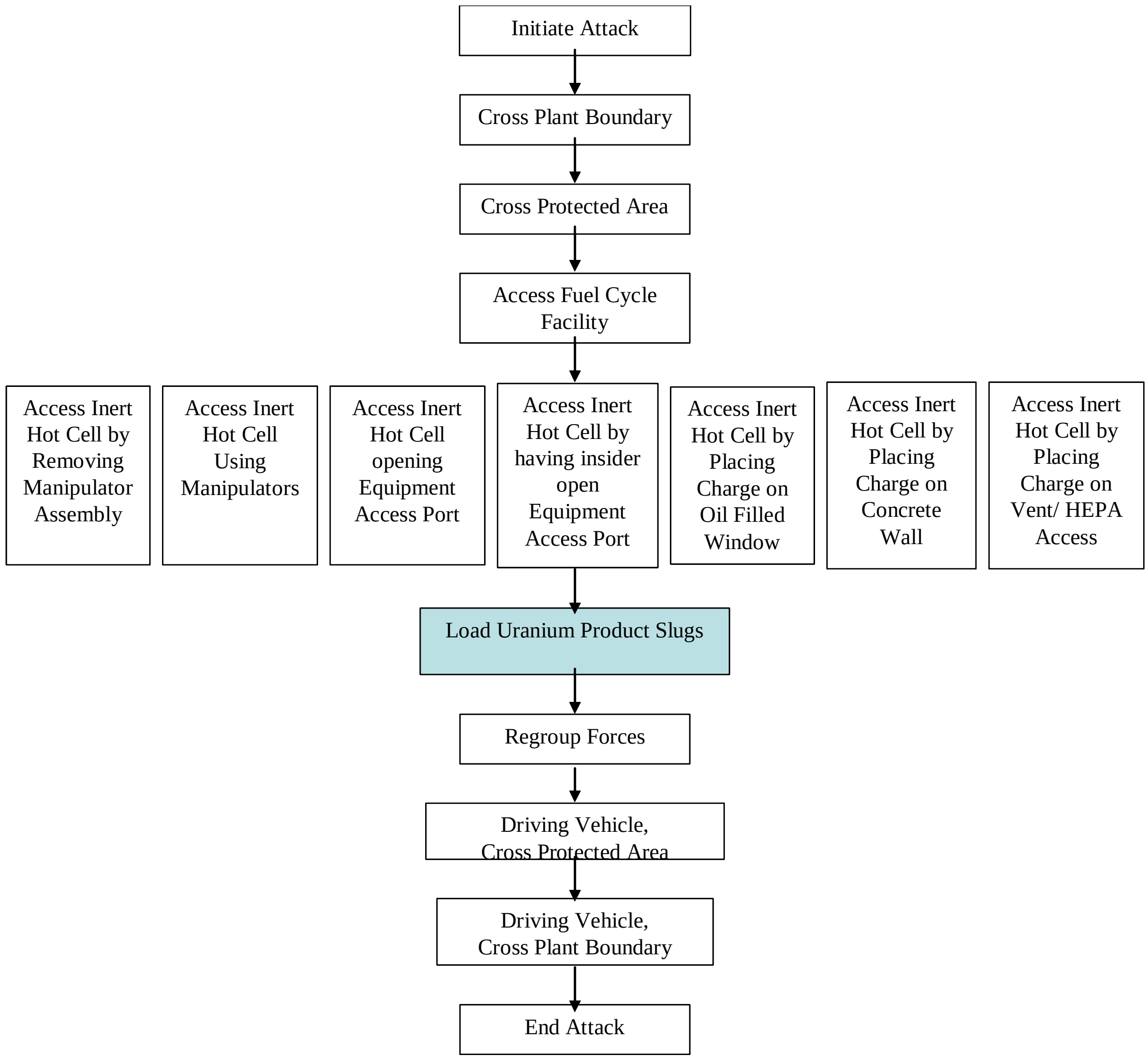


Figure D.4-10. Adversary Sequence Diagram for Theft of TRU/Uranium Product (in Process Cell)

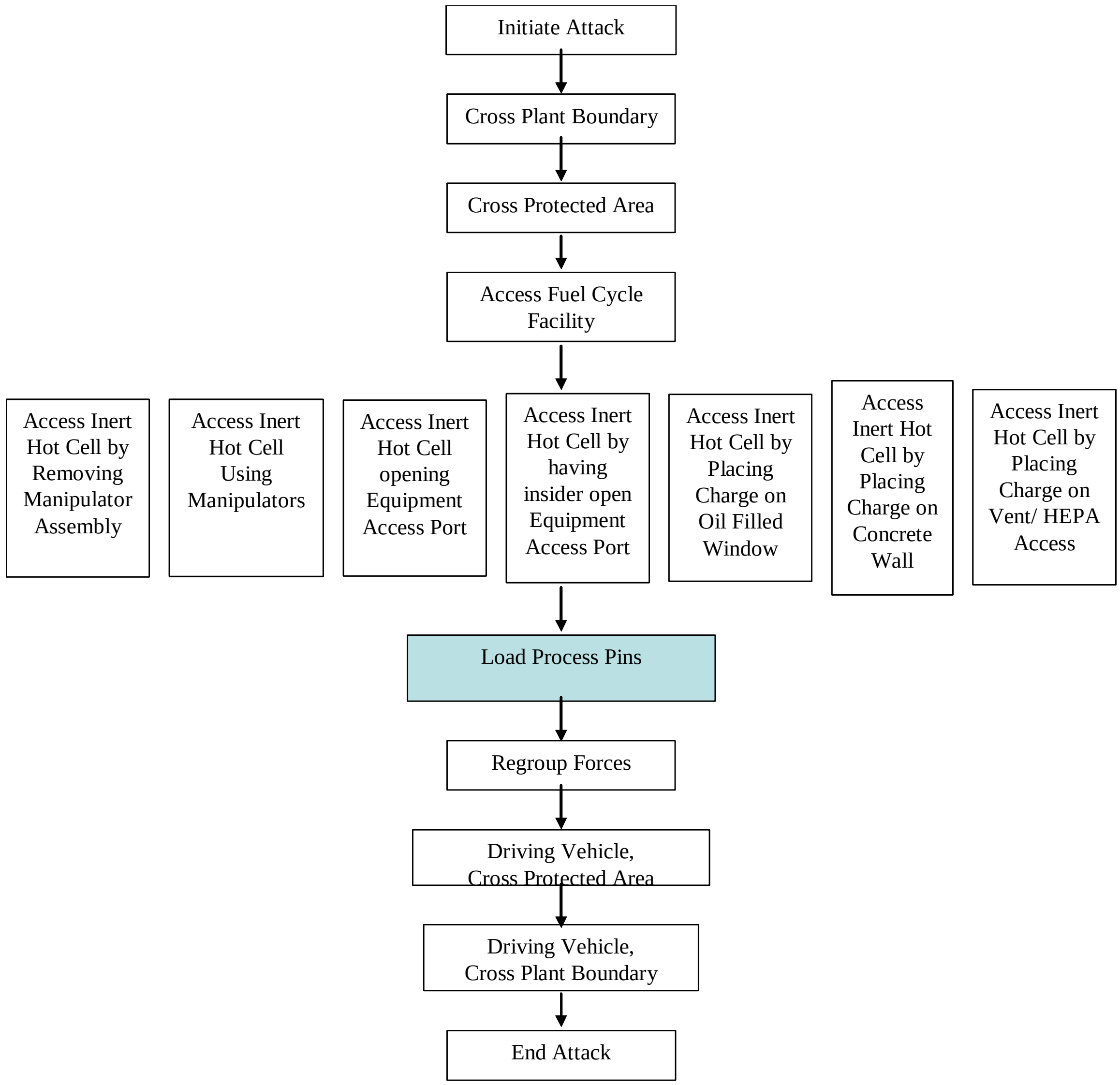


Figure D.4-11. Adversary Sequence Diagram for Theft of Processed Pins (in Process Cell)

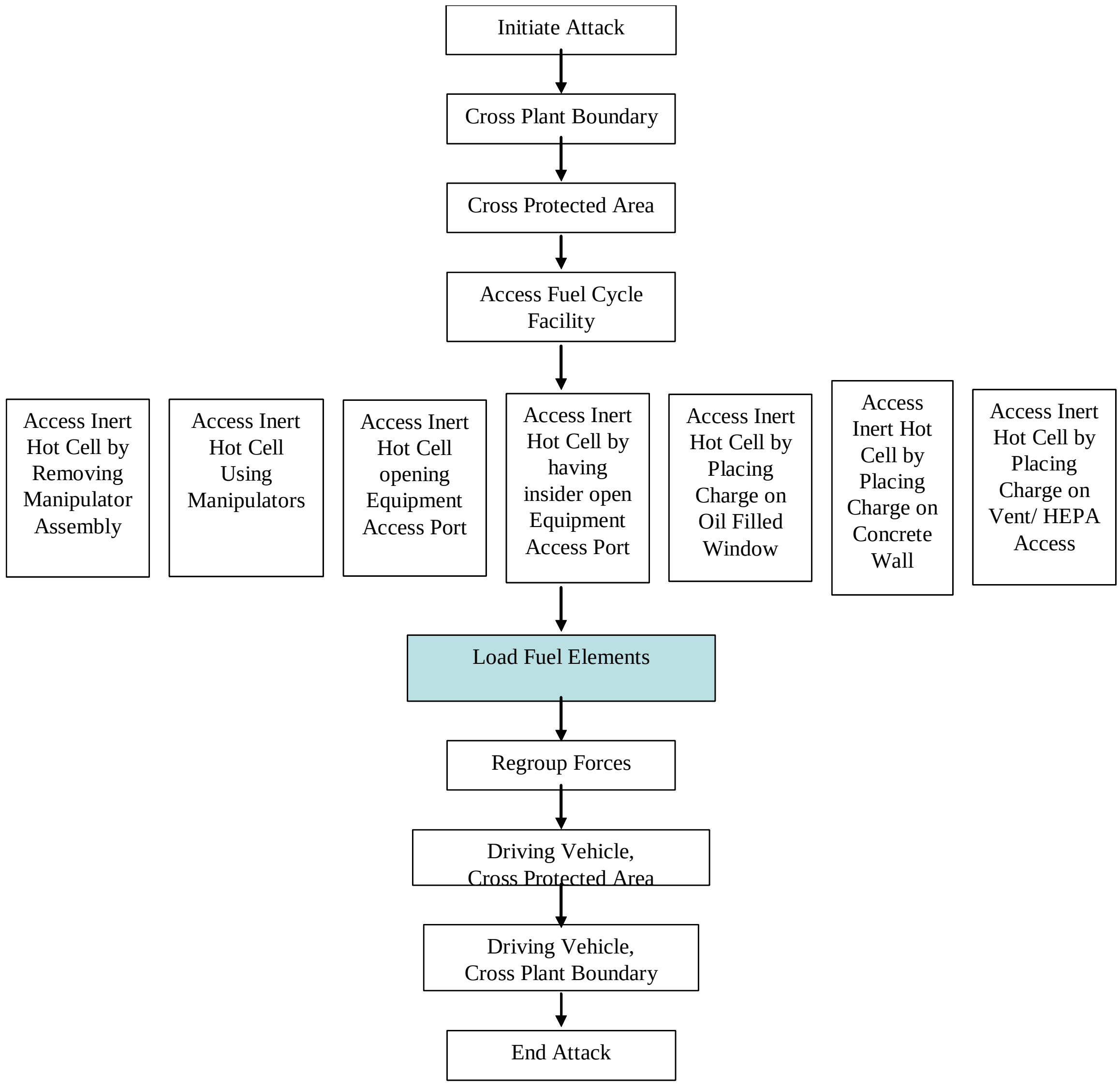


Figure D.4-12. Adversary Sequence Diagram for Theft of Fuel Elements (in Process Cell)

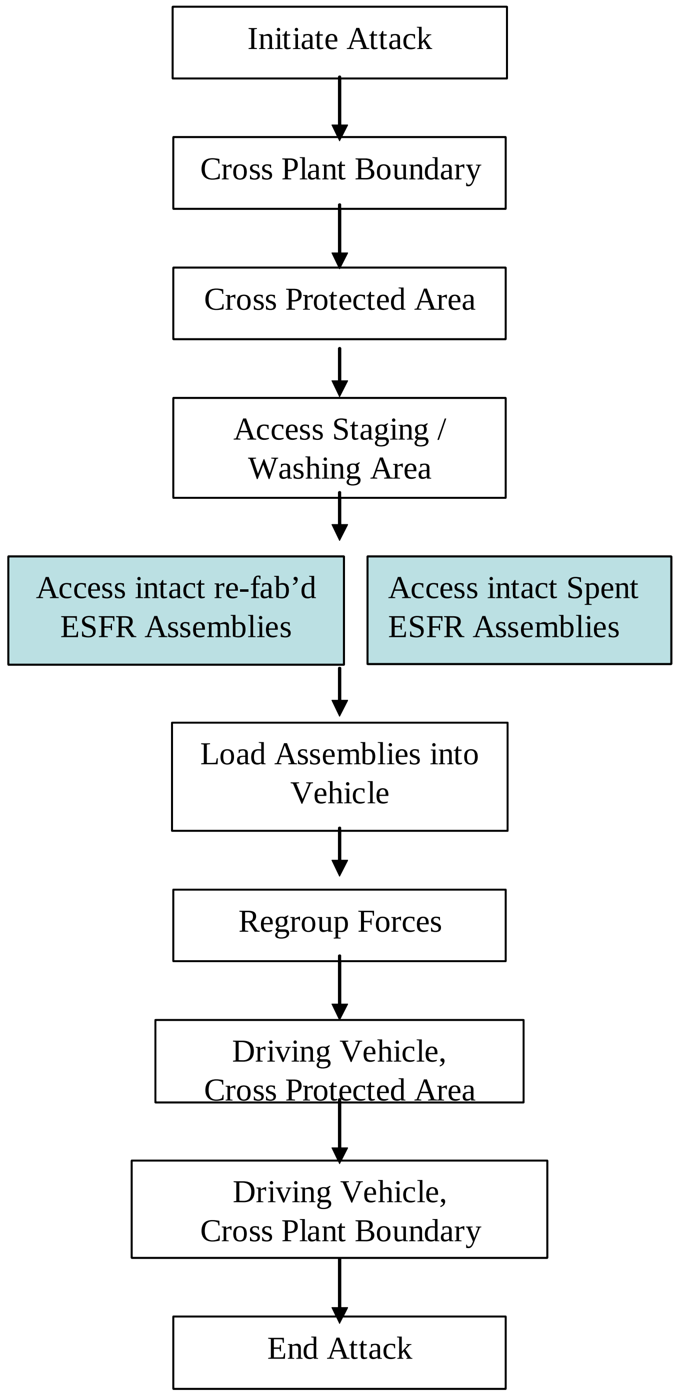


Figure D.4-13. Adversary Sequence Diagram for Theft of newly Re-fabricated or Spent ESFR Fuel Assemblies in Staging/Washing Area

D.4.4.3 Qualitative Analysis of Selected Theft Pathway

For the purpose of demonstrating the methodology, the adversary pathway identified in Figure D.4-10 will be analyzed qualitatively. This particular pathway was selected because the U/TRU slugs represent the stage of the electrochemical process where the material is in a readily portable form (solid metallic slugs), and the TRU concentration is high compared to potentially downblended fuel – i.e. this is a relatively attractive target for theft.

To succeed, the adversary must cross the site and PIDAS boundaries, access the Fuel Cycle Facility, access the inert hot cell, collect U/TRU slugs and the escape the site. The consequence of adversary success is the theft of 1 SQ or more of fissile material.

When analyzing plant designs in a conceptual phase, one will find that is it is less complicated to analysis the plant design in a qualitative manner, due to the exact design of the plant having not yet being completed. It is also advantageous to perform the first PP analysis prior to developing a PP design in order to identify areas of interest, potential pathways, and targets. When performing a qualitative analysis, the exact answers for each system are not always known. Therefore it is beneficial to use high, low, medium and no ranking system. In order to keep a consistent definition of high, low, medium and no, it is beneficial to define ranges of acceptable values for each ranking. The following binning process was used for this qualitative example.

Table D.4-2. Proposed Physical Protection Qualitative Measures and Metrics for the Evaluation of Conceptual Nuclear Facility Designs

Metrics	Range/Value			
	High	**Medium**	**Low**	**No**
Probability of Detection, P_d	1> P_d ≥0.9	0.9> P_d ≥0.8	0.8> P_d ≥0.2	0.2> P_d =0
	0.95	0.85	0.5	0.1
Delay Time, t_d	60m≥ t_d >30m	30m≥ t_d >10m	10m≥ t_d >1m	1m≥ t_d =0
	45m	20m	5.5m	0.5m
Response Time, t_r	1m≥ t_r =0	10m≥ t_r >1m	30m≥ t_r >10m	60m≥ t_r >30m
	0.5m	5.5m	20m	45m
Measures	**Range/Value**			
	High	**Medium**	**Low**	**No**
Probability of Adversary Success, P_s	1> P_s ≥0.8	0.8> P_s ≥0.5	0.5> P_s ≥0.1	0.1> P_s =0
	0.9	0.65	0.3	0.05
PP Resources, PPR (% of operating Cost)	>10%	10%>%>5%	5%>%>0%	0
	10	5	1	0
Consequences, C_R (Reactor Radiological)	Offsite Release	Onsite Release	Building Release	No Radiological Release
	CDF>10^{-6} Without mitigation	CDF>10^{-6} With mitigation	CDF<10^{-6}	No Core Damage
Consequences, C_E (economic)	Permanent Loss of NSSS	Cleanup of NSSS > 1 yr	Cleanup of NSSS < 1 yr	NSSS unaffected
Consequences, C_D (RDD Radiological)	Urban Contamination with loss of life	Urban Contamination	Localized Contamination	No Radiological Release
Consequences, C_t (SNM Theft)	1 SQ of unirradiated or irradiated direct use material	1 SQ of unirradiated indirect use material	1 SQ of irradiated indirect use material	Unsuccessful theft

The probability of adversary detection and delay for each step of the pathway is assessed in Table D.4-3, along with a description of the reasoning behind the ranking.

Table D.4-3. Qualitative Analysis of Each Step along the Theft Pathway

Task		Probability of Detection	Delay	Assessment Description
1	Initiate Attack	Low	No	The militarily trained force is assumed to achieve both strategic and tactical surprise.
2	Cross Plant Boundary	Low	No	The outer boundary is typically a simple fence and or vehicle barrier. Note that they will be detected by various sensors at this point.
3	Cross Protected Area	Medium	Medium	The PIDAS boundary is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this, but not without detection. At this point, defensive forces are moving in and engaging the adversary
4	Access Fuel Cycle Facility	High	High	When the sensors alarm, the building will be locked down. The adversary will have to force (probably via explosives) their way in. If the insider's task is to be inside the building, they can defeat the locks and open a door. This step must be performed while under fire. If the building is hardened; multiple breaching charges (while under fire) will be required.
5	Access Inert Hot Cell…			
5a	By Removing Manipulator Assembly	High	Medium	Very time intensive, thus unlikely to be completed.
5b	Using Manipulators	High	Low	The hot cell boundary must still be breached to remove fuel.
5c	Opening Equipment Access Port	High	Medium	Alarm interlocks will prevent motorized opening. Manual opening requires more time.
5d	Having Insider Open Equipment Access Port	Medium	Low	The insider may be able to defeat the interlocks, or synchronize the attack to a time that the access port is open.
5e	Placing Charge on Oil Filled Window	High	Low	Despite their thickness, the hot cell windows are readily breached with explosive charges, however, it may take more than one. If the proposed shutters are in place, additional charges (and thus additional time) will be required.
5f	Placing Charge on Concrete Wall	High	High	Hot cell walls are extremely thick. Multiple very large explosive charges will be required. If the reinforcing bars and other intrinsic features of the cell wall are designed with physical protection in mind, even multiple charges may be insufficient.

Task		Probability of Detection	Delay	Assessment Description
5g	Placing Charge on Vent/HEPA Access	High	Medium	Since there is already an opening, this has a higher chance of success. However, the opening must still be enlarged (through reinforced concrete) sufficiently to allow one or more adversaries into the hot cell.
6	Load TRU/Uranium Product Slugs	Low	Low	The adversaries must be equipped with self-contained breathing equipment. Any adversary that is loading fuel slugs is not available to engage the defensive forces. The adversary is in a restrictive location, one of which the defensive forces are already aware. However, the adversaries inside the cell are expected to be alone.
7	Regroup Forces	No	No	Regrouping must occur under fire, through known access points (the opened door), and in a known location (within the PIDAS).
8	Driving Vehicle, Cross Protected Area	No	Low	Complete defensive force response (including heavier weapons and armored vehicles) will have arrived by this point. Vehicles will be placed under heavy fire to disable them as an avenue of escape. Dismounted adversaries have to cross the PIDAS while under fire.
9	Driving Vehicle, Cross Plant Boundary	No	Low	Since the defensive forces will be converging on the adversaries, is it assumed that successful escape from the PIDAS constitutes a breakout. Accordingly it is easier to then continue on through the plant boundary.
10	End Attack	No	No	Only the adversary gets to decide when to quit.

The next step in the qualitative analysis is to determine the response force times. The following values where used:

Option	Response Force Time (s)
A	150
B	300
C	600

To analyze the results of the quantitative analysis EASI v200 was used. Probability of Guard Communication was assumed to be 1.0 and all standard deviations were estimated to be 10% of the mean values. The mean value of for each range was used in the analysis. Analysis of Pathway 5a is shown below for each of the response force times.

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		150	15		
6			**Theft of TRU/Uranium Product Slugs Pathway 5a**						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	
17		9	Cross Plant Boundary	0.1	M	330	33	360	Critical Detection Point
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure D.4-14. Probability of Interruption with PPS Option A

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		300	30		
6			**Theft of TRU/Uranium Product Slugs Pathway 5a**						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	
17		9	Cross Plant Boundary	0.1	M	330	33	360	Critical Detection Point
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure D.4-15. Probability of Interruption with PPS Option B

	A	B	C	D	E	F	G	H	I
1									
2			**Estimate of Adversary Sequence Interruption**	Probability of Guard Communication		Force Time (in Mean	Standard Deviation		
5				1		600	60		
6			Theft of TRU/Uranium Product Slugs Pathway 5a						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.5	M	30	3	6210	
10		2	Cross Plant Boundary	0.5	M	30	3	6180	
11		3	Cross Protected Area	0.85	M	1200	120	6150	
12		4	Access Fuel Cycle Facility	0.95	M	2700	270	4950	
13		5	Access Inert Hot Cell by Removing Manipulator Assembly	0.95	M	1200	120	2250	
14		6	Load TRU/Uranium Product Slugs	0.5	M	330	33	1050	
15		7	Regroup Forces	0.1	M	30	3	720	
16		8	Cross Protected Area	0.1	M	330	33	690	Critical Detection Point
17		9	Cross Plant Boundary	0.1	M	330	33	360	
18		10	End Attack	0.1	M	30	3	30	
19		11					0	0	
31						6210			
32			Probability of Interruption:	1.00					

Figure D.4-16. Probability of Interruption with PPS Option C

The Probability of Adversary Success for the remaining scenarios are reported below.

Table D.4-4. Summary of Qualitative Analysis for Access Inert Hot Cell: Probability of Adversary Success

Access Inert Hot Cell		Option A		Option B		Option C	
5a	By removing manipulator assembly	0.00	No	0.00	No	0.00	No
5b	Using manipulators	0.00	No	0.00	No	0.00	No
5c	Opening equipment access port	0.00	No	0.00	No	0.00	No
5d	Having insider open equipment access port	0.00	No	0.00	No	0.00	No
5e	Placing charge on oil filled window	0.00	No	0.00	No	0.00	No
5f	Placing charge on concrete wall	0.00	No	0.00	No	0.00	No
5g	Placing charge on vent/HEPA access	0.00	No	0.00	No	0.00	No

D.4.4.3.1 Insights for Further Study from Qualitative Analysis of Theft

Because the adversary gets to determine when and where to initiate an attack, they will most likely succeed in arriving at and crossing the plant boundary. Performing this step with detection is low. Pushing the plant boundary and or the detection boundary out farther will provide more response time for the defensive forces, and thus reduce the probability of future steps succeeding.

The adversary will then need to cross the PIDAS boundary. The probability of detection of crossing the boundary is greater than the probability of detection of crossing the site boundary. In addition, the PIDAS boundary is generally more robust than the site boundary and thus the delay for the adversary will be greater. In addition, the PIDAS boundary can be strengthened (i.e. remotely operated weapons or equivalent) to reduce the probability of adversaries successfully getting across.

The Fuel Cycle Facility is assumed above to be a non-hardened building surrounding the hot cells. Construction of the building as a hardened structure will reduce the probability dramatically, as entrance by explosive breaching charges will be required. Hardening at this step provides the largest benefit against an adversary attack as they are forced to stop and set up charges, while still outside the facility and exposed to defensive fire. At this point detection is extremely likely and the delay is quite long.

The potential insider has the greatest ability to increase the adversary's overall probability of success. If the insider can pre-open doors or hot cell access ports, or can overcome interlocks during an attack, the probability of success increases noticeably. Steps to reduce the potential influence of the insider (guard controlled overrides, automatically closing doors, guards inside the facility) will have a large benefit compared to their cost.

The next greatest weakness in accepting the hot cells as secure rooms is the presence of the windows and adversary access to the manipulators. These windows must be large enough to provide the operators with a view of the work area. Accordingly, they are typically large enough for a person to easily get through the opening if the window is removed. Ballistic glass, shutters, and covers will reduce the probability that an adversary can successfully use the windows to access the hot cells before the defensive forces neutralize them. The manipulators can allow the adversary to access material inside the hot cell and using proper procedures remove the material from the hot cells. Features which lock out manipulators from unauthorized access will neutralize the adversary's ability.

A typical defensive force response is to converge on the adversaries with overwhelming firepower (i.e. superior numbers with heavier weapons). Any barrier that slows down the adversary reduces the probability of success. Additionally, even if the adversary successfully accesses the hot cell and obtains U/TRU fuel slugs, they will have to fight through all remaining defensive forces to escape. Their escape has to go through known areas by known routes (i.e. the existing holes in the fences and barriers). This gives great advantage to the defensive forces.

Overall, the ESFR facility is deemed to have a low probability of adversary success, because although some steps are rated as high or moderate, the adversary has to accomplish all steps, in a serial fashion to succeed. However, at many points, the probability can be reduced even more.

D.4.4.4 Quantitative Analysis of Selected Theft Pathway

The methodology can also be demonstrated quantitatively. This study examines the PPS requirements for 3 example pathways to the following targets: Spent Fuel Storage Cask staged in Parking Area, ESFR New Fuel in ESFR Spent Fuel and New Fuel Storage Cell, and ESFR Refabricated Fuel in Fuel Services Building – Staging Washing Area. These areas are identified in the following Figures D.4-17 and D.4-18 as Target 1, 2 and 3 respectively.

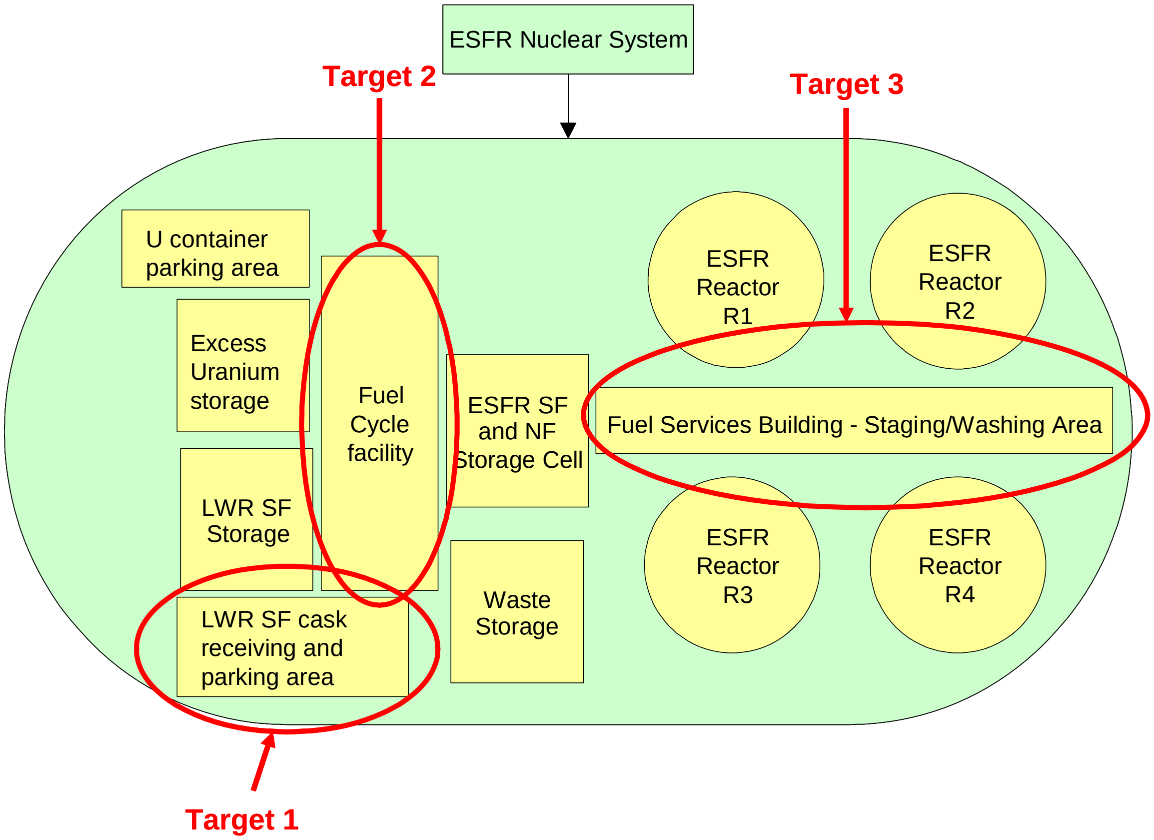


Figure D.4-17. Schematic Identification of Three Targets for Quantitative Analysis of ESFR

From this schematic layout of the facility, one can overlay the targets on a conceptual layout of the facility. By observation, one can identify the shortest path for the adversary, this in shown in the Figure D.4-18.

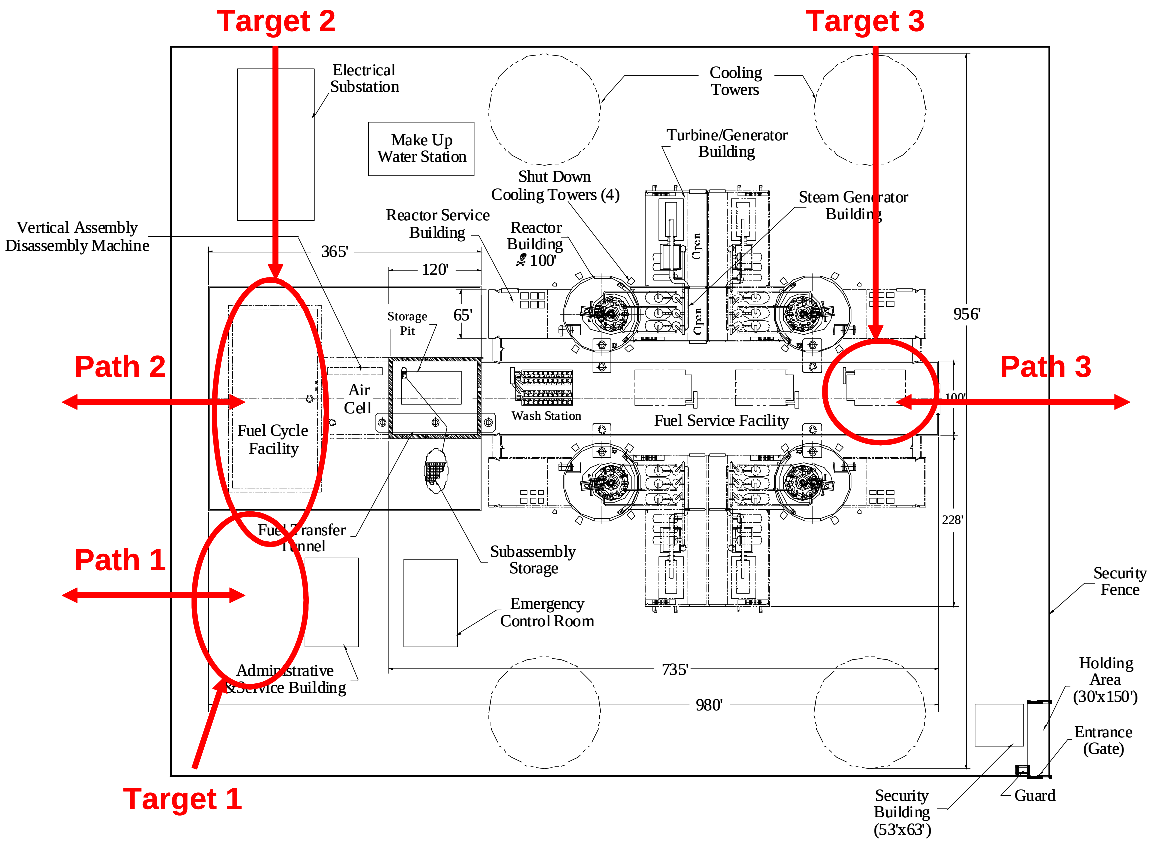


Figure D.4-18. Identification of Physical Location of Three Target Areas for Quantitative Analysis

With the locations identified and the pathways outlined, detailed Adversary Sequence Diagrams can be developed in preparation for pathway analysis. These are shown in Figures D.4-19 to D.4-21.

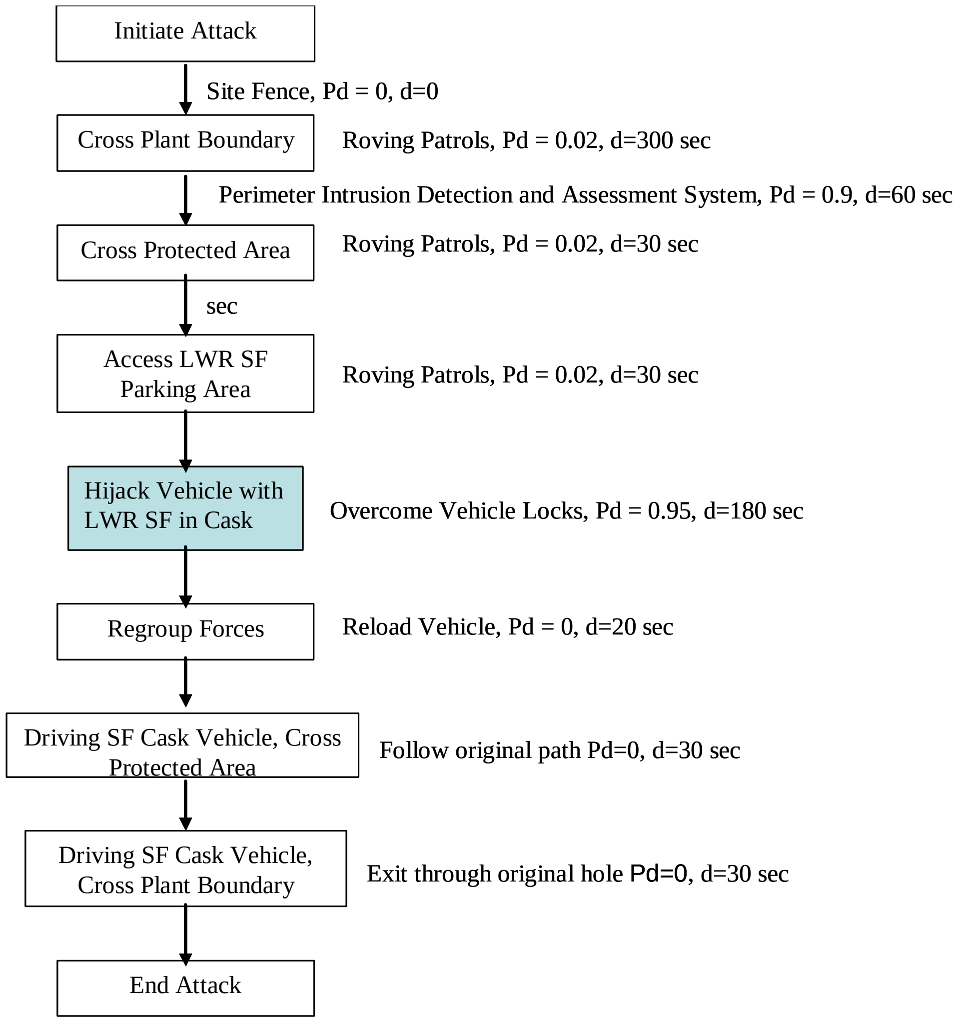


Figure D.4-19. Annotated Adversary Sequence Diagram for Theft of SF Shipping Casks

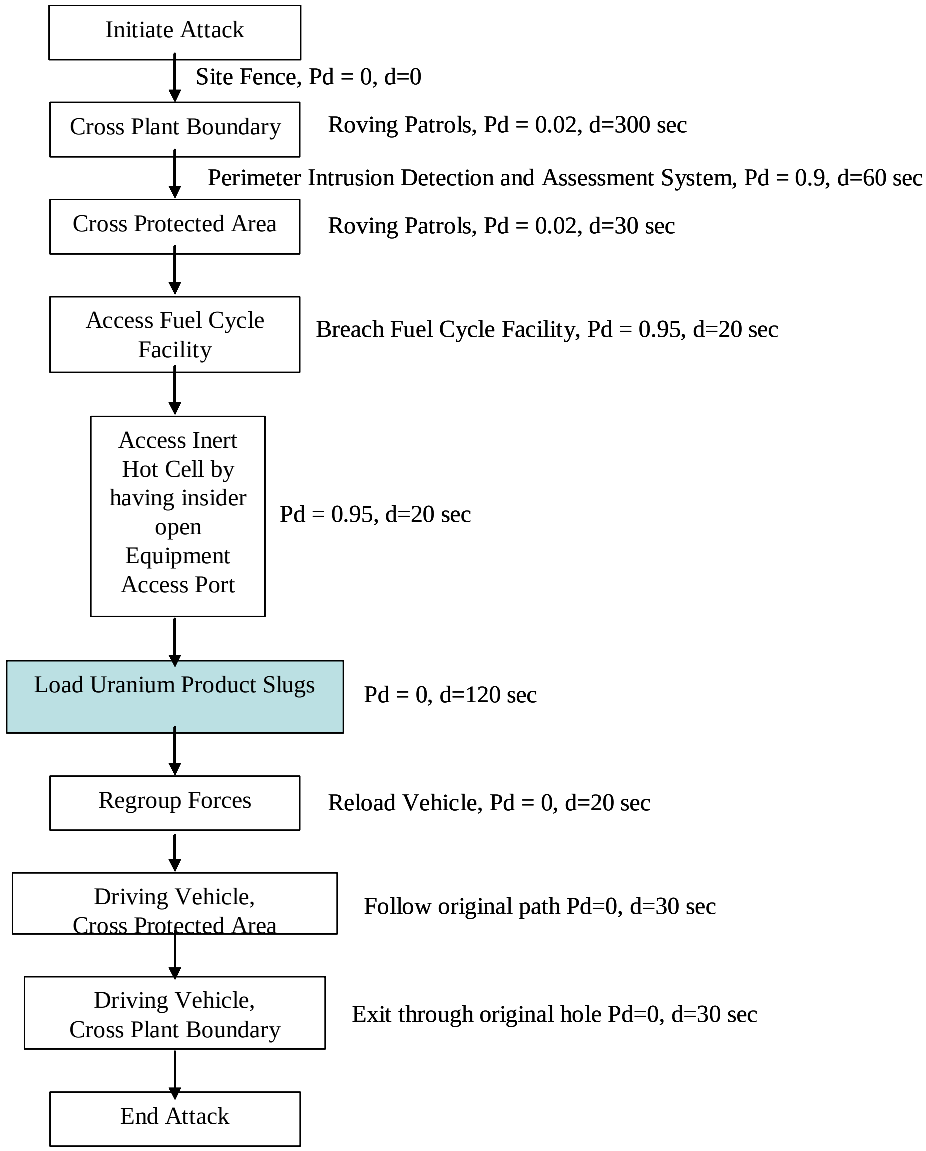


Figure D.4-20. Annotated Adversary Sequence Diagram for Theft of Uranium Product Slugs

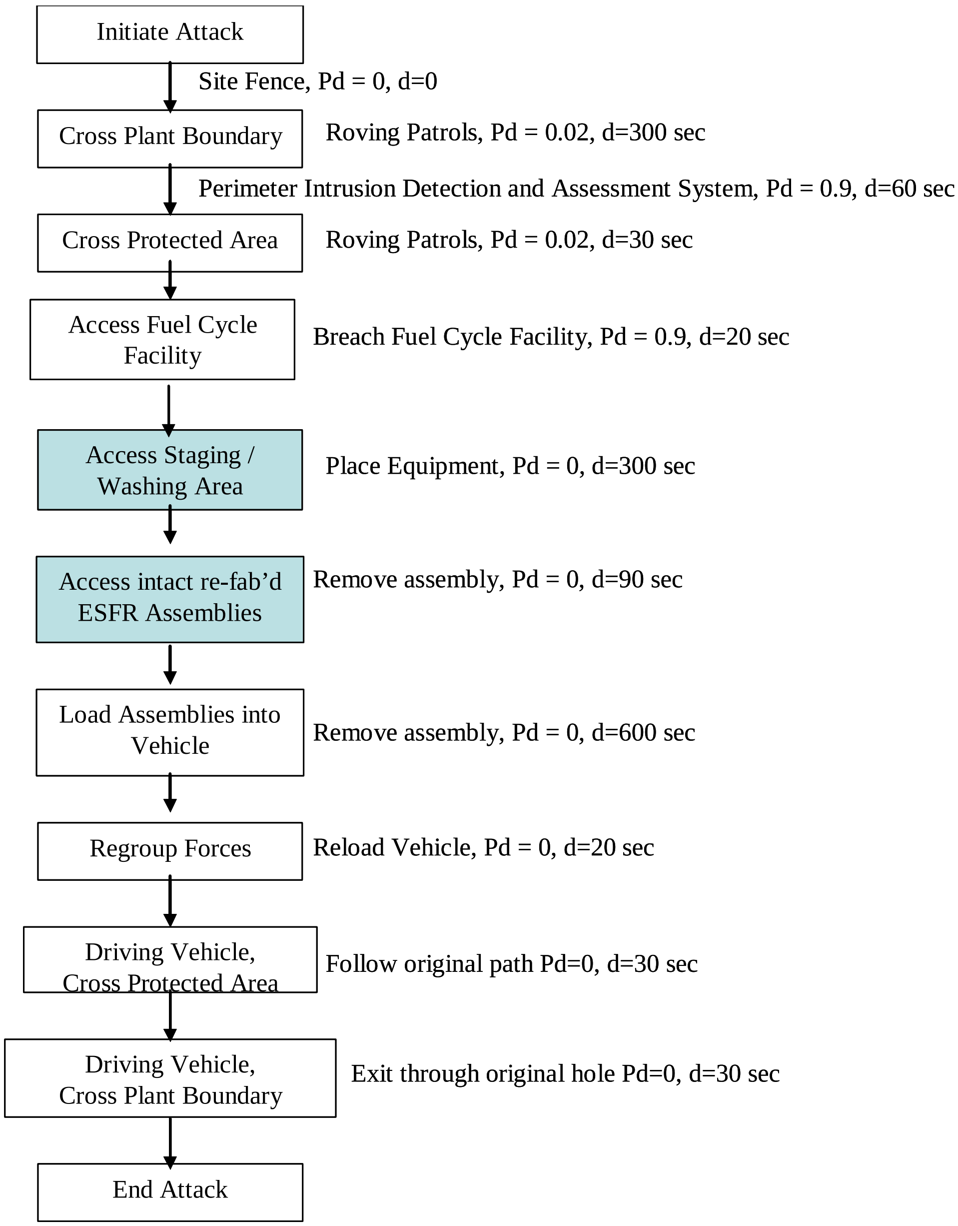


Figure D.4-21. Annotated Adversary Sequence Diagram for Theft of Refabricated ESFR Assemblies

With the annotated adversary diagrams completed, it is necessary to define the PPS systems in terms of the response force in order to determine the probability of interruption. For this level of coarse pathway analysis, it is only necessary to examine the necessary response force time. A preliminary analysis has been completed using 3 different response times to examine the variation in the probability of interruption. The following table details the options.

Option	Response Force Time (s)
A	150
B	300
C	600

To perform the quantitative analysis EASI v2000 was used. Probability of Alarm Communication was assumed to be 0.95 and all standard deviations were estimated at 10% of the mean values.

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		150	15		
6			**Theft of Spent Fuel Shipping Casks**						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	710	
10		2	Cross Plant Boundary	0.02	M	300	30	710	
11		3	PIDAS	0.9	M	60	6	410	
12		4	Cross Protected Area	0.02	M	30	3	350	
13		5	Access LWR SF Parking Area	0.02	M	30	3	320	
14		6	Hijack Vehicle with LWR SF Cask	0.95	M	180	18	290	Critical Detection Point
15		7	Regroup Forces	0	M	20	2	110	
16		8	Cross Protected Area	0	M	30	3	90	
17		9	Cross Plant Boundary	0	M	30	3	60	
18		10	End Attack	0	M	30	3	30	
31						710			
32			Probability of Interruption:	1.00					

Figure D.4-22. Pi for Target 1 with PPS option A

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		300	30		
6			**Theft of Spent Fuel Shipping Casks**						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	710	
10		2	Cross Plant Boundary	0.02	M	300	30	710	
11		3	PIDAS	0.9	M	60	6	410	
12		4	Cross Protected Area	0.02	M	30	3	350	Critical Detection Point
13		5	Access LWR SF Parking Area	0.02	M	30	3	320	
14		6	Hijack Vehicle with LWR SF Cask	0.95	M	180	18	290	
15		7	Regroup Forces	0	M	20	2	110	
16		8	Cross Protected Area	0	M	30	3	90	
17		9	Cross Plant Boundary	0	M	30	3	60	
18		10	End Attack	0	M	30	3	30	
31						710			
32			Probability of Interruption:	0.89					

Figure D.4-23. Pi for Target 1 with PPS option B

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		600	60		
6			**Theft of Spent Fuel Shipping Casks**						
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	710	
10		2	Cross Plant Boundary	0.02	M	300	30	710	Critical Detection Point
11		3	PIDAS	0.9	M	60	6	410	
12		4	Cross Protected Area	0.02	M	30	3	350	
13		5	Access LWR SF Parking Area	0.02	M	30	3	320	
14		6	Hijack Vehicle with LWR SF Cask	0.95	M	180	18	290	
15		7	Regroup Forces	0	M	20	2	110	
16		8	Cross Protected Area	0	M	30	3	90	
17		9	Cross Plant Boundary	0	M	30	3	60	
18		10	End Attack	0	M	30	3	30	
31						710			
32			Probability of Interruption:	0.01					

Figure D.4-24. Pi for Target 1 with PPS option C

Table D.4-5. Summary of Quantitative Analysis for Targets 1, 2, and 3 Probability of Adversary Success

Target	Option A	Option B	Option C
Theft of SF Shipping Casks	0.00	0.11	0.99
Theft of Uranium Product Slugs	0.00	0.54	1.00
Theft of Refabricated ESFR Assemblies	0.01	0.01	0.01

D.4.4.4.1 Insights for Further Study from Quantitative Analysis of Theft

The quantitative study provides some insight for further study. It is observed that the packaging of the ESFR fuel in the Staging/Washing area provides significant advantage to delaying the theft. Detection occurs early and delay occurs late. The delays in obtaining the target allow the response force to prevent the adversary force from obtaining the target. This is not the case with Target 2, uranium product slugs, where the response force is working on containing the adversary after obtaining the target.

The presence of an insider significantly aids the adversary by eliminating the delay in penetrating the inert hot cell to obtain the target. More fidelity is needed to further examine the pathway.

Further study is needed to be able to set performance requirements for the PPS and identify protection “shells” for each of the target areas which should lead to suggestions for reconfiguration of the plant.

The model also needs to look at the response force deployment strategy. The size of the plant introduces complexity in the placement and movement of these forces. This will test the hypothesis that only interruption is necessary for consideration at the course pathway analysis.

D.4.5 Sabotage Scenario Example Analysis

The following section will outline the target identification for the ESFR and potential pathways with regards to a potential sabotage scenario. In addition, both qualitative and quantitative examples will be presented to demonstrate the methodology.

D.4.5.1 Sabotage Target Identification

This section identifies a potential sabotage scenario and pathway for an analysis of a sabotage event at the ESFR. this would lead to loss of the shutdown cooling system (SCS) for the ESFR.

The layout for the ESFR is shown in Figure D.4-2.

The sabotage event to be analyzed is the destruction of the shutdown cooling systems (SCS) by crushing the air intakes. The sabotage of the air intakes on each of the four SCSs would not cause an immediate radiological release to the public, but it could potentially cause irreparable damage to the facility and would require an immediate shutdown of the entire facility.

D.4.5.2 Sabotage Pathway Identification

Once the targets are identified, then pathways to those targets can be identified, as in the following figure. The pathways are analyzed in terms of Adversary Sequence Diagrams for sabotage as described in Figure D.4-30.

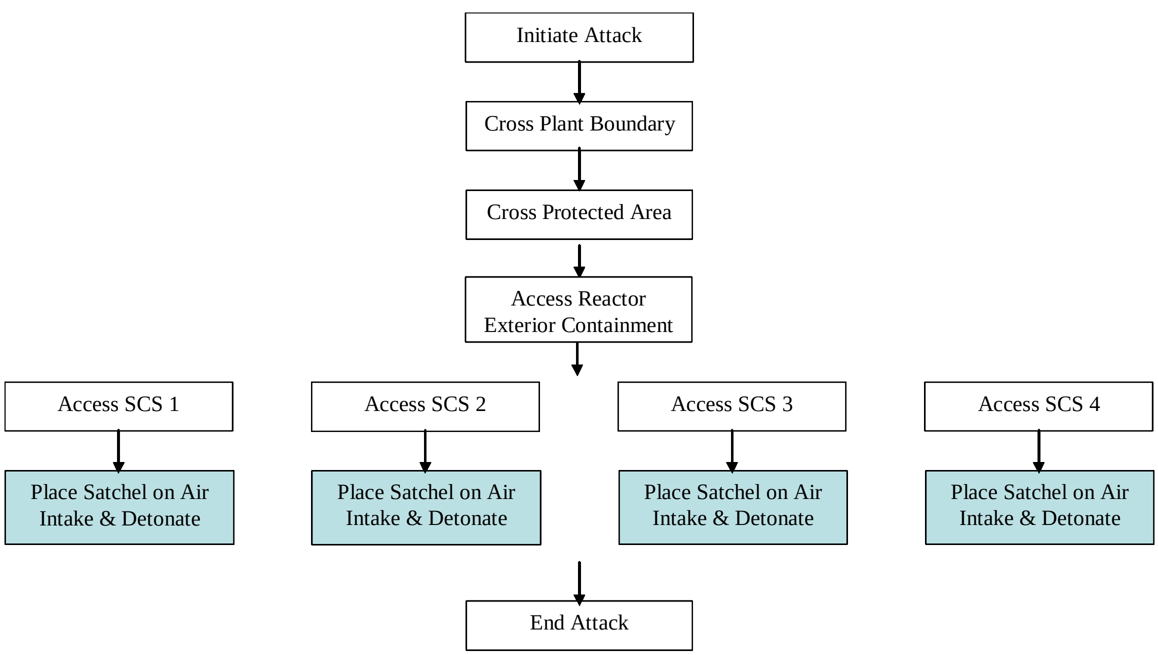


Figure D.4-30. Adversary Sequence Diagram for Sabotage of SCS on Reactors 1-4

For sabotage scenarios, the attack ends after the damage to the system has been done. It is not necessary for the adversaries to exit from the plant, as it is with the theft scenarios. Therefore the response forces have less time to interrupt the adversaries. They must interrupt before the sabotage has occurred in order for to overcome the adversaries.

D.4.5.3 Qualitative Analysis of Selected Sabotage Pathway

For the purpose of demonstrating the methodology, the adversary sequence diagram identified in Figure D.4-30 will be analyzed quantitatively. It is assumed the destruction of each air intake on each reactor occurs simultaneously, therefore the adversary group is assumed to be large enough to divide into four groups to accomplish their mission.

To succeed, the adversary must cross the site and PIDAS boundaries, access the reactor exterior containment, and destroy the air intakes on all four reactors. The adversary does not need to escape the site in order for the mission to be considered successful. The consequence of adversary success is the sabotage of all four air intakes resulting in loss of shutdown cooling capabilities on all four units, resulting in an immediate shutdown of the entire facility.

When analyzing designs in the conceptual phase, one will find that it is less complicated to analysis the plant design in a qualitative manner, due to the exact design of the plant having not yet been completed. It is also advantageous to perform the first PP analysis prior to developing a PP design in order to identify areas of interest, potential pathways and targets. When performing a qualitative analysis, the exact answers for each system are not always known. Therefore it is beneficial to use the high, medium, low and no ranking system. It is beneficial to define ranges of acceptable values for each ranking. The ranges for the qualitative analysis are shown in Table D.4-2.

The probability of adversary detection and delay for each step of the pathway is assed in Table D.4-6, along with a description of the ranking.

Table D.4-6. Qualitative Analysis of Each Step Along the Sabotage Pathway

	Task	Probability of Detection	Delay	Assessment Description
1	Initiate Attack	Low	No	The militarily trained force is assumed to achieve both strategic and tactical surprise.
2	Cross Plant Boundary	Low	No	The outer boundary is typically a simple fence and or vehicle barrier. Not that they will be detected by various sensors at this time.
3	Cross Protected Area	Medium	Medium	The PIDAS bounder is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this, but not without detection. At this point, defensive forces are moving in and engaging the adversary.
4	Access Reactor Exterior containment	High	Low	When the sensors alarm, the building will be locked down. The adversary will have to force (probably via explosives) their way in. If the insider's task is to be inside the building, they can defeat the locks and open a door. This step will most likely be performed while under fire.
5	Access SCS	Medium	No	The SCS air intakes are located on the roof of the reactor exterior containment and will be more easily accessible. There will most likely be no sensors in this area.
6	Place Satchel on Air Intake & Detonate	High	Medium	The placing of the explosives on the air intakes and their detonation will require a sufficient amount of time. Detection at this point is extremely likely once the explosion occurs.
7	End Attack			

The next step in the qualitative analysis is to determine the response force times. The following values where used:

Option	Response Force Time (s)
A	150
B	300
C	600

To analyze the results of the quantitative analysis EASI v200 was used. Probability of Guard Communication was assumed to be 1.0 and all standard deviations were estimated to be 10% of the mean values. The mean value of for each range was used in the analysis. Analysis of Pathway 5a is shown below for each of the response force times.

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		150	15		
6				**Sabotage of Air Intakes**					
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.1	M	30	3	2820	
10		2	Cross Plant Boundary	0.1	M	30	3	2790	
11		3	Cross Protected Area	0.85	M	1200	120	2760	
12		4	Access Reactor Exterior Containment	0.95	M	330	33	1560	
13		5	Accss SCS	0.85	M	30	3	1230	
14		6	Place Satchel on Air Intake and Detonate	0.95	M	1200	120	1200	Critical Detection Point
15		7	End Attack				0	0	
31						2820			
32			Probability of Interruption:	1.00					

Figure D.4-31. Probability of Interruption with PPS Option A

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		300	30		
6				**Sabotage of Air Intakes**					
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0.1	M	30	3	2820	
10		2	Cross Plant Boundary	0.1	M	30	3	2790	
11		3	Cross Protected Area	0.85	M	1200	120	2760	
12		4	Access Reactor Exterior Containment	0.95	M	330	33	1560	
13		5	Accss SCS	0.85	M	30	3	1230	
14		6	Place Satchel on Air Intake and Detonate	0.95	M	1200	120	1200	Critical Detection Point
15		7	End Attack				0	0	
31						2820			
32			Probability of Interruption:	1.00					

Figure D.4-32. Probability of Interruption with PPS Option B

Estimate of Adversary Sequence Interruption	Probability of Guard Communication	1
	Force Time (in Mean	600
	Standard Deviation	60

Sabotage of Air Intakes

Task	Description	P(Detection)	Location	Delays (in Seconds): Mean:	Standard Deviation	Rt	
1	Initiate Attack	0.1	M	30	3	2820	
2	Cross Plant Boundary	0.1	M	30	3	2790	
3	Cross Protected Area	0.85	M	1200	120	2760	
4	Access Reactor Exterior Containment	0.95	M	330	33	1560	
5	Accss SCS	0.85	M	30	3	1230	
6	Place Satchel on Air Intake and Detonate	0.95	M	1200	120	1200	Critical Detection Point
7	End Attack				0	0	
				2820			

Probability of Interruption:	1.00

Figure D.4-33. Probability of Interruption with PPS Option C

The probability of Adversary Success is reported below.

Table D.4-7. Results of Qualitative Analysis for Air Intake Destruction: Probability of Adversary Success

Target	Option A		Option B		Option C	
Destruction of Air Intakes	0.00	No	0.00	No	0.00	No

D.4.5.3.1 Insights for Further Study from Qualitative Analysis of Sabotage

Because the adversary gets to determine when and where to initiate an attack, they will most likely succeed in arriving at and crossing the plant boundary. The probability of detection is low when performing this step. Pushing the plant boundary out farther will provide more response time for defensive forces, and thus reduce the probability of future steps succeeding.

The adversary will then need to cross the PIDAS boundary. The probability of detection of crossing the PIDAS boundary is greater than the probability of detection of crossing the site boundary. In addition, the PIDAS boundary is generally more robust than the site boundary and thus the delay for the adversary will be greater. In addition, the PIDAS boundary can be strengthened to reduce the probability of adversaries successfully getting across.

The reactor exterior containment is assumed to be a hardened building surrounding the reactor and will require multiple breaching charges will be required. This will aid in delaying the adversary. The potential insider has the greatest ability to increase the adversary's overall probability of success. If the insider can unlock doors in the adversary's pathway the probability of success increases noticeably. Steps to reduce the potential influence of the insider will have a large benefit compared to their cost.

The next greatest weakness is the actual air intakes. Increasing the robustness of these will require the adversary to use multiple sets of explosives in order to destroy the air intake and increase the delay allowing for response forces to respond. The location of the air intakes is also not typically considered to be a target area and lacks the presences of sensors. The addition of sensors to this area will increase the probability of detection.

D.4.5.4 Quantitative Analysis of Selected Sabotage Pathway

The methodology can also be demonstrated quantitatively. This study examines the PPS for the same pathway that was analyzed in the qualitative example. However, a more detailed analysis was performed along the pathway. Again, the adversary group is assumed to be divided into four groups acting along the same timeline.

The target areas are shown in Figure D.4-34. From the schematic layout of the facility, one can identify the shortest pathway for the adversary. This is shown in Figure D.4-35.

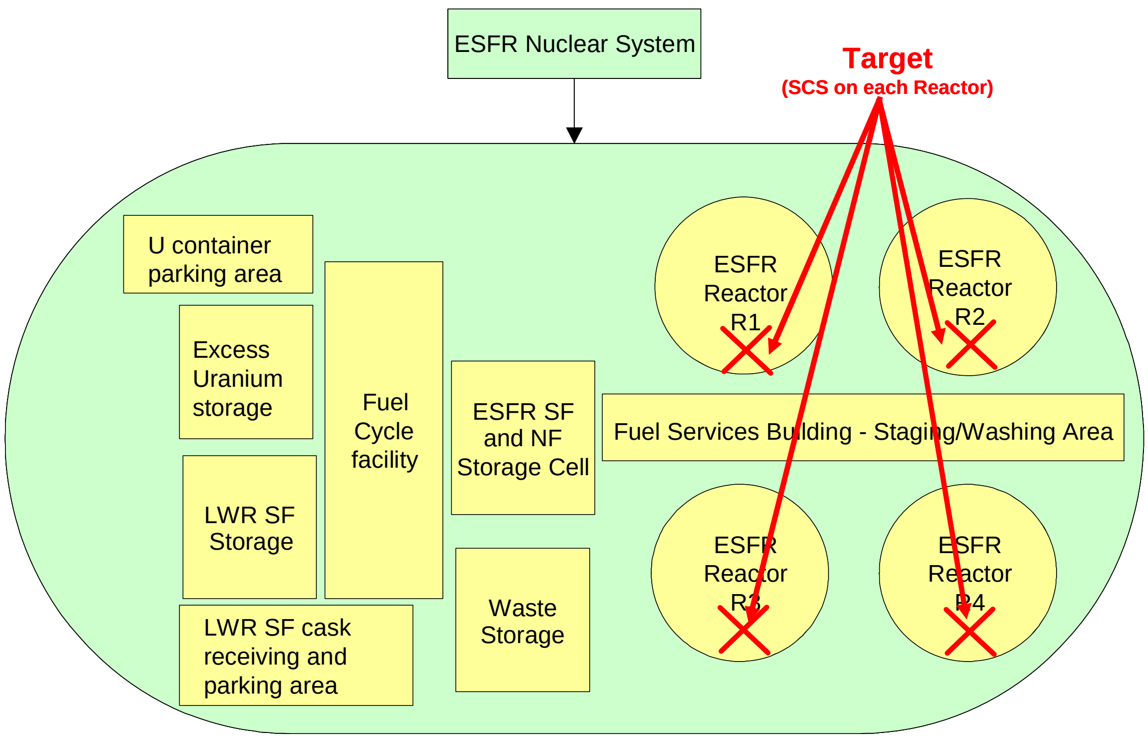


Figure D.4-34. Schematic identification of the four targets for analysis of the ESFR

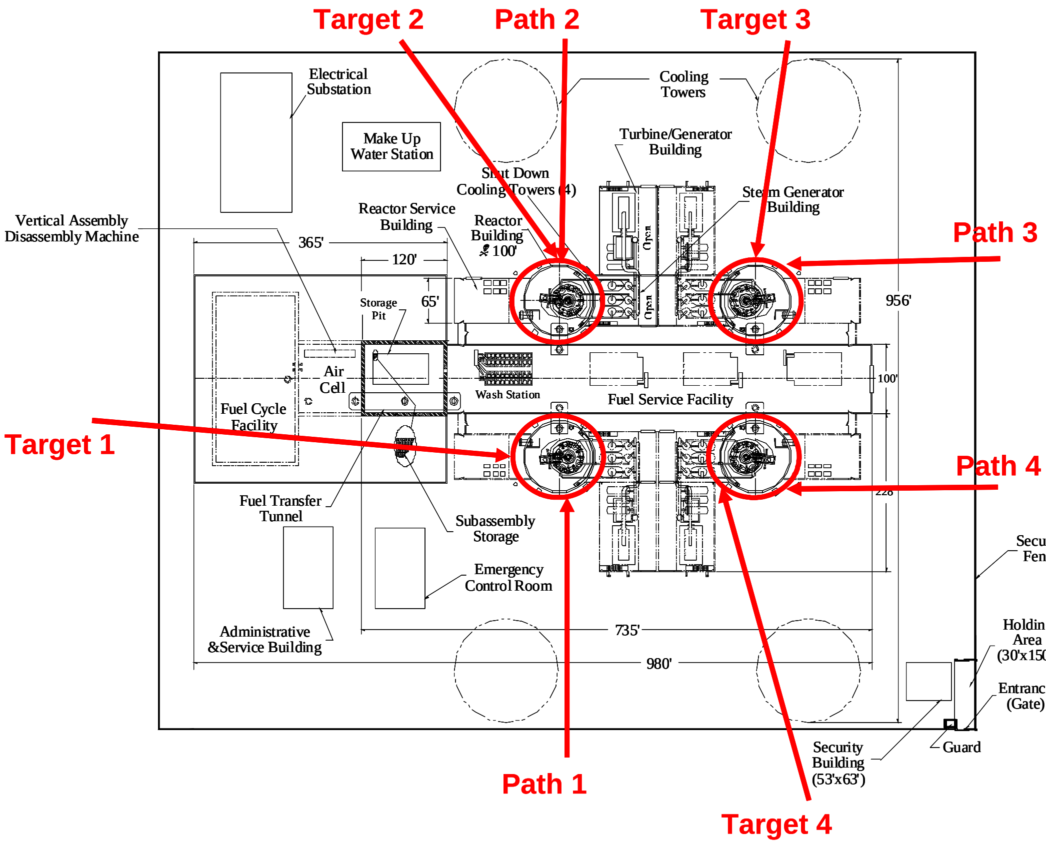


Figure D.4-35. Identification Pathways to the Four Target Areas

With the locations identified and the pathways outlined, detailed Adversary Sequence Diagrams can be developed in preparation for pathway analysis. This is shown in Figure D.4-36

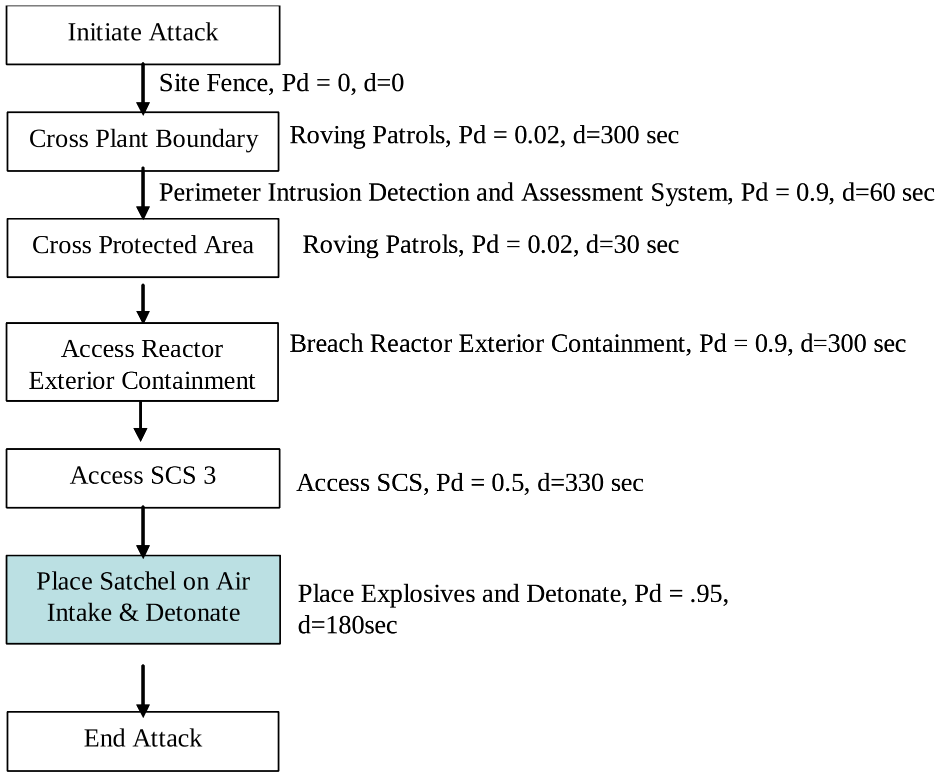


Figure D.4-36. Annotated Adversary Sequence Diagram for the Sabotage of the SCS Air Intakes

The next step in the qualitative analysis is to determine the response force times. The following values where used:

Option	Response Force Time (s)
A	150
B	300
C	600

To analyze the results of the quantitative analysis EASI v200 was used. Probability of Guard Communication was assumed to be 1.0 and all standard deviations were estimated to be 10% of the mean values. The mean value of for each range was used in the analysis. Analysis of Pathway 5a is shown below for each of the response force times.

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		150	15		
6				**Sabotage of Air Intakes**					
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	900	
10		2	Cross Plant Boundary	0.02	M	300	30	900	
11		3	PIDAS	0.9	M	60	6	600	
12		4	Cross Protected Area	0.02	M	30	3	540	
13		5	Access Reactor Exterior Containment	0.9	M	300	30	510	
14		6	Accss SCS	0.5	M	30	3	210	
15		7	Place Satchel on Air Intake and Detonate	0.95	M	180	18	180	Critical Detection Point
16		8	End Attack					0	
31						900			
32			Probability of Interruption:	1.00					

Figure D.4-37. Probability of Interruption with PPS Option A

	A	B	C	D	E	F	G	H	I
1									
2			***Estimate of***	Probability of					
3			***Adversary***	Guard		Force Time (in			
4			***Sequence***	Communication		Mean	Standard Deviation		
5			***Interruption***	1		300	30		
6				**Sabotage of Air Intakes**					
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	900	
10		2	Cross Plant Boundary	0.02	M	300	30	900	
11		3	PIDAS	0.9	M	60	6	600	
12		4	Cross Protected Area	0.02	M	30	3	540	
13		5	Access Reactor Exterior Containment	0.9	M	300	30	510	Critical Detection Point
14		6	Accss SCS	0.5	M	30	3	210	
15		7	Place Satchel on Air Intake and Detonate	0.95	M	180	18	180	
16		8	End Attack					0	
31						900			
32			Probability of Interruption:	0.99					

Figure D.4-38. Probability of Interruption with PPS Option B

	A	B	C	D	E	F	G	H	I
1									
2			**Estimate of**	Probability of					
3			**Adversary**	Guard		Force Time (in			
4			**Sequence**	Communication		Mean	Standard Deviation		
5			**Interruption**	1		600	60		
6		**Sabotage of Air Intakes**							
7						Delays (in Seconds):			
8		Task	Description	P(Detection)	Location	Mean:	Standard Deviation	Rt	
9		1	Initiate Attack	0	M	0	0	900	
10		2	Cross Plant Boundary	0.02	M	300	30	900	
11		3	PIDAS	0.9	M	60	6	600	Critical Detection Point
12		4	Cross Protected Area	0.02	M	30	3	540	
13		5	Access Reactor Exterior Containment	0.9	M	300	30	510	
14		6	Accss SCS	0.5	M	30	3	210	
15		7	Place Satchel on Air Intake and Detonate	0.95	M	180	18	180	
16		8	End Attack					0	
31						900			
32			Probability of Interruption:	0.31					

Figure D.4-39. Probability of Interruption with PPS Option C

The probability of Adversary Success is reported below.

Table D.4-8. Results of Quantitative Analysis for Air Intake Destruction: Probability of Adversary Success

Target	Option A	Option B	Option C
Destruction of Air Intakes	0.00	0.01	0.69

D.4.5.4.1 Insights for Further Study from Quantitative Analysis of Sabotage

The quantitative study provides some insight for further study. For option A and B, the probability of adversary success is extremely low. However, for option C the response force time must occur significantly earlier in the pathway in order to interrupt the adversary; however, detection earlier along the pathway is less likely to occur. In addition, the overall pathways are significantly shorter than for the theft scenarios; seeing as, the adversary must be interrupted before the sabotage occurs, where as, in the theft scenarios, the adversary must be interrupted prior to exiting the facility.

The presence of an insider could significantly decrease the adversary's delay times and probability of detection; and thus increase the probability of adversary success. More fidelity is needed to further examine the pathway. Further study is also need to be able to set performance requirements for the PPS and identify additional protection of the targets which should lead to suggestions of reconfiguration of the plant.

The model also needs to look at the response force deployment strategy in further detail. The size of the plant and the abundant amount of potential targets introduces complexity in the placement and movement of these forces.