INL/EXT-15-34036

# Example Work Domain Analysis for a Reference Sodium Fast Reactor

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January 2015

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

# ABSTRACT

The nuclear industry is currently designing and building a new generation of reactors that will include different structural, functional, and environmental aspects, all of which are likely to have a significant impact on the way these plants are operated. In order to meet economic and safety objectives, these new reactors will all utilize advanced technologies to some extent, including new materials and advanced digital instrumentation and control systems. New technologies will affect not only operational strategies, but will also require a new approach to how functions are allocated to humans or machines to ensure optimal performance. Uncertainty about the effect of large-scale changes in plant design will remain until sound technical bases are developed for new operational concepts and strategies. Up-to-date models and guidance are needed for the development of operational concepts for complex socio-technical systems. This report describes how the classical Work Domain Analysis method has been adapted to develop operational concept frameworks for new plants. This adaptation of the method is better able to deal with the uncertainty and incomplete information typical of first-of-a-kind designs. Practical examples are provided of the systematic application of the method in the operational analysis of sodium-cooled reactors. Insights from this application and its utility are reviewed and arguments for the formal adoption of Work Domain Analysis as a value-added part of the Systems Engineering process are presented.


NOTE: It is assumed that readers are familiar with previous milestone reports; hence, some important background information that would have added substantially to the bulk of this report has been omitted. References to previous reports are included where relevant.

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# ACRONYMS and ABBREVIATIONS

| | |
|---|---|
| AdvNPP | Advanced Nuclear Power Plant |
| CAA | Contextual Activity Analysis |
| CEA | Commissariat à l'énergie atomique |
| CRDM | Control Rod Drive Mechanism |
| CWA | Cognitive Work Analysis |
| EBR | Experimental Breeder Reactor |
| EDG | Emergency Diesel Generator |
| FAF | Functional Abstraction Framework |
| FOAK | First-of-a-Kind |
| HSI | Human-system interface |
| HVAC | Heating, Ventilation and Air Conditioning |
| HX | Heat Exchanger |
| I&C | Instrumentation and Control |
| IHX | Intermediate Heat Exchanger |
| INL | Idaho National Laboratory |
| LWR | Light Water Reactor |
| NaK | Sodium/Potassium |
| NIOSH | National Institute for Safety and Health |
| NPP | Nuclear Power Plant |
| OSHA | Occupational Safety and Health |
| PRISM | Power Reactor Innovative Small Module |
| SFR | Sodium Fast Reactor |
| SSC | Structures, Systems and Components |
| StrAn | Strategies Analysis |
| UPS | Uninterruptible Power Supply |
| WDA | Work Domain Analysis |

# 1 Introduction

Advanced nuclear reactors currently being designed are all expected to be simpler, safer, and more economical. These plants will be characterized by unique structural and functional designs, unconventional processes, materials, structures, and/or operations. This includes, for example, modular structures, coolants other than water (molten salt, helium, carbon dioxide, or liquid metal eutectics like sodium/potassium or lead/bismuth), and also the ability to use excess heat for industrial applications such as hydrogen generation and seawater desalination. One of the most important operational changes will be automation; new instrumentation and control (I&C) technologies now make it possible to automate systems in ways not possible with the analog systems used by older nuclear power plants (NPPs). These new digital technologies will require many changes to how operators manage and interact with the plant. Developing detailed descriptions of how these plants will be operated and by whom will become one of the more challenging aspects of the introduction of these advanced nuclear power plants (AdvNPPs), not only into the U.S. nuclear fleet, but in the rest of the world.

The detailed examination of these issues will include the development of Operational Concepts for AdvNPPs to inform system, functional, and operational design and licensing basis. This requires the analysis of the impacts of the following:

- Unique operational conditions & scenarios,
- Operational requirements of various product streams (steam, process heat, electricity),
- Increased use and reliance on passive safety systems,
- High levels of automation with humans in supervisory roles,
- Increased use of computer-based operator support tools for control room and field work,
- Remote surveillance and on-line monitoring, and
- Reduced use of local control stations.

Much of the difficulty in analyzing these challenges is due to the lack of operating experience and valid technical bases for the operation of new reactor designs. New automation philosophies must be informed not only by the technical capabilities, but also by the tasks that operators are required to perform, as well as their abilities and limitations in performing those tasks under various operational conditions. Human factors engineering and systems engineering methods currently practiced in the nuclear industry do not offer specific analytic tools for deciding how to design the operation of a new plant, including the application of new types of automation. A systematic process is needed to address this gap and produce reliable information for the design of robust and resilient systems that allow dynamic collaboration between operators and plant systems.

In response to these challenges, a modified Work Domain Analysis (WDA) methodology was developed at Idaho National Laboratory (INL) for the definition of operational concepts for new plants. This report is the first phase of the development of a framework for the analysis and definition of operational concepts for AdvNPPs. It documents the results of the application of this methodology to the analysis of a generic Sodium Fast Reactor (SFR), based upon information obtained from predecessor designs like the Experimental Breeder Reactor (EBR-II) and other advanced designs currently in progress around the world. The report also describes the roles of human and system agents for that plant, and the systems involved in a variety of operational conditions.

The report concludes with a description of how this example WDA will be applied in the development of a reference operational concept document for AdvNPPs.

NOTE: The modified WDA methodology, which includes the analysis of the systems involved in a variety of operational conditions as well as the expected roles of human and system agents, will be described in more detail in a report to be published in May 2015.

# 2 Methodology

## 2.1 Adaptation of the Cognitive Work Analysis method

The five phases of the classical Cognitive Work Analysis (CWA) method consist of WDA, Control Task Analysis, Strategies Analysis, Social Organization and Cooperation Analysis, and Worker Competencies Analysis, see Reference [3] and [4] These phases are meant to guide the analyst through the process of answering the question of why the system exists, what activities are conducted within the domain, how the activities are achieved and who performs it. The CWA method also focuses on identifying properties of the work environment and of the workers themselves that determine possible constraints on the ways that humans might interact with systems in the environment, without explicitly identifying specific sequences of actions.

The classical CWA method had to be adapted for this project to accommodate the many uncertainties that exist early in a new engineering project. A slightly modified version of the CWA was therefore developed as a framework for the analysis of operational concepts. The adapted CWA method places particular emphasis on WDA, but also includes Contextual Activities Analysis (CAA) and Strategies Analysis (StrAn), as will be described later. These are the most useful phases of CWA when plant design information is still immature.

Because operational concepts need to be developed for a new plant during the very early phases of design, it was found more beneficial to focus on the mission of the plant, its primary functions and the main systems required for those functions. This approach does not eliminate the other phases of CWA, but postpones its analysis until the plant design has sufficiently matured to enable the identification and analysis of lower-level systems and their functions.

## 2.2 Work Domain Analysis Method

The modified WDA process follows the basic approach described by Vicente [4] but some terminology and definitions were adopted from Jenkins et al. [1], Lintern [5], and Naikar [2], [3].

The primary purpose of the WDA for the development of operational concepts is to model the relationships between missions, goals, functions, processes, systems and constraints in such a way that a clear path is developed from high-level requirements to operational strategies.

The analysis typically starts by studying the overall mission and goals of the enterprise. For NPPs this is usually described in three very clear statements: 1) generate electricity economically, 2) protect workers, the public, and the environment, and 3) protect assets. This is followed by an analysis of the primary and secondary functions required to achieve these goals and how their achievement would be measured in terms of operational or productivity values, such as "supply capacity and availability, net generation, thermal performance, coolant inventory, water consumption". Next, the physical processes and effects (for example, produce fission heat, transport coolant, and generate electricity), necessary to support the functions are identified, and finally the systems (e.g., reactor, pumps, steam generators, heat exchangers, and turbine generators) that are used to produce those physical effects are identified.

### 2.2.1 Functional Abstraction Framework

The outcome of the traditional WDA is an abstraction hierarchy, called the Functional Abstraction Framework (FAF) that decomposes the sociotechnical system in terms of the missions, goals, functions, processes, and systems, and also the relationship between the entities in the various levels. Relationships between entities in the FAF are mapped by means-ends links, as explained in Section 2.2.2. These links can also be used to identify constraints and dependencies between entities. The five levels of abstraction in the framework are briefly described below.

| Level | Level Name | Description |
|---|---|---|
| 1 | **Mission and Domain Purposes** | The missions and purposes describe the reasons for the existence of the system. The purposes are independent of time and exist for the lifetime of the system. |
| 2 | **Values and Priority Measures** | Values and priority measures provide a means to determine how well the system is achieving its functional purposes. The way that the system is configured to meet these needs is contextually dependent and thus also describes the constraints on the functional purposes. |
| 3 | **Operational Functions** | These are the general functions of the work system that are necessary for achieving the functional purposes. The functions have the ability to influence one or more of the values and priority measures and they link the purpose-independent processes with the object-independent functions. |
| 4 | **Operational processes** | These processes describe the processes that are performed by the physical objects in order to perform purpose-related functions. In particular, they capture the functional capabilities and limitations that enable or inhibit the purpose-related functions of physical objects in the work system. |
| 5 | **Structures, Systems and Components** | The boundaries of an analysis will limit these objects to the systems of direct relevance to the chosen operational scenario, rather than every single object in the plant. |

In previous work the traditional representation of an abstraction hierarchy was used to illustrate the result of the FAF, as shown in Figure 1. This diagram illustrates how the different levels of the WDA can be populated and how the links between the entities in each level provide information about the "why, what, how" dependencies and relationships. For example, the links between "Physical functions and effects" and "Physical components" indicate that often more than one system is required for a process, and that several processes may require the same systems.

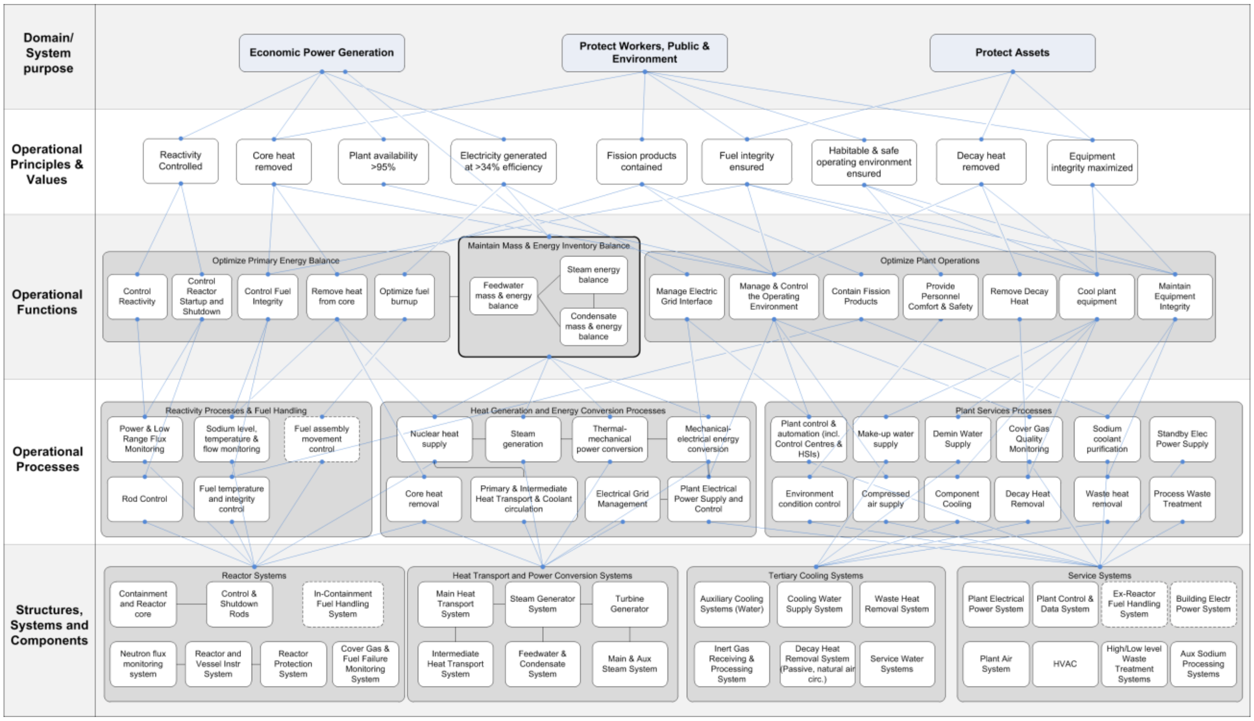


**Figure 1: Graphical Functional Abstraction Framework for a Generic SFR**

However, in extending previous analyses that were relatively simple, it became clear that the traditional graphical presentation of the framework (as shown in Figure 1) is not feasible when applied to large sociotechnical systems due to the visual complexity and difficulty in following the links. To ensure that the FAF becomes a useful analysis tool it was decided to present the information as a look-up table rather than the traditional format. An example of the look-up table is discussed in Section 2.2.2.

### 2.2.2 Means-Ends Links

The relationships between the five levels of the FAF are called means-ends links, which eventually also provide a means to identify constraints, as described in Section 2.2.3 below.

Traditionally, means-ends links have been represented by lines between entities in the FAF, as depicted in Figure 1 above. When the FAF for a large and complex sociotechnical system such as a First-of-a-Kind (FOAK) NPP design is represented graphically, it becomes very difficult to read and follow the links. Therefore, a look-up table was selected as the format for the FAF with the means-ends links presented as references in the look-up table, as shown in Figure 2, which is only an extract from the full table for the purpose of illustrating the format. The complete FAF table for the generic SFR can be found in Section 3.

In the example in Figure 2, item number 2.3, "Fuel Efficiency", is used to illustrate the use of the look-up table format. Fuel efficiency can be described as one of the results of the sustained breeder effect, actinides burned, and fuel damage mitigated. The first reference listed in the means-ends column is 1.1. Following this reference will answer the question of "why is this needed?" in this case to "Generate Electricity Economically". Following the reference from Fuel Efficiency to the level below provides the answer to "how can it be achieved?" in this case, by removal of process heat (reference 3.2). In the same manner all references for the entire FAF can be examined.

This method may seem more elaborate than the graphical representation, but it is more accurate and also easier to modify.

| 1. Domain Purposes | Means/Ends Links |
|---|---|
| *1.1 Generate Electricity Economically* | 2.1, 2.2, 2.3, 2.4 |
| *1.2 Protect workers, public, environment* | 2.2, 2.5, 2.6 |
| *1.3 Protect Assets* | 2.3, 2.6 |

| 2. Values and Measures | Level 1 | Level 2 | Level 3 | |
|---|---|---|---|---|
| 2.3 | *Fuel Efficiency* | | | To Level 1: 1.1 |
| | | 2.3.1 Breeder effect sustained | | |
| | | 2.3.2 Actinides burned | | To Level 3: 3.2 |
| | | 2.3.3 Fuel damage minimized | | |

| 3. Operational Functions | Level 1 | Level 2 | Level 3 | |
|---|---|---|---|---|
| 3.2 | *Remove process heat* | | | To Level 2: 2.1, 2.2 |
| | | 3.2.1 Remove heat from core | | |
| | | | 3.2.1.1 Transport heat from primary sodium to IHX | To Level 4: 4.3, 4.4 |
| | | 3.2.2 Remove reactor decay heat | | |
| | | | 3.2.2.1 Remove heat from primary sodium to Na-NaK HX | |
| | | 3.2.3 Remove waste heat | | |
| | | | 3.2.3.1 Transfer heat from IHX to secondary sodium | |
| | | | 3.2.3.2 Remove heat from secondary systems | |
| | | | 3.2.3.3 Reject or receive heat using steam generator | |
| | | | 3.2.3.4 Remove waste heat from components | |

**Figure 2 : Functional Abstraction Framework as a Look-Up Table**

The same method can be applied either top-down or bottom up, for example, by focusing on an element in any level and then determining why that element is needed and what is needed to ensure that it will serve that purpose.

### 2.2.3 Constraints

One of the most important applications of the WDA results is the definition of operational strategies, which can be defined as a sequence of short-term and long-term operations that transform goals, plans, decisions, policy, rules and procedures into the technical processes necessary for humans and systems to produce the defined production outcomes of the enterprise. The success and quality of the output will be influenced by the constraints that are imposed upon the sociotechnical system as a whole. Constraints could be any one or a combination of these conditions:

- Technical or physical
- Environmental
- Psychological
- Organizational
- Political
- Regulatory

As explained in a previous report (Hugo et al. 2014 [2]), constraints can be either *causal* (that is, determined by physical or natural laws), or *intentional* (determined by social laws, conventions, policies or values). For example, the structure, functions and dependencies of a complex sociotechnical system like a NPP are influenced by the properties of the thermohydraulic processes, materials and specific technologies. It is also influenced by regulations, company policy, market requirements, design conventions and many other intangible constraints. The analysis of a system therefore depends upon the degree to which the behavior of the human and system agents within the system is influenced by the relationship and interaction between causal and intentional constraints. The analysis of the FAF will help all stakeholders to understand the functional and physical context (that is, the Work Domain) within which the NPP staff will perform their tasks. For example, the environmental, physical and functional requirements of the plant will impose physical as well as mental constraints on workers.

Most industrial processes are influenced by situation and resource, and the operational strategy is thus also influenced by the extent to which the enterprise succeeds in mobilizing the available resources under the conditions imposed by the constraints on either humans or systems, or both:

- *Effect on humans* - typically causal and intentional constraints identified in complex systems include constraints imposed upon the behavior or activities of people due to:
  - purpose or mission of a system (causal as well as intentional);
  - the physical situation, including environmental conditions (causal);
  - specific operational situations, such as operator response time, accuracy or situation awareness (causal);
  - the available means by which activities can be performed (causal and intentional);
  - organizational structures, specific actor roles and definitions (intentional);
  - human capabilities and limitations, such as physical strength, mental workload or fatigue (causal);
- *Effect on systems* - causal as well as intentional constraints may also be imposed upon the ability of systems to perform a function due to:
  - physical limitations imposed by material properties (intentional);
  - reliability limits under adverse operational conditions, such as temperature, pressure, speed, etc. (intentional);
  - inability of operators to act quickly enough to either initiate or stop a function (causal);
  - spatial limitations in plant layout, preventing systems to be located in optimal positions (intentional);
  - limits in production capacity of a system or component, such as flow rate, volume, tolerance, heat conductivity or dissipation, speed, etc. (intentional);
  - limits in the control capability of the automation system (causal and intentional);
  - limits imposed by industry codes or regulations for reliability, safety or quality (intentional).

The key constraints that are likely to influence specific operational design decisions for a typical SFR are summarized in Table 1:

**Table 1: Constraints and their Effects**

| Constraint | Effect |
|---|---|
| Environmental | Environmental constraints include all external physical conditions that may influence human or system performance. This includes temperature, humidity, air quality, wind, vibration, radiation, lighting, etc. All of these conditions could be very hazardous to human health and good performance and may require various means to protect personnel health and safety. Many of these measures will be mandated by National Institute for Safety and Health (NIOSH) or Occupational Safety and Health (OSHA) regulations. |
| Human Factors | Human abilities and limitations vary along many dimensions. The design of the main control room and human-system interfaces of the AdvNPP must consider basic physical and sensory capacities, including vision, hearing, manual dexterity, strength, and reach. Cognitive functions, such as attention, memory, information processing, appreciation and understanding of hazards can influence the safety, effectiveness and productivity of the work environment. The resulting design will have an impact on operators' ability to interact with systems, equipment, and each other, and also to execute procedures. |
| Organizational | The guiding principle for the AdvNPP organization is to ensure that the physical assets and organizational resources in the operations domain are aligned with the direction set out in their corporate strategy. This would include development of policies and guidelines for specific constraints, such as work hours, staffing, safety, environmental protection, asset protection, security, and/or communication. |
| Regulatory | There are many regulations that influence the operation of a NPP. These include the industrial and occupational safety regulations mentioned above, but the most significant regulations during the design phase of a new plant are those dealing with licensing. The most direct regulatory basis for the human factors aspects of plant operations can be found in 10 CFR 50.52: Licenses, Certifications, and Approvals for Nuclear Power Plants. This part governs the issuance of early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power facilities. This regulation includes reference to various aspects of HFE, for example, human-system interface (HSI), procedures, training and staffing. Specific references emphasize the importance of early establishment of a Human Factors Engineering program that would help to inform the development of operational concepts, such as 10 CFR 50.34(f)(2). |
| Technical or physical | Technical and physical constraints are found in system characteristics and performance parameters such as size of equipment, speed, accuracy, location, material, tolerances (temperature, pressure, strength), etc. These constraints will influence the design, selection or placement of equipment. The constraints will also have a significant effect on human performance and ultimately on the design of HSIs and workspaces. |

Constraints will influence the functional capabilities and limitations of systems and will also determine capabilities of the physical objects, tools or other resources that must be available to the operators to perform their tasks.

### 2.2.4 Contextual Activity Analysis

The constraints associated with what needs to be accomplished in a system are modeled by the Contextual Activity Analysis (CAA). The contextual constraints can be specific operational conditions within a defined scenario, such as upset condition or transition. The table format shown in Figure 3 is typically used to identify the correlation between plant functions and operational conditions. In particular, the CAA provides the "course of action" basis for many subsequent decisions regarding operating practices and procedures and the associated control and monitoring artifacts.

**SFR Operational Concepts**
**Contextual Activities: Upset Events (End State conditions)**

| Functions \ Situations | Reactor Scram with normal Decay Heat Removal | Trip and Coastdown of one Primary Pump | Sodium leakage from intermediate piping | Decrease of intermed. coolant flow | Increase of primary coolant flow | Decrease of feedwater flow | Loss of offsite power | Spurious control rod insertion | Spurious control rod withdrawal | Seismic Event OBE |
|---|---|---|---|---|---|---|---|---|---|---|
| Control Reactor Startup and/or Shutdown | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Remove Decay Heat | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Transport Heat from Primary to Secondary Sodium Systems | ✓ | ✓ | ? | ? | ? | ? | ⊘ | ? | ? | ⊘ |
| Cool Plant Equipment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Convert Mechanical Energy to Electricity | ⊘ | ⊘ | ⊘ | ⊘ | ? | ? | ⊘ | ⊘ | ⊘ | ⊘ |
| Generate Steam | ⊘ | ⊘ | ⊘ | ? | ? | ? | ⊘ | ⊘ | ⊘ | ⊘ |
| Provide Personnel Comfort and Safety | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Symbol Explanation:**

| | |
|---|---|
| ✓ | The function can and typically does occur in this condition |
| ? | The function could occur in this condition, but typically does not |
| ⊘ | The function is not possible, not necessary, or prohibited in this condition |

**Figure 3: Contextual Activities for a SFR**

The results from the CAA are used in the development of the Strategies Analysis (StrAn), discussed below.

### 2.2.5 Strategies Analysis

The StrAn models alternative pathways (or strategies) from one system state to another. The strategies adopted under a particular situation may vary depending on the constraints within the given situation. The strategy used depends on variables, such as experience, knowledge, training, workload, available tools, and whether it is a human or automated agent that performs the activity or some combination (shared automation) of both agents.

The diagram in Figure 4 is an example of the format used to identify strategies. In the example, four possible strategies to move from "Identify reactor not scrammed" to "Reactor scrammed" were identified. See Section 3.5.3 for further details of this event.

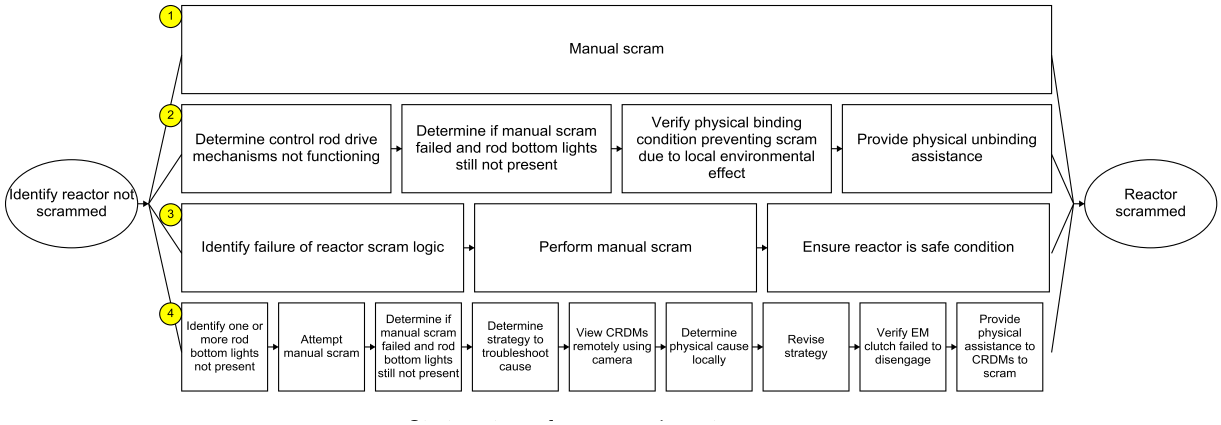


**Figure 4: Strategies Analysis Diagram**

### 2.2.6 Mode and State Analysis

The operational strategies derived from the analysis of operational conditions described earlier will result in decisions about the development of an operating scheme to handle the specific conditions and the transitions between them. Many of these of operational conditions may be non-existent in light water reactors (LWRs), such as reduced power operations, novel refueling methods, on-line maintenance, unplanned shutdowns for sodium or argon leaks, or load following that automatically adjusts power output. These modes and states will inevitably create complexities and require innovative treatments in the design and use of I&C systems, as well as appropriate HSIs. In order to guide decisions about automation and function allocation, it will be beneficial to define plant operation schemes in terms of a collection of discrete-event systems, that is, systems that perform discrete functions in uniquely definable operational modes and states. The key principles of a mode/state-based approach to automation will form part of the WDA Methodology Report, to be published in May 2015.

# 3 Work Domain Analysis for a Generic SFR Design

This section contains the descriptions as well as graphical results of the analysis of the functional and structural architecture of a typical SFR and its associated operational characteristics.

## 3.1 Work Domain Analysis Procedure

The modified WDA was applied to a generic SFR design by following these steps:

1. Identify and obtain all available source material on advanced reactors,
2. Identify the key missions and strategies for the identified designs,
3. From available material, compile a list of typical structures, systems and components (SSC),
4. Identify and summarize key operating principles for the identified designs,
5. Compile a list of functions for all SSC listed,
6. Develop a breakdown structure of SSC and functions, to three levels where possible,
7. Identify as many operational conditions as possible, including normal operations and anticipated operational occurrences,
8. Develop a first-order abstraction hierarchy for the identified systems and functions (for normal operations only),
9. Develop a first-order abstraction hierarchy for selected operational occurrences,
10. Reiterate steps 3 and 6 to refine and develop a set of FAF tables,
11. Develop a set of CAA tables for all conditions identified in step 7 and describe specific constraints identified, and
12. Develop a set of StrAn diagrams for key operational conditions.

## 3.2 Characterization of operational conditions

The operation of a NPP is characterized in terms of specific conditions, the evolution of those conditions over time, specific performance parameters involved, start and end states of various systems, and many more. The accurate definition of operational conditions is important in planning the response to normal, abnormal, and emergency conditions where decisions that are made are dependent on availability and comprehensibility of large amounts of data and information. The determination of operational conditions and response strategies is therefore a vital aspect of operational concept development. The analysis of the operational impact of AdvNPP configurations must include, for example, the effect of fuel type and design, different coolants, plant layout, and plant siting. The result from the CAA described below is a key ingredient of the operational strategy and also forms an essential input to function allocation, task analysis, automation design, operating procedures, and control room design.

## 3.3 Structure of the analysis results

A generic system and functional breakdown was developed from a review of a number of predecessor and emerging designs. Although the naming and definition of these systems may differ in some emerging SFR designs, it was found that this breakdown is sufficiently generic to inform the development of the WDA. A comprehensive discussion of this system and functional breakdown is beyond the scope of this report, but will be addressed again in a future milestone report. The full breakdown for the generic SFR is included in Appendix A for reference purposes.

The result of the WDA of a generic SFR design is presented in the following sections. It should be noted that sections 2-4 explore the response to three anticipated operational occurrences (that is, low-probability conditions that may occur during the lifetime of the plant and must therefore be considered in the design). These three anticipated operational occurrences (sections 2-4) were selected to demonstrate the basis for FAF, CAA, and StrAn:

1. First, the FAF for normal operation is presented, followed by an analysis of operational conditions in the CAA for normal operation.
2. FAF, CAA and StrAn for a Loss of Off-site Power event,
3. FAF, CAA and StrAn for a Water-to-sodium leak event,
4. FAF, CAA and StrAn for an Earthquake (minor to moderate).

## 3.4 Normal Operations

During normal power operation the reactor is critical and generating electricity. Normal power operation can also be defined as any power level at or above the minimum rated capacity of the turbine generator to generate electricity. Most SFRs will have the capability of ramping power levels up and down between this minimum rating and 100% power. Some designs will also be capable of load following (that is, responding automatically to electric power grid demand).

### 3.4.1 Normal Operations – Functional Abstraction Framework

The complete FAF for SFR Normal Operations (see Table 2, sections 4.1- 4.9), indicates the minimum main and subsystems that are required to perform the following physical processes (note that the order of functions is different in the table due to the multiple means-ends links involved):

- Fission Heat Production
- Reactivity Control
- Conversion of thermal energy to electrical energy
- Coolant Circulation
- Sodium Coolant Purification
- Fuel Handling

The FAF also shows the most important functions (see Table 2, sections 1.1-1.3) that are supported by the physical processes. The top level of the hierarchy shows that three primary missions that are served during normal operations:

1. Generate Electricity Economically
2. Protect workers, public, environment
3. Protect Assets

The means to measure whether these high-level goals or purposes were achieved are indicated in the second level.

NOTE:

- Where possible these measures are indicated in quantitative terms, but most measures are shown as qualitative values.
- No provision was made for heat addition by means of electrical induction or resistance heating of sodium pipes or heat addition by means of the steam generator. These were important functions of EBR-II, but no information was available on this function for more advanced designs.

**Table 2: Functional Abstraction Framework for Generic SFR**

| 1. Domain Purposes | Means/Ends Links |
|---|---|
| *1.1 Generate Electricity Economically* | 2.1, 2.2, 2.3, 2.4 |
| *1.2 Protect workers, public, environment* | 2.2, 2.5, 2.6 |
| *1.3 Protect Assets* | 2.3, 2.6 |

| **2. Values and Measures** | Level 1 | | Level 2 | | Level 3 | Means/Ends Links |
|---|---|---|---|---|---|---|
| *2.1* | *Reactivity Control* | | | | | To Level 1: 1.1, 1.2<br>To Level 3: 3.1 |
| | | 2.1.1 | Reactivity balanced | | | |
| | | 2.1.2 | Neutron flux distribution stable | | | |
| | | 2.1.3 | Conservative shutdown margin | | | |
| *2.2* | *Heat Removal* | | | | | To Level 1: 1.1, 1.2, 1.3<br>To Level 3: 3.2.1, 3.2.2, 3.2.3 |
| | | 2.2.1 | Core Heat Removed | | | |
| | | | | 2.2.1.1 | Core safety and integrity ensured | |
| | | | | 2.2.1.2 | Coolant circulated (forced and convective flow) | |
| | | 2.2.2 | Reactor decay heat removed | | | |
| | | 2.2.3 | Secondary sodium system heat removed | | | |

| | | | | | |
|---|---|---|---|---|---|
| | | 2.2.4 | Waste heat removed (components) | | |
| *2.3* | *Fuel Efficiency* | | | | To Level 1: 1.1<br>To Level 3: 3.3 |
| | | 2.3.1 | Breeder effect sustained | | |
| | | 2.3.2 | Actinides burned | | |
| | | 2.3.3 | Fuel damage mitigated | | |
| *2.4* | *Plant Productivity* | | | | To Level 1: 1.1<br>To Level 3: 3.2, 3.3., 3.4 |
| | | 2.4.1 | > 95% Availability | | |
| | | 2.4.2 | Electrical output > 34% efficiency | | |
| *2.5* | *Personnel, Public and Environmental Safety* | | | | To Level 1: 1.2, 1.3<br>To Level 3: 3.2, 3.4 |
| | | 2.5.1 | Fission product release prevented | | |
| | | 2.5.2 | Work space safety and habitability maintained | | |
| | | 2.5.3 | Hazardous materials mitigated | | |
| | | 2.5.4 | Human event response requirements minimized (passive safety) | | |
| *2.6* | *Asset Protection* | | | | To Level 1: 1.3<br>To Level 3: 3.2, 3.4 |
| | | 2.6.1 | Equipment damage mitigated | | |
| | | 2.6.2 | Plant Security maintained | | |
| | | 2.6.3 | Waste heat removed | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 2.6.4 | Habitable and safe work environment maintained | | | |

| **3. Operational Functions** | Level 1 | | Level 2 | | Level 3 | |
|---|---|---|---|---|---|---|
| *3.1* | *Generate Fission Heat* | | | | | To Level 2: 2.1, 2.3<br>To Level 4: 4.1, 4.2, 4.5.1 |
| | | 3.1.1 | Control Reactivity | | | |
| | | 3.1.2 | Regulate primary sodium flow | | | |
| | | 3.1.3 | Regulate primary sodium temperature | | | |
| | | 3.1.4 | Control fuel assembly movement | | | |
| *3.2* | *Remove process heat* | | | | | To Level 2: 2.1, 2.2<br>To Level 4: 4.3, 4.4 |
| | | 3.2.1 | Remove heat from core | | | |
| | | | | 3.2.3.1 | Transfer heat from IHX to secondary sodium | |
| | | | | 3.2.1.1 | Transport heat from primary sodium to IHX | |
| | | 3.2.2 | Remove reactor decay heat | | | |
| | | | | 3.2.2.1 | Remove heat from primary sodium to Na-NaK HX | |
| | | | | 3.2.2.2 | Transfer heat from IHX to secondary sodium | |
| | | 3.2.3 | Remove waste heat | | | |

| | | | | |
|---|---|---|---|---|
| | | 3.2.3.2 | Remove waste heat from secondary systems | |
| | | 3.2.3.3 | Reject heat using steam generator | |
| | | 3.2.3.4 | Remove waste heat from components | |
| *3.3* | *Convert Heat to Electricity* | | | To Level 2: 2.4<br><br>To Level 4: 4.2, 4.5 |
| | | 3.3.1 | Maintain Mass and Energy Inventory Balance | |
| | | 3.3.2 | Optimize fuel burn-up | |
| | | 3.3.3 | Control heat-to-electricity energy conversion | |
| *3.4* | *Manage & control the operating environment* | | | To Level 2: 2.3, 2.4, 2.5, 2.6<br><br>To Level 4: 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 |
| | | 3.4.1 | Contain fission products | |
| | | 3.4.2 | Cool plant equipment | |
| | | 3.4.3 | Maintain equipment integrity | |
| | | 3.4.4 | Maintain safe and habitable work environment | |
| | | 3.4.5 | Provide manual and automatic control of plant processes | |
| | | 3.4.6 | Supply services to plant | |
| | | 3.4.7 | Control the electric grid interface | |

| | | | | |
|---|---|---|---|---|
| | | 3.4.8 Manage fuel movements | | |

| **4. Operational Processes** | Level 1 | Level 2 | Level 3 | |
|---|---|---|---|---|
| 4.1 | *Reactivity control* | | | To Level 3: 3.1, 3.4<br>To Level 5: 5.1 |
| | | 4.1.1 | Neutron Flux Monitoring | |
| | | 4.1.2 | Control and Shutdown Rod Control | |
| | | 4.1.3 | Reactivity balance | |
| | | 4.1.4 | Power level adjustment | |
| 4.2 | *Fuel handling and optimization* | | | To Level 3: 3.1.3, 3.2.1<br>To Level 5: 5.1.2, 5.1.4, 5.2 |
| | | 4.2.1 | Fuel assembly movement control | |
| | | 4.2.2 | Fuel temperature and integrity control | |
| 4.3 | *Heat Transport* | | | To Level 3: 3.1, 3.2<br>To Level 5: 5.3., 5.4, 5.7 |
| | | 4.3.1 | Core Heat Removal | |
| | | 4.3.2 | Reactor Decay Heat Removal | |
| | | 4.3.3 | Component Heat Removal | |
| | | 4.3.4 | Waste Heat Removal | |
| | | 4.3.5 | Secondary system heat removal | |
| 4.4 | *Coolant circulation* | | | To Level 3: 3.2, 3.4.2 |

| | | | | |
|---|---|---|---|---|
| | | 4.4.1 | Forced sodium circulation | To Level 5: 5.3, 5.4, 5.7 |
| | | 4.4.2 | Convection cooling | |
| | | 4.4.3 | Air (natural draft) cooling (Air/NaK HX) | |
| *4.5* | *Energy conversion* | | | To Level 3: 3.1, 3.3, 3.4<br>To Level 5: 5.5, 5.6.1, 5.6.4 |
| | | 4.5.1 | Fission Heat Generation | |
| | | 4.5.2 | Steam Generation | |
| | | 4.5.3 | Steam-to-mechanical energy conversion | |
| | | 4.5.4 | Mechanical-to-electrical energy conversion | |
| *4.6* | *Plant and System Automation* | | | To Level 3: 3.4.5, 3.4.7<br>To Level 5: 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 5.9, 5.10 |
| | | 4.6.1 | Manual process/component monitoring & control | |
| | | 4.6.2 | Automatic process/component monitoring & control | |
| | | 4.6.3 | Remote surveillance and in-service inspection | |
| *4.7* | *Operation Support* | | | To Level 3: 3.4<br>To Level 5: 5.5.2, 5.6.2, 5.6.4, 5.8, 5.9 |
| | | 4.7.1 | Environmental condition control (heating, ventilation, air conditioning) | |
| | | 4.7.2 | Waste handling | |

| | | | | |
|---|---|---|---|---|
| | | 4.7.3 | Local electrical power supply | |
| | | 4.7.4 | Plant water demineralization and supply | |
| | | 4.7.5 | Potable water supply | |
| | | 4.7.6 | Compressed air supply and pneumatic component control | |
| | | 4.7.7 | Sodium processing and purification | |
| | | 4.7.8 | Electrical grid monitoring and control (voltage, frequency, load, etc.) | |
| | | 4.7.9 | Inert gas supply and processing | |
| | | 4.7.10 | Electrical (Induction & resistance) pipe heating | |
| | | 4.7.11 | Plant communication | |
| *4.8* | *Protection Processes* | | | To Level 3: 3.2, 3.4<br>To Level 5: 5.10 |
| | | 4.8.1 | Reactor Protection | |
| | | 4.8.2 | Sodium Fire Protection | |
| | | 4.8.3 | Plant Fire Protection | |
| | | 4.8.4 | Seismic Monitoring | |
| | | 4.8.5 | Radiation Monitoring | |
| | | 4.8.6 | Plant Surveillance and Inspection | |

| | | | | | |
|---|---|---|---|---|---|
| | | 4.8.7 | Plant Safeguard and Security | | |
| *4.9* | *Fuel Handling Processes* | | | | To Level 3: 3.1.3, 3.4.8<br><br>To Level 5: 5.2 |
| | | 4.9.1 | Core Component Movement | | |
| | | 4.9.2 | Spent fuel removal | | |
| | | 4.9.3 | Fresh fuel loading | | |

| **5. Structures, Systems & Components** | Level 1 | | Level 2 | | Level 3 | |
|---|---|---|---|---|---|---|
| *5.1* | *Reactor Containment and Core* | | | | | To Level 4:<br>4.1.1, 4.1.2, 4.1.3, 4.1.4<br>4.2.1, 4.3.1, 4.3.2, 4.5.1,<br>4.7.6, 4.8.1 |
| | | 5.1.1 | Reactor Vessel | | | |
| | | 5.1.2 | Core Assemblies | | | |
| | | 5.1.3 | Reactivity Control System | | | |
| | | | | 5.1.3.1 | Control and Shutdown Rods | |
| | | | | 5.1.3.2 | Neutron Flux Monitoring System | |
| | | | | 5.1.3.3 | Reactor Vessel Instrumentation System | |
| | | 5.1.4 | Rotating Plugs | | | |
| | | 5.1.5 | Reactor Hot Pool | | | |
| | | 5.1.6 | Reactor Cold Pool | | | |
| | | 5.1.7 | Guard Vessel | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *5.2* | *In-reactor Fuel Handling System* | | | | | To Level 4: 4.2.1, 4.6.1, 4.6.2, 4.6.3 |
| | | 5.2.1 | Fuel Assembly Handling Machine | | | |
| | | 5.2.2 | Refueling Support Equipment | | | |
| | | 5.2.3 | Ex-containment Sodium Tank | | | |
| *5.3* | *Primary Cooling System* | | | | | To Level 4: 4.3.1, 4.3.2, 4.4.1, 4.4.2, 4.7.9 |
| | | 5.3.1 | Primary Sodium Pumps | | | |
| | | 5.3.2 | Intermediate Heat Exchanger | | | |
| | | 5.3.3 | Argon cover gas system | | | |
| | | 5.3.4 | Decay Heat Removal System | | | |
| *5.4* | *Secondary Cooling System* | | | | | To Level 4: 4.3.5, 4.4.1 |
| | | 5.4.1 | Intermediate Sodium Pumps | | | |
| | | 5.4.2 | Auxiliary Heat Exchanger | | | |
| | | 5.4.3 | Secondary Argon Systems | | | |
| | | 5.4.4 | Passive Heat Removal System | | | |
| *5.5* | *Energy Conversion Systems* | | | | | To Level 4: 4.5, 4.7.3, 4.7.8 |
| | | 5.5.1 | Steam Systems | | | |
| | | | | 5.5.1.1 | Steam Generator | |
| | | | | 5.5.1.3 | Feedwater and Condensate System | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 5.5.2 | Turbo-Generator | | | |
| | | | | 5.5.2.1 | High-Pressure Turbine | |
| | | | | 5.5.2.2 | Low-Pressure Turbine | |
| | | | | 5.5.2.3 | Generator | |
| 5.6 | *Plant Service Systems* | | | | | To Level 4: 4.6 |
| | | 5.6.1 | Normal and Automated Electrical Facilities | | | |
| | | | | 5.6.1.1 | Plant Electrical Supply System | |
| | | | | 5.6.1.2 | Building Electrical Supply System | |
| | | | | 5.6.1.3 | Emergency/ Standby Generators & UPS | |
| | | 5.6.2 | Inert Gas Distribution and Processing System | | | To Level 4: 4.7.9 |
| | | | | 5.6.3.1 | Argon Storage and Supply | |
| | | | | 5.6.3.2 | Nitrogen Storage and Supply | |
| | | 5.6.3 | Electrical Na Pipe Heating Systems | | | To Level 4: 4.7.10 |
| | | 5.6.4 | Plant Control and Data Facilities | | | |
| | | | | 5.6.4.1 | Distributed Control System | |

| | | | | |
|---|---|---|---|---|
| | | 5.6.4.2 Control Room & HSI | | |
| | | 5.6.4.3 Remote Shutdown Facility | | |
| | 5.6.5 Plant Compressed Air Supply System | | | To Level 4: 4.7.1, 4.7.4, 4.7.5, 4.7.6, 4.7.11 |
| | | 5.6.5.1 Service Air System | | |
| | | 5.6.5.2 Instrument Air System | | |
| | 5.6.6 Demineralized Water Supply System | | | |
| | 5.6.7 Potable Water Supply System | | | |
| | 5.6.8 Plant Communication System | | | |
| | 5.6.9 Heating, Ventilation & Air Conditioning | | | |
| *5.7 Auxiliary Cooling Systems* | | | | To Level 4: 4.3.3, 4.3.5, 4.6 |
| | 5.7.1 Component Cooling Water System | | | |
| | 5.7.2 Cooling Towers | | | |
| | 5.7.3 Nitrogen Cryogenic Cooling System | | | |
| | 5.7.4 Chilled Water System | | | |
| | 5.7.5 Condenser Water System | | | |
| *5.8 Sodium Processing Systems* | | | | To Level 4: 4.6, 4.7.7 |

| | | | | |
|---|---|---|---|---|
| | | 5.8.1 | Sodium Storage and Surge Tanks | |
| | | 5.8.2 | Primary Sodium Purification System | |
| | | 5.8.3 | Secondary Sodium Purification System | |
| | | 5.8.4 | Sodium Dump System | |
| | | 5.8.5 | Sodium Cold Trap | |
| | | 5.8.6 | Nuclide Trap | |
| *5.9* | *Waste Handling System* | | | To Level 4: 4.7.2 |
| | | 5.9.1 | High-level Radioactive Waste Treatment System | |
| | | 5.9.2 | Low-Level Radioactive Waste Treatment System | |
| | | 5.9.3 | Effluent Treatment and Disposal System | |
| *5.10* | *Protection Systems* | | | To Level 4: 4.8 |
| | | 5.10.1 | Reactor Protection System | |
| | | 5.10.2 | Reactor Shutdown System | |
| | | 5.10.3 | Radiation Monitoring System | |
| | | 5.10.4 | Post-event Instrumentation System | |
| | | 5.10.5 | Sodium Leak Detection System | |
| | | 5.10.6 | Sodium Fire Protection System | |

| | | | | | |
|---|---|---|---|---|---|
| | | 5.10.7 | Plant Fire Protection System | | |
| | | 5.10.8 | Seismic Monitoring System | | |
| | | 5.10.9 | Radiation Monitoring System | | |
| | | 5.10.10 | Plant Surveillance and Inspection System | | |
| | | 5.10.11 | Sodium Dump System | | |
| | | 5.10.12 | Steam Dump System | | |
| | | 5.10.13 | Plant Security System | | |

### 3.4.2 Normal Operations – Contextual Activities Analysis

The identification of operational conditions for the CAA is based on review of operating experience from EBR-II and information from designs like Power Reactor Innovative Small Module (PRISM). The identification process is described in Hugo et al. (2014) [2].

Table 3 describes the functions that apply during the identified operational conditions – these are called "contextual activities". The rows in the diagram show the applicable functions and the columns show the different operational conditions that are possible as the plant transitions from the lowest operational state (e.g., "Unrestricted Fuel Handling") to the highest state (e.g., "Full Power Operation"). The marked cells in the grid indicate the correspondence between functions and conditions, as follows:

NOTE: The symbols used in the Contextual Activities tables below are as follows:

| | |
|---|---|
| ✓ | = The function can and typically does occur in this condition |
| ? | = The function could occur in this condition, but typically does not |
| ⃠ | = The function is not possible, not necessary, or prohibited in this condition |

**Examples:**

| Function | Explanation |
|---|---|
| Convert shaft power to electricity | Electricity is only produced during full power operation and when the generator is synchronized to the grid. |
| Maintain Active Reactor Cooling | Active cooling is required during all conditions, except during Cold Shutdown and Unrestricted Fuel Handling. |
| Maintain Equipment Integrity | This function is always required, regardless of the condition. |
| Optimize Fuel Burnup | Optimal fuel burnup is not possible during Cold Shutdown or Fuel Handling. All other conditions where the reactor is critical will allow optimal fuel burnup. |

## Table 3: Contextual Activities - Normal Operations

| Functions \ Situations | Full Power Operations (Steady State) | Reduced/ Low Power Operations | Reactor Startup | Hot Standby | Reactor Shutdown | Fuel Handling | Comments |
|---|---|---|---|---|---|---|---|
| Remove Heat from Core | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Control Reactivity | ✓ | ✓ | ✓ | ✓ | ✓ | ⊘ | For fuel handling: although reactor is subcritical, reactivity is still controlled. |
| Control Reactor Startup and Shutdown | ✓ | ✓ | ✓ | ✓ | ✓ | ⊘ | Shutdown is possible from a steady state or low power. |
| Balance Reactor Power | ✓ | ✓ | ⊘ | ⊘ | ⊘ | ⊘ | |
| Contain Fission Products | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Remove Decay Heat | ✓ | ✓ | ✓ | ✓ | ✓ | ? | Heat removal also occurs through natural convection when reactor is shut down |
| Transport Heat from Primary to Secondary Sodium Systems | ✓ | ✓ | ✓ | ✓ | ⊘ | ⊘ | |
| Maintain Equipment Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Cool Plant Equipment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Optimize Fuel Burnup | ✓ | ? | ⊘ | ⊘ | ⊘ | ⊘ | Optimal fuel burnup only possible at operating temperatures. |
| Control Fuel Temperature and Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Convert Mechanical Energy to Electricity | ✓ | ✓ | ⊘ | ⊘ | ⊘ | ⊘ | |
| Manage Electric Grid Interface for electricity export | ✓ | ✓ | ⊘ | ⊘ | ⊘ | ⊘ | |
| Provide commercial electrical power to plant | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Provide standby electrical power | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | |
| Manage & Control the Operating Environment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Generate Steam | ✓ | ✓ | ⊘ | ✓ | ⊘ | ⊘ | |
| Provide Personnel Comfort and Safety | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Ensure Safe and Habitable Operating Environment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Protect Assets | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |

In combination, the marked cells in the Contextual Activity diagram indicate the underlying constraints of the particular operational mode.

## 3.5 Loss of Off-site Power

Loss of off-site power is defined as the loss of electrical power from the grid or from the turbine generator to the high-voltage bus. The typical changes that occur automatically are the following:

1. The reactor scrams automatically,
2. The primary sodium pumps (auto trip) stop,
3. Secondary sodium and recirculating pumps (auto trip) stop,
4. All electrical heating of the primary and secondary systems is lost,
5. All motor driven pumps stop, except equipment supplied from uninterruptible power supply (UPS), e.g., turning gear oil pumps, seal oil pumps and the emergency feedwater charging pump, and
6. Emergency Diesel Generators (EDGs) start and load.

Recovering from this event will depend primarily upon how quickly the EDGs startup and how quickly systems can return to normal operation. Regardless of the speed of system recovery, mitigation strategies typically involve operator action to ensure that the reactor has scrammed, all automated plant functions have occurred, and that reactor cooling systems (passive as well as active) are functioning correctly.

### 3.5.1 Loss of Off-site Power – Functional Abstraction Framework

Table 4 shows the systems and functions that are involved in the event and in achieving a safe plant condition.

**Table 4: Functional Abstraction - Loss of Off-Site Power**

| **1. Mission Strategy** | **Means/Ends Links** |
|---|---|
| *1.1 Establish Safe Plant Condition after Loss of Off-site Power* | |

| **2. Values and Measures** | Level 1 | Level 2 | | Means/Ends Links |
|---|---|---|---|---|
| *2.1* | *Reactivity Control* | | | To Level 1: 1.1<br><br>To Level 3: 3.1, 3.2, 3.3 |
| | | 2.1.1 | Reactor scrammed | |
| | | 2.1.2 | Decay heat removed | |
| | | 2.1.3 | Core safety ensured | |
| | | 2.1.4 | System monitoring and control maintained | |
| | | 2.1.5 | Emergency electric power available | |
| | | 2.1.6 | Feedwater added to steam generator | |

| | | | | |
|---|---|---|---|---|
| | | 2.1.7 | Excess steam pressure vented to atmosphere | |
| | | 2.1.8 | Na primary and intermediate pumps tripped | |
| | | 2.1.9 | Electrical Na pipe heating restored | |
| | | 2.1.10 | Mechanical and thermal stresses minimized | |
| | | 2.1.11 | Workers, public, assets and environment protected | |

| **3. Operational Functions** | Level 1 | | Level 2 | |
|---|---|---|---|---|
| *3.1* | *Control Reactivity* | | | To Level 2: 2.1<br>To Level 4: 4.1 |
| | | 3.1.1 | Regulate primary sodium flow (Aux Pump on battery power) | |
| *3.2* | *Remove process heat* | | | To Level 2: 2.1<br>To Level 4: 4.2, 4.3, 4.4, 4.5 |
| | | 3.2.1 | Remove heat from core | |
| | | 3.2.2 | Remove reactor decay heat | |
| | | 3.2.3 | Remove waste heat | |
| *3.3* | *Manage & control the operating environment* | | | To Level 2: 2.1<br>To Level 4: 4.3, 4.4, 4.5 |
| | | 3.3.1 | Cool plant equipment | |
| | | 3.3.2 | Maintain equipment integrity | |
| | | 3.3.3 | Maintain safe and habitable work environment | |
| | | 3.3.4 | Maintain manual and automatic control of plant processes | |
| | | 3.3.5 | Supply instrument air | |
| | | 3.3.7 | Provide emergency electrical power | |
| | | 3.3.8 | Provide air assist for control rod drives | |
| | | 3.3.9 | Protect turbine generator rotational parts | |

| **4. Operational Processes** | Level 1 | Level 2 |
|---|---|---|

| | | | | |
|---|---|---|---|---|
| *4.1* | *Reactivity control* | | | To Level 3: 3.1<br>To Level 5: 5.1 |
| | | 4.1.1 | Control and Shutdown Rod Control | |
| *4.2* | *Heat Transport* | | | To Level 3: 3.2<br>To Level 5: 5.2, 5.4, 5.4, 5.5 |
| | | 4.2.1 | Core Heat Removal | |
| | | 4.2.2 | Reactor Decay Heat Removal | |
| *4.3* | *Plant and System Automation* | | | To Level 3: 3.3<br>To Level 5: 5.6 |
| | | 4.3.1 | Manual process/component monitoring & control | |
| | | 4.3.2 | Automatic process/component monitoring & control | |
| | | 4.3.3 | Remote surveillance and in-service inspection | |
| *4.4* | *Protection Processes* | | | To Level 3: 3.3<br>To Level 5: 5.6 |
| | | 4.4.1 | Emergency electrical power supply | |
| *4.5* | *Operation Support* | | | To Level 3: 3.3<br>To Level 5: 5.4, 5.5 |
| | | 4.5.1 | Auxiliary steam generation for heating, ventilation and air conditioning (HVAC) | |
| | | 4.5.2 | Turbine system lubrication | |
| | | 4.5.3 | Compressed air supply and pneumatic component control | |

| **5. Structures, Systems & Components** | Level 1 | | Level 2 | |
|---|---|---|---|---|
| *5.1* | *Reactor Containment and Core* | | | To Level 4: 4.1, 4.2, 4.3, 4.4 |
| | | 5.1.1 | Control and Shutdown Rods | |
| | | 5.1.2 | Neutron Flux Monitoring System | |
| | | 5.1.3 | Reactor Vessel Instrumentation System | |
| *5.2* | *Primary Cooling System* | | | To Level 4: 4.2, 4.3 |
| | | 5.2.1 | Primary Sodium Pumps | |
| | | 5.2.2 | Intermediate Heat Exchanger | |

| | | | | |
|---|---|---|---|---|
| 5.3 | *Secondary Cooling System* | | | To Level 4: 4.2, 4.3 |
| | | 5.3.1 | Intermediate Sodium Pumps | |
| | | 5.3.2 | Auxiliary Heat Exchanger | |
| | | 5.3.4 | Passive Heat Removal System | |
| 5.4 | *Energy Conversion Systems* | | | To Level 4: 4.2, 4.3 |
| | | 5.4.1 | Steam Generator System | |
| | | 5.4.2 | Feedwater and Condensate System | |
| | | 5.4.4 | Auxiliary steam boiler system | |
| 5.5 | *Plant Service Systems* | | | To Level 4: 4.3, 4.4 |
| | | 5.5.1 | Normal and Automated Electrical Facilities | |
| | | 5.5.2 | Plant Control and Data Facilities | |
| | | 5.5.3 | Control Room & HSI | |
| | | 5.5.4 | Remote Shutdown Facility | |
| | | 5.5.5 | Emergency/Standby Generators & UPS | |
| | | 5.5.6 | Demineralized Water Supply System | |
| | | 5.5.7 | Turbine Generator Lubrication & Seal System | |
| | | 5.5.8 | Plant and Instrument Compressed Air Supply System | |
| | | 5.5.9 | Building Electrical Power System | |
| 5.6 | *Protection Systems* | | | To Level 4: 4.4 |
| | | 5.6.1 | Reactor Protection System | |
| | | 5.6.2 | Reactor Shutdown System | |
| | | 5.6.3 | Plant Surveillance and Inspection System | |

### 3.5.2 Loss of Off-site Power – Contextual Activities Analysis

Table 5 describes the various possible emergent conditions during loss of off-site power.

**Table 5: Contextual Activities - Loss of Off-Site Power**

| Functions \ Situations | EDG does not start | UPS not functioning correctly | Portable EDG not available | Reactor does not scram | Passive decay removal system not open | TG not tripped automatically | TB lube oils sytem not functioning | Steam dump system not activated | Emergency Feedwater Pump not started |
|---|---|---|---|---|---|---|---|---|---|
| Remove Heat from Core | ✓ | ✓ | ✓ | ✓ | Manual action | ✓ | ✓ | ✓ | ✓ |
| Maintain criticality | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Maintain reactor subcritical | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Control Reactor Startup and/or Shutdown | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Contain Fission Products | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Remove Decay Heat | ✓ | ✓ | ✓ | ✓ | Manual action | ✓ | ✓ | ✓ | ✓ |
| Transport Heat from Primary to Secondary Sodium Systems | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Maintain Equipment Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Cool Plant Equipment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Optimize Fuel Burnup | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Control Fuel Temperature and Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Convert Mechanical Energy to Electricity | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Manage Electric Grid Interface | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Provide standby electrical power | Deploy portable EDG | ⃠ | ⃠ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Maintain Control Functions | Short duration only | Short duration only | Short duration only | Manual scram | ✓ | ✓ | ✓ | ✓ | ✓ |
| Generate Steam | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ | ⃠ |
| Provide Personnel Comfort and Safety | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ensure Safe and Habitable Operating Environment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Protect Assets | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

### 3.5.3 Loss of Off-site Power – Strategies Analysis

The most critical action after a loss of normal power is to ensure that emergency power is available to the cooling systems. For this purpose both EDGs should start and load immediately. If one or both EDGs should fail to start or load, operators will attempt to identify and correct the fault as soon as possible. If this still fails, they will start a skid-mounted EDG to restore power to equipment essential for protecting assets such as the turbine generator.

Figure 5 and Figure 6 describe the various alternative strategies to recover from the condition, with or without automatic reactor scram.

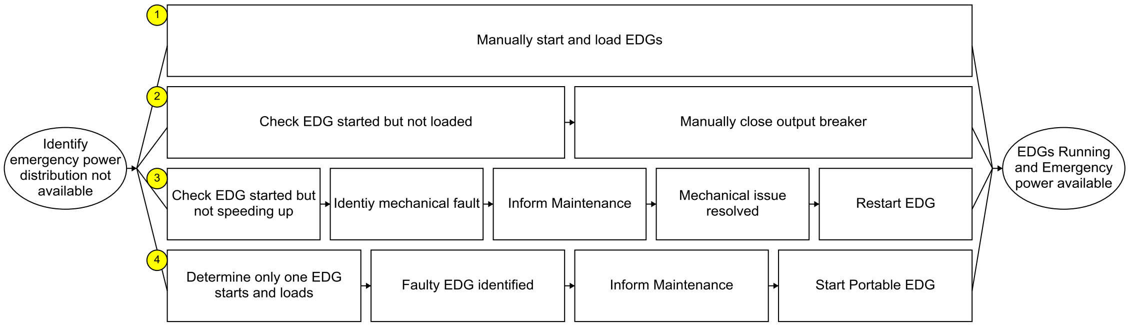


**Figure 5: Strategies Analysis - Mitigation of autostart failure of EDGs after Loss of Off-Site Power**

The loss of normal electrical power may affect a number of systems that will require a shutdown. If for some reason automatic reactor scram fails to actuate, there are various strategies to ensure the reactors scrams, depending on the severity of system failures, such as failed Control Rod Drive Mechanisms.

A potential emergent condition during or immediately following a loss of off-site power is a failure of the reactor to scram automatically. A typical cause would be malfunctioning of the control rod drive mechanisms. Figure 6 shows four possible strategies to scram the reactor.

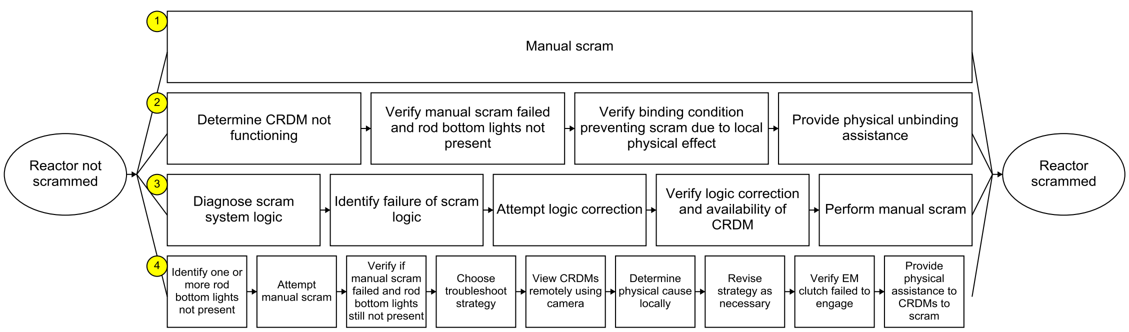


**Figure 6: Strategies Analysis - Mitigation of failed automatic reactor scram**

## 3.6 Water-to-Sodium Leak

A water-to-sodium leak results in a reaction that creates heat and liberates hydrogen, causing rapidly increasing temperature and pressure in the affected systems. The magnitude of the temperature and pressure changes depends on the size of the leak. Localized high temperature and pressure could cause failure of systems like secondary systems heat exchangers.

The analysis below indicates that the ultimate objective is not only to protect workers, public and the environment, but also to prevent damage to equipment and facilities.

### 3.6.1 Water-to-Sodium Leak – Functional Abstraction Framework

Table 6 shows the systems and functions that are involved in the event and in achieving a safe plant condition.

## Table 6: Functional Abstraction - Water-to-Sodium Leak

| 1. Mission Strategy | Means/Ends Links |
|---|---|
| *1.1 Protect workers, public, assets and environment* | |

| 2. Values and Measures | Level 1 | | Level 2 | Means/Ends Links |
|---|---|---|---|---|
| *2.1* | *Reactivity Control* | | | To Level 1: 1.1<br>To Level 3: 3.1 |
| | | 2.1.1 | Reactor scrammed | |
| | | 2.1.2 | Decay heat removed | |
| | | 2.1.3 | Core safety ensured | |
| | | 2.1.4 | System monitoring and control maintained | |
| | | 2.1.5 | Feedwater side of HXs argon blanketed | |
| | | 2.1.6 | SG feedwater dumped | |
| | | 2.1.7 | Secondary Na dumped, with argon blanket | |
| | | 2.1.8 | Na recirculation pumps tripped | |
| | | 2.1.9 | Electrical Na pipe heating secured | |
| | | 2.1.10 | Mechanical and thermal stresses minimized | |
| | | 2.1.11 | Workers, public, assets and environment protected | |

| 3. Operational Functions | Level 1 | | Level 2 | Means/Ends Links |
|---|---|---|---|---|
| *3.1* | *Control Reactivity* | | | To Level 2: 2.1<br>To Level 4: 4.1, 4.3 |
| | | 3.1.1 | Regulate primary sodium flow | |
| *3.2* | *Remove process heat* | | | To Level 2: 2.1<br>To Level 4: 4.2, 4.4, 4.5 |
| | | 3.2.1 | Remove heat from core | |
| | | 3.2.2 | Remove reactor decay heat | |

| | | | | |
|---|---|---|---|---|
| | | 3.2.3 | Remove waste heat | |
| 3.3 | *Manage & control the operating environment* | | | To Level 2: 2.1<br>To Level 4: 4.3, 4.4, 4.5 |
| | | 3.3.1 | Contain fission products | |
| | | 3.3.2 | Cool plant equipment | |
| | | 3.3.3 | Maintain equipment integrity | |
| | | 3.3.4 | Maintain safe and habitable work environment | |
| | | 3.3.5 | Provide manual and automatic control of plant processes | |
| | | 3.3.6 | Supply services to plant | |
| | | 3.3.7 | Drain secondary sodium system | |
| | | 3.3.8 | Activate sodium fire protection system | |

| **4. Operational Processes** | Level 1 | | Level 2 | |
|---|---|---|---|---|
| 4.1 | *Reactivity control* | | | To Level 3: 3.1<br>To Level 5: 5.1 |
| | | 4.1.1 | Control and Shutdown Rod Control | |
| 4.2 | *Heat Transport* | | | To Level 3: 3.2<br>To Level 5: 5.2, 5.3 |
| | | 4.2.1 | Core Heat Removal | |
| | | 4.2.2 | Reactor Decay Heat Removal | |
| 4.3 | *Plant and System Automation* | | | To Level 3: 3.3<br>To Level 5: 5.5 |
| | | 4.3.1 | Manual process/component monitoring & control | |
| | | 4.3.2 | Automatic process/component monitoring & control | |
| | | 4.3.3 | Remote surveillance and in-service inspection | |
| 4.4 | *Protection Processes* | | | To Level 3: 3.3.2, 3.3.3, 3.3.4<br>To Level 5: 5.6 |
| | | 4.4.1 | Sodium Fire Protection | |
| | | 4.4.2 | Plant Fire Protection | |

| | | | | |
|---|---|---|---|---|
| 4.5 | *Operation Support* | | | To Level 3: 3.3.3, 3.3.35, 3.3.6<br><br>To Level 5: 5.5 |
| | | 4.5.1 | Environmental condition control (heating, ventilation, air conditioning) | |
| | | 4.5.2 | Compressed air supply and pneumatic component control | |

| **5. Structures, Systems & Components** | Level 1 | | Level 2 | |
|---|---|---|---|---|
| 5.1 | *Reactor Containment and Core* | | | To Level 4: 4.1 |
| | | 5.1.1 | Control and Shutdown Rods | |
| | | 5.1.2 | Neutron Flux Monitoring System | |
| | | 5.1.3 | Reactor Vessel Instrumentation System | |
| 5.2 | *Primary Cooling System* | | | To Level 4: 4.2.1 |
| | | 5.2.1 | Primary Sodium Pumps | |
| | | 5.2.2 | Intermediate Heat Exchanger | |
| 5.3 | *Secondary Cooling System* | | | To Level 4: 4.2.2 |
| | | 5.3.1 | Intermediate Sodium Pumps | |
| | | 5.3.2 | Auxiliary Heat Exchanger | |
| | | 5.3.3 | Secondary Argon Systems | |
| 5.4 | *Energy Conversion Systems* | | | To Level 4: 4.2.2 |
| | | 5.4.1 | Steam Generator | |
| | | 5.4.2 | Feedwater and Condensate System | |
| | | 5.4.3 | Emergency Feedwater Charging Pump | |
| 5.5 | *Plant Service Systems* | | | To Level 4: 4.5 |
| | | 5.5.1 | Normal and Automated Electrical Facilities | |
| | | 5.5.2 | Plant Control and Data Facilities | |

| | | | | | |
|---|---|---|---|---|---|
| | | | 5.5.3 | Control Room & HSI | |
| | | | 5.5.4 | Remote Shutdown Facility | |
| | | | 5.6.5 | Plant and Instrument Compressed Air Supply System | |
| | | | 5.6.6 | Emergency/Standby Generators & UPS | |
| | | | 5.6.7 | Demineralized Water Supply System | |
| | | | 5.6.8 | Turbine Generator Lubrication & Seal System | |
| | *5.6* | *Protection Systems* | | | To Level 4: 4.4 |
| | | | 5.6.1 | Reactor Protection System | |
| | | | 5.6.2 | Reactor Shutdown System | |
| | | | 5.6.3 | Sodium Fire Protection System | |
| | | | 5.6.4 | Plant Fire Protection System | |
| | | | 5.6.5 | Passive Heat Removal System | |
| | | | 5.6.6 | Steam Dump System | |
| | | | 5.6.7 | Plant Surveillance and Inspection System | |

Table 6 highlights the typical ultimate purpose of any strategy to mitigate a condition that challenges the safety and integrity of plant systems. Protecting workers, public and the environment is necessary in the unlikely event of a radioactive release, but more typically actions will be taken to protect assets and prevent any emergent condition that may damage plant equipment or facilities.

### 3.6.2 Water-to-Sodium Leak – Contextual Activities Analysis

Table 7 shows the most important functions that are involved in several emergent conditions during a water-to-sodium leak.

**Table 7: Contextual Activities - Water-to-Sodium Leak**

| Functions \ Situations | EDG does not start | UPS not functioning correctly | Portable EDG not available | Reactor does not scram | Passive decay removal system not open | TG not tripped automatically | TB lube oils sytem not functioning | Steam dump system not activated | Emergency Feedwater Pump not started |
|---|---|---|---|---|---|---|---|---|---|
| Remove Heat from Core | ✓ | ✓ | ✓ | ✓ | Manual action | ✓ | ✓ | ✓ | ✓ |
| Maintain criticality | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Maintain reactor subcritical | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Control Reactor Startup and/or Shutdown | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Contain Fission Products | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Remove Decay Heat | ✓ | ✓ | ✓ | ✓ | Manual action | ✓ | ✓ | ✓ | ✓ |
| Transport Heat from Primary to Secondary Sodium Systems | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Maintain Equipment Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Cool Plant Equipment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Optimize Fuel Burnup | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Control Fuel Temperature and Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Convert Mechanical Energy to Electricity | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Manage Electric Grid Interface | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Provide standby electrical power | Deploy portable EDG | ⊘ | ⊘ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Maintain Control Functions | Short duration only | Short duration only | Short duration only | Manual scram | ✓ | ✓ | ✓ | ✓ | ✓ |
| Generate Steam | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Provide Personnel Comfort and Safety | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ensure Safe and Habitable Operating Environment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Protect Assets | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

### 3.6.3 Water-to-Sodium Leak – Strategies Analysis

Figure 7 below describes five alternative strategies to prevent a water-to-sodium reaction or to recover from the condition.

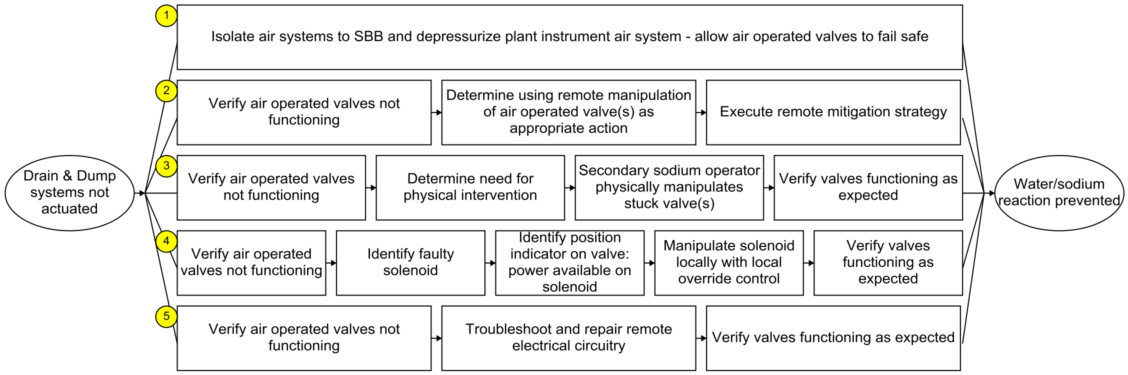


**Figure 7: Strategies Analysis - Mitigation of the Secondary Na Drain Systems Failure**

However, depending on the severity and also the location of the condition, it may be possible to misdiagnose the exact nature of the condition. Figure 8 describes alternative strategies to ensure that the condition is diagnosed as quickly as possible to recover from the condition or to minimize the consequences of a water-to-sodium reaction.

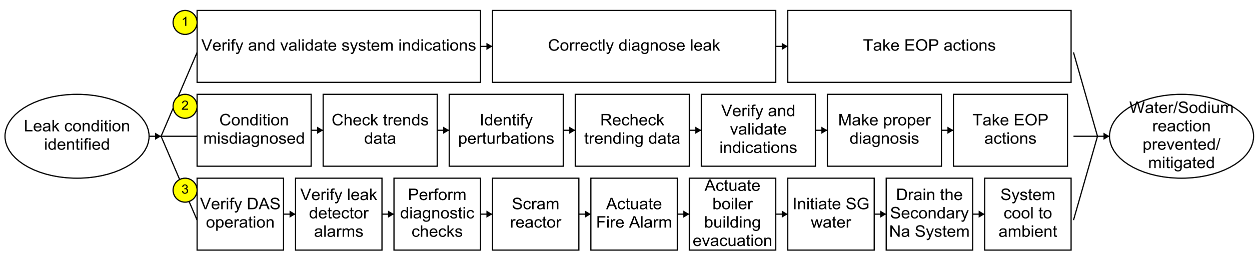


**Figure 8: Strategies Analysis - Mitigation of misdiagnosed condition**

## 3.7 Earthquake (minor to moderate)

An earthquake presents two hazards: 1) reactor shutdown may not be possible if control and safety rods or their drive mechanisms bind, and 2) piping systems may fail, releasing water, sodium or high-pressure steam. The Seismic Monitoring System and Reactor Protection Systems scram the reactor (control and safety rods). Operator action involves ensuring the reactor has scrammed and placing plant system in as safe a condition as possible. Depressurization and draining of some sodium and water systems may be desirable. An earthquake may also cause a loss of normal electrical power, leading in severe cases to a station black-out.

### 3.7.1 Earthquake – Functional Abstraction Framework

Table 8 shows the systems and functions that are involved in the event and in achieving a safe plant condition.

**Table 8: Functional Abstraction - Minor to Moderate Earthquake**

| 1. Mission Strategy | | Means/Ends Links |
|---|---|---|
| *1.1 Establish Safe Plant Condition after Earthquake* | | |

| 2. Values and Measures | | Level 1 | Level 2 | |
|---|---|---|---|---|
| | 2.1 | *Reactivity Control* | | To Level 1: 1.1<br><br>To Level 3: 3.1, 3.2, 3.3 |
| | | 2.1.1 | Reactor scrammed | |
| | | 2.1.2 | Decay heat removed | |
| | | 2.1.3 | Fuel integrity and core safety ensured | |
| | | 2.1.4 | System monitoring and control maintained | |
| | | 2.1.5 | Feedwater side of HXs argon blanketed | |
| | | 2.1.6 | Emergency electric power available | |
| | | 2.1.7 | Steam generator feedwater dumped | |
| | | 2.1.8 | Excess steam pressure vented to atmosphere | |
| | | 2.1.9 | Secondary Na dumped with argon blanket | |
| | | 2.1.10 | Electrical Na pipe heating secured | |
| | | 2.1.11 | Mechanical and thermal stresses minimized | |
| | | 2.1.12 | Workers, public, assets and environment protected | |

| 3. Operational Functions | | Level 1 | Level 2 | |
|---|---|---|---|---|
| | 3.1 | *Control Reactivity* | | To Level 2: 2.1<br>To Level 4: 4.1 |
| | | 3.1.1 | Regulate primary sodium flow | |
| | 3.2 | *Remove process heat* | | To Level 2: 2.1<br>To Level 4: 4.2 |
| | | 3.2.1 | Remove heat from core | |
| | | 3.2.2 | Remove reactor decay heat | |
| | | 3.2.3 | Remove waste heat | |
| | 3.3 | *Manage & control the operating environment* | | To Level 2: 2.1<br>To Level 4: 4.3, |

| | | | | |
|---|---|---|---|---|
| | | 3.3.1 | Cool plant equipment | 4.4, 4.5 |
| | | 3.3.2 | Maintain equipment integrity | |
| | | 3.3.3 | Maintain safe and habitable work environment | |
| | | 3.3.4 | Maintain manual and automatic control of plant processes | |
| | | 3.3.5 | Supply instrument air | |
| | | 3.3.6 | Provide emergency electrical power | |
| | | 3.3.7 | Provide air assist for control rod drives | |
| | | 3.3.8 | Protect turbine generator rotational parts | |

| **4. Operational Processes** | Level 1 | Level 2 | | |
|---|---|---|---|---|
| *4.1* | *Reactivity control* | | | To Level 3: 3.1<br>To Level 5: 5.1 |
| | | 4.1.1 | Control and Shutdown Rod Control | |
| *4.2* | *Heat Transport* | | | To Level 3: 3.2, 3.3<br><br>To Level 5: 5.2, 5.3, 5.5 |
| | | 4.2.1 | Core Heat Removal | |
| | | 4.2.2 | Reactor Decay Heat Removal | |
| *4.3* | *Plant and System Automation* | | | To Level 3: 3.3<br><br>To Level 5: 5.5 |
| | | 4.3.1 | Manual process/component monitoring & control | |
| | | 4.3.2 | Automatic process/component monitoring & control | |
| | | 4.3.3 | Remote surveillance and in-service inspection | |
| *4.4* | *Protection Processes* | | | To Level 3: 3.2, 3.3<br><br>To Level 5: 5.2, 5.3, 5.4, 5.5 |
| | | 4.4.1 | Emergency electrical power supply | |
| | | 4.4.2 | Seismic monitoring and detection | |
| *4.5* | *Operation Support* | | | To Level 3: 3.3 |

| | | | | |
|---|---|---|---|---|
| | | 4.5.1 | Auxiliary steam generation for HVAC | To Level 5: 5.5 |
| | | 4.5.2 | Turbine system lubrication | |
| | | 4.5.3 | Compressed air supply and pneumatic component control | |

| **5. Structures, Systems & Components** | Level 1 | | Level 2 | |
|---|---|---|---|---|
| *5.1* | *Reactor Containment and Core* | | | To Level 4: 4.1 |
| | | 5.1.1 | Control and Shutdown Rods | |
| | | 5.1.2 | Neutron Flux Monitoring System | |
| | | 5.1.3 | Reactor Vessel Instrumentation System | |
| *5.2* | *Primary Cooling System* | | | To Level 4: 4.2, 4.3 |
| | | 5.2.1 | Primary Sodium Pumps | |
| | | 5.2.2 | Intermediate Heat Exchanger | |
| *5.3* | *Secondary Cooling System* | | | To Level 4: 4.2, 4.3 |
| | | 5.3.1 | Intermediate Sodium Pumps | |
| | | 5.3.2 | Auxiliary Heat Exchanger | |
| *5.4* | *Energy Conversion Systems* | | | To Level 4: 4.2, 4.4, 4.5 |
| | | 5.4.2 | Feedwater and Condensate System | |
| | | 5.4.4 | Auxiliary steam boiler system | |
| *5.5* | *Plant Service Systems* | | | To Level 4: 4.5 |
| | | 5.5.1 | Normal and Automated Electrical Facilities | |
| | | 5.5.2 | Plant Control and Data Facilities | |
| | | 5.5.3 | Control Room & HSI | |
| | | 5.5.4 | Remote Shutdown Facility | |
| | | 5.5.5 | Emergency/Standby Generators & UPS | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 5.5.6 | Demineralized Water Supply System | | |
| | | | 5.5.7 | Turbine Generator Lubrication & Seal System | | |
| | | | 5.5.8 | Plant and Instrument Compressed Air Supply System | | |
| | | | 5.5.9 | Building Electrical Power System | | |
| | *5.6* | *Protection Systems* | | | | To Level 4: 4.4 |
| | | | 5.6.1 | Reactor Protection System | | |
| | | | 5.6.2 | Steam Sump System | | |
| | | | 5.6.3 | Emergency Feedwater Charging Pump | | |
| | | | 5.6.4 | Passive Heat Removal System | | |
| | | | 5.6.5 | Reactor Shutdown System | | |
| | | | 5.6.6 | Plant Surveillance and Inspection System | | |

### 3.7.2 Earthquake – Contextual Activities Analysis

The response to an earthquake requires immediate actions to prevent or mitigate the results of equipment damage that might lead to a radioactive release. For this reason, like with loss of power, the ultimate purpose is also to protect workers, public and the environment. In addition, much attention is paid to actions necessary to protect assets and prevent any emergent condition that may damage plant equipment or facilities. Figure 9 and Figure 10 show how equipment damage from an earthquake might affect the availability of several functions, for example, the ability to supply emergency electric power to essential equipment.

## Table 9: Contextual Activities - Minor to Moderate Earthquake

| Functions \ Situations | Reactor does not scram | Station Blackout | EDG failed to start | Portable EDG not available | Piping systems failed (leak) | Component damage | Personnel injury | MCR habitability compromised | Passive decay heat removal system failed |
|---|---|---|---|---|---|---|---|---|---|
| Remove Heat from Core | ✓ | ✓ | ✓ | ✓ | ? | ? | ? | ? | Limited |
| Maintain criticality | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Maintain reactor subcritical | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Control Reactor Startup and/or Shutdown | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Contain Fission Products | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Remove Decay Heat | ✓ | ✓ | ✓ | ✓ | ? | ? | ? | ? | Limited |
| Transport Heat from Primary to Secondary Sodium Systems | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Maintain Equipment Integrity | ✓ | Depending on time to start EDG | Deploy portable EDG | ? | Depending on severity of damage | Depending on severity of damage | ✓ | Depending on severity of damage | ✓ |
| Cool Plant Equipment | ✓ | Depending on time to start EDG | ✓ | ✓ | Depending on severity of damage | Depending on severity of damage | ✓ | ✓ | Limited |
| Optimize Fuel Burnup | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Control Fuel Temperature and Integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Convert Mechanical Energy to Electricity | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Protect turbine generator rotational parts | ✓ | Depending on time to start EDG | Depending on time to start EDG | Depending on time to start EDG | ✓ | ✓ | ✓ | ✓ | ✓ |
| Provide standby electrical power | ✓ | Deploy portable EDG | Deploy portable EDG | ⊘ | ✓ | ✓ | ✓ | Depending on severity of damage | ✓ |
| Maintain Control Functions | Manual scram | Depending on time to start EDG | Short duration only | ⊘ | Depending on severity of damage | Depending on severity of damage | ✓ | Short duration only | ✓ |
| Generate Steam | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ | ⊘ |
| Provide Personnel Comfort and Safety | ✓ | Limited | Limited | Limited | ✓ | ✓ | ✓ | Limited | ✓ |
| Ensure Safe and Habitable Operating Environment | ✓ | Limited | Limited | Limited | ✓ | ✓ | ✓ | Limited | ✓ |
| Protect Assets | ✓ | Depending on time to start EDG | ✓ | Limited | Depending on severity of damage | Depending on severity of damage | ✓ | ✓ | Limited |

Three specific emergent conditions are identified:

1. EDGs fail to start automatically (same as in Section 3.5.2 above), leading to actions to attempt a manual start, or in worst cases to start the portable diesel generator. As shown in Table 9, equipment damage may severely affect the availability of certain functions. For example, if EDGs fail to start, emergency power from uninterruptible power supplies (UPSs) will be available only for a short duration.

2. Reactor does not scram automatically (Figure 9), leading to four possible strategies to scram the reactor manually.
3. Evacuation of certain plant areas, coupled with strategies to identify and recover injured personnel.

### 3.7.3 Earthquake – Strategies Analysis

As indicated above, an earthquake may result in two possible responses, depending on the severity: in most cases the immediate response is to ensure that the reactor is scrammed, either automatically or manually. In more severe cases the second priority is to ensure that all personnel are safe and accounted for. This will require announcing station evacuation and determining possible injured staff. The following two diagrams illustrate the likely course of action.

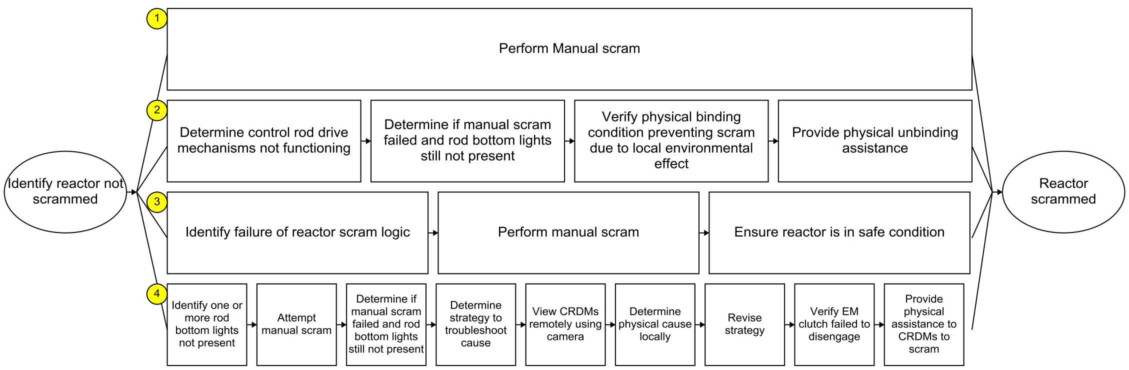


**Figure 9: Strategies Analysis - Earthquake - Mitigation of Failed Automatic Scram**

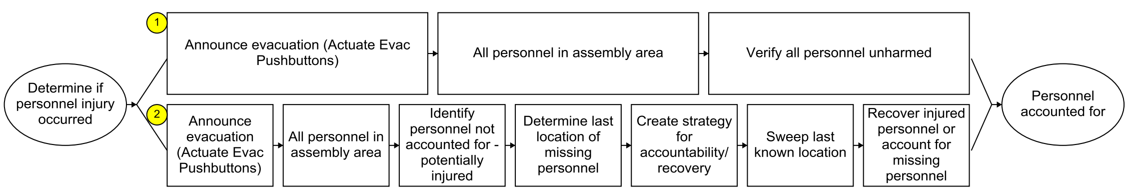


**Figure 10: Strategies Analysis – Earthquake - Mitigation of Personnel Injury**

# 4 Conclusion

The characteristics of SFRs and other emerging AdvNPP designs will require definition of operational modes and states that are not common with more conventional light water reactors. Innovative operational strategies will have to make provision for conditions unique to SFRs, such as high levels of automation, load following, unconventional fuel handling and refueling methods, on-line maintenance, and remote surveillance, among others. These new operational modes will require new operator tasks such as production planning, control of in-reactor fuel handling from the control room, monitoring for sodium leaks, and others. New plant modes and tasks will also create complexities and require innovative treatments in the design and use of advanced HSIs. Ultimately, all of these conditions will require development of a new family of normal, emergency, and off-normal operating procedures for conditions not familiar to operators of conventional NPPs. The progress achieved on this project to date shows that WDA is an excellent tool for supporting this development.

Based on practical application over the past three years, WDA will be invaluable in creating a structured approach to Operational Concept development that accounts for human performance, even for FOAK systems such as SFRs. It will make an important contribution to the design process by helping the design team as well as project managers to understand the operational requirements from a human perspective and how technology can help or hinder operators in meeting those requirements. Specifically, it will offer a structured and systematic way to consider the role of humans in the process, to analyze design trade-offs and to specify requirements. The method can also aid project managers by describing the systematic integration of human functions in the systems engineering process. Above all, an integrated WDA approach will help the design team understand the human requirements of work and how technology may help or hinder operators, technicians, engineers and managers in meeting those requirements. WDA experts can facilitate design discussions by describing the impact of various design choices on the execution of human work. In this way WDA supports the engineering design process at different levels.

WDA is not limited to operational concepts for SFR only, but is widely applicable to varied operational design situations where operational principles are being defined or modified. It would also apply to NPP plant upgrades and consideration of emergency response to long-duration events such as extended station blackout. In going from an older design to a new FOAK design, the Contextual Activity Analysis part of the WDA will prove to be particularly valuable in helping to identify and characterize expected differences in responsibilities, roles, and automation for normal and abnormal operations. Early assumptions, such as modularity, plant layout, and higher levels of automation will be highlighted and verified in the analysis. For a new SFR design, information like this, combined with human performance criteria, could also be used during later stages of the project life cycle to assess the crew performance aspects associated with identified SFR operational concepts.

It was shown that there are several key characteristics that distinguish an SFR from an LWR plant. These differences will have a significant on operational concepts.

There are many aspects of future plant configurations that will have an impact on operations. These include; effect of core design, different coolants, reactor to power conversion unit ratios, modular plant layout, modular versus central control rooms, plant siting, and the design of human-automation collaboration. Multi-modular plants are expected to have a significant impact on overall operational concepts.

Examples of factors to consider in the operational design of multi-modular plants are:

- Operating states
- Operational coordination of multiple units
- Control systems for multiple units
- Human system interface for multiple units

A discussion of these characteristics as well as the methodology to develop the Operational Concept Document is beyond the scope of this report but will be dealt with in future milestone reports - WDA Methodology Report, to be published in May 2015, and the Reference Operational Concept Document for SFRs to be published in September 2015.

The extensive literature on CWA and WDA and recent results from this Operational Concepts project suggest that the nuclear industry needs to adopt new methodologies for the way operating concepts are developed and the roles of humans are defined. All of the results so far make a strong case for not relying on paradigms that might have applied thirty or forty years ago when control system technology was primitive compared to today's advanced automation systems and HSIs. We should recognize that new technology often requires not just new design techniques, but also new mental models. This will enable us to cross the chasm between the old, often ineffective paradigms, and advanced design approaches that are not just different, but add significant value in both human and technological terms. From a project management point of view, the appropriate use of WDA in the design life cycle also has the potential to reduce the risk of additional iterations, project cancellations or rejected deliverables, and reduces the time associated with "trial and error" approaches. Successful integration of WDA into existing project activities such as modeling, simulation, and prototyping can mitigate rising project costs.

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# APPENDIX A

## Generic SFR System + Functional Breakdown

| No | Level 1 Systems | *Level 1 Function* | Level 2 Systems | *Level 2 Function* | Level 3 Systems/Components | *Level 3 Function* |
|---|---|---|---|---|---|---|
| **1** | **Plant Electrical Power System** | *Provide electrical power supply and distribution from off-site.* | | | | |
| | | | Transmissions Switchyard | *Provide connection for export of electricity to the grid (e.g. 220kV)* | | |
| | | | Plant Area Switchyard | *Provide connections for the supply of electricity to the plant (e.g. 22kV or 33kV).* | | |
| **2** | **Building Electrical Power System** | *Distribute and controls AC and DC electrical power for plant systems.* | | | | |
| | | | Medium Voltage AC Distribution System | *Provide distribution of electrical power to plant systems (e.g. 11kV).* | | |
| | | | Standby AC Power Supply System | *Provide standby electrical power in the event of loss of main electrical supply.* | | |
| | | | Low Voltage AC Distribution System | *Provide low voltage electrical power to plant systems* | | |
| | | | DC and Low Voltage Vital AC Power Supply | *Provide DC and Low Voltage AC to plant systems.* | | |

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| **3** | **Plant Air System** | *Provide all on-site compressed air for service equipment and instruments during normal operation and shutdown conditions.* | | | | |
| | | | Service Air System | *Provide compressed air to the Plant Air System and the Instrument Air System* | | |
| | | | | | Air Compressors and associated subsystems | *Provide compressed air to the Plant Air System and subsystems.* |
| | | | Instrument Air System | *Provide compressed air to all plant instruments and pneumatic controls during normal operations and shutdown conditions.* | | |
| **4** | **Radioactive Waste Systems** | *Collect, process, store, sample and package all liquid and solid radioactive wastes.* | | | | |
| | | | Liquid Radioactive Waste System | *Collect, process, sample and store all liquid radioactive wastes.* | | |
| | | | Solid Radioactive Waste System | *Collect, process, sample and store all solid radioactive wastes.* | | |

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| 5 | **Heating, Ventilation and Air Conditioning (HVAC)** | *Provide temperature, humidity and cleanliness control of the atmosphere for personnel safety and comfort and proper operation of equipment within the plant structures, and prevent the release of airborne radioactivity to the outside environment.* | | |
| | | | Turbine Building HVAC | *Provide heating, ventilation and air conditioning for the Turbine Building* |
| | | | Steam Generator Building HVAC | *Provide heating, ventilation and air conditioning for the SG Building* |
| | | | Control Building HVAC | *Provide heating, ventilation and air conditioning for the Control Building* |
| | | | Reactor Building HVAC | *Provide heating, ventilation and air conditioning for the Reactor Building* |
| | | | Auxiliary Building HVAC | *Provide heating, ventilation and air conditioning for the Auxiliary Building* |
| | | | Support Buildings HVAC | *Provide heating, ventilation and air conditioning for the Support Buildings* |

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| **6** | **Sodium Fire Protection System** | *Contain and extinguish sodium fires and prevent Na or NaK ignition. Limit consequences of sodium and NaK spills and subsequent fires in cells containing primary and Ex-reactor sodium tank (ERST) sodium. Use drain pipes and catch pans for cells containing non-radioactive Na/NaK to limit the consequences.* | | |
| | | | Primary Sodium Fire Protection System | *Provide fire protection for all areas containing primary and secondary sodium.* |
| | | | ERST Sodium Fire Protection System | *Contain and extinguish ERST sodium fires and prevent ignition. Limit consequences of sodium spills and subsequent fires.* |
| | | | Non-Radioactive Sodium/NaK Fire Protection System | *Contain and extinguish non-radioactive sodium or NaK fires and prevent ignition. Limit consequences of sodium and NaK spills and subsequent fires.* |
| **7** | **Containment System** | *Provide containment and support for the reactor core and primary sodium.* | | |
| | | | Reactor Vessel | *Provide containment and platform for reactor core assemblies, including fuel assemblies.* |

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| | | | Guard Vessel | *Provide an outer containment vessel around the reactor vessel to eliminate any sodium leaks.* |
| | | | Reactor Head | *Provide a platform for the rotating plugs, in-reactor fuel handling mechanisms, and associated equipment.* |
| | | | Rotating Plugs | *Provide a means to rotate fuel handling components over any core assembly. Provide a seal between the inert argon gas system and the atmosphere. Provide platform for control rod drive mechanisms.* |
| **8** | **Recirculating Gas Cooling System** | *Provide cooling to inerted cells and components within the reactor building complex.* | | |
| | | | Argon Cooling System | |
| **9** | **Plant Fire Protection System** | *Detect fires or smoke in the plant by means of smoke and flame detectors and extinguish and contain by means of water sprinklers, carbon dioxide and other clean agent fire extinguishing systems.* | | |
| | | | Auxiliary Fire System | *Provide fire suppression by means of water sprinklers, carbon dioxide and other clean agent fire extinguishing systems.* |

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| | | | Detection/Alarm System | *Detect fires or smoke in the plant by means of smoke and flame detectors that result in alarms and actuation of automatic fire suppression systems.* | | |
| **10** | **Reactor Core System** | *Generate and transfer fission heat to the sodium of the primary heat transport system.* | | | | |
| | | | Fuel assemblies | *Provide source of fission heat* | | |
| | | | Reactivity Control System | *Provide control of reactor activity during normal operations by means of insertion or withdrawal of control rods.* | | |
| | | | | | Control Rod Drive Mechanisms | *Provide electromechanical means to power the control rods. Provide a means to raise and lower control rods* |
| | | | Standby Shutdown System | *Shutdown the reactor by means of insertion of the shutdown rods, or prepare for startup by withdrawing the shutdown rods.* | | |
| | | | | | Shutdown Rod Drive Mechanism | *Provide electromechanical means to power the shutdown rods.* |

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| **11** | **Fuel Handling System** | *Move and rotate core assemblies within the reactor vessel. Transfer all types of irradiated and unirradiated core assemblies into and from the reactor vessel.* | | |
| | | | In-Containment Fuel Handling System | *Provide a means to transfer core assemblies between the core location, the in-vessel storage locations, and the transfer location within the reactor containment.* |
| | | | Ex-reactor Fuel Handling System | *Transfer new core assemblies into the reactor vessel and deposit or retrieve irradiates assemblies.* |
| | | | Ex-reactor Sodium Tank (ERST) | *Receive and store conditioned and preheated fuel assemblies* |
| | | | Core Component Receiving Equipment | *Allow acceptance and inspection of new core assemblies and insertion of new assemblies into the Core Component Conditioning Station for preheating.* |
| | | | Transfer Cask | *Allow retrieval of unirradiated core assemblies and also maintain inerting and temperature control of all core assemblies.* |

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| | | | Core Component Discharge Equipment | *Transfer non-irradiated core assemblies out of the Ex-reactor Fuel Handling Machine to suitable locations.* | | | |
| 12 | **Heat Transport System** | *1) Remove heat from hot primary sodium and deliver heat to Steam Generator System via the Intermediate Heat Transport System. 2) Return cooled primary sodium to the reactor. 3) Isolate radioactive primary sodium from SG. 4) Remove heat from shutdown reactor. 5) Provide signals to automation system and Plant Protection System* | | | | | |
| | | | Primary Heat Transport System (PHTS) | *Circulate primary sodium coolant through the Reactor Core System to maintain fuel cladding integrity.* | | | |
| | | | | | Primary Sodium Pumps | *Circulate primary sodium coolant through the reactor to remove heat and transfer that heat to the Secondary Sodium System through the Intermediate Heat Exchanger.* | |
| | | | | | Primary Sodium Pump Cooling System | *Provide a means to cool the Primary Sodium Pump motors.* | |

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| | | | Primary Sodium Lube Oil System | *Provide lubricating oil for the Primary Sodium Pump bearings.* |
| | Intermediate Heat Transport System (IHTS) | *Transfer heat energy from the primary sodium coolant to intermediate sodium coolant via the Intermediate Heat Exchanger (IHX) and deliver heat energy to the SG to convert feedwater to superheated steam production.* | | |
| | | | Intermediate Sodium Pumps | *Transfer intermediate sodium from the secondary sodium system through the Intermediate Heat Exchangers for heating and back to the secondary sodium system to transfer this heat to the steam generation system for superheated steam production.* |
| | | | Intermediate Sodium Pump Lube Oil System | *Provide lubricating oil for the Intermediate Sodium Pump bearings.* |
| | | | Intermediate Loop Drain Tanks | *Provide a means to store drained Secondary Sodium for maintenance or for rapid draining during emergency conditions.* |

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| | | | | | Intermediate Heat Exchangers | *Provide a means to transfer Primary Sodium heat to the Secondary Sodium System. It also Provide for radiation barrier to limit personnel exposure to irradiated sodium flowing through the reactor core.* |
| | | | Drain System | *Provide a means to drain the Secondary Sodium System for maintenance or for rapid draining during emergency conditions.* | | |
| **13** | **Decay Heat Removal System** | *Remove decay heat from the reactor vessel when the normal decay heat removal system is unavailable, by means of a primary Na-to-NaK and NaK to Air heat exchangers to extract heat from the primary sodium pool. Use natural convection to circulate NaK.* | | | | |
| | | | Auxiliary Decay Heat Removal System (ADHRS) | *Transfer decay heat from the primary sodium pool to the NaK loop through the ADHRS Heat Exchanger and reject heat from the loop to ambient air through the Natural Draft Heat Exchanger (Nak to Air HX).* | | |

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| **14** | **Steam Generator System** | *Receive heated secondary sodium from IHTS, transfer heat to water, return cooled secondary sodium to the IHTS. Provide superheated steam to the Main and Auxiliary Steam System for conversion to electric power in the Turbine Generator.* | | |
| | | | Steam Generators | *Provide flow of intermediate sodium system into and out of the sodium side of the steam generator system while transferring heat to the feedwater and producing the required quantity of superheated steam.* |
| | | | SG Leak Detection | *Detect sodium leaks at the Steam Generator.* |
| **15** | **Feedwater and Condensate System** | *Receive condensate from the condenser hotwell and transfer feedwater to the inlet of the steam generators. Polish, heat, chemically treat and deaerate condensate/feedwater.* | | |
| | | | Feedwater Heater Drain System | *Allow draining of feedwater from the higher pressure heater and routing to the deaerator, and draining to the lower pressure heater and routing to the condenser.* |

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| | *Receive condensate from the condenser hotwell and transfer feedwater to the inlet of the steam generators. Polish, heat, chemically treat and deaerate condensate/feedwater.* | | |
| | | Steam Generator Cooling Subsystem | *Remove decay heat from the Steam Generator System during shutdown conditions.* |
| | | Auxiliary Boiler Feedwater System | *Supply feedwater to the auxiliary boiler at the required rate, pressure, temperature, and purity to meet auxiliary steam system needs at all operating conditions, including plant shutdown, startup, and low-power operation.* |
| | | Condensate System | *Transfer condensate from the condenser hotwell to the deaerator. Also removes dissolved gases from condensate to ensure feedwater purity during normal operation and transient conditions.* |

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| **17** | **Main and Auxiliary Steam System** | *1) Supply superheated steam generated in the Steam Generators to the high-pressure turbine. 2) Provide steam for the condensate system deaerator. 3) Provide low pressure steam to the glands of the main turbine. 4) Provide low pressure steam to maintain pressure in the condensate system deaerator* | | | | | |
| | | | Main Steam System | *Transport superheated steam from the Steam Generators to the turbine-generator over the specified load following range of reactor power.* | | | |
| | | | | | Steam Turbine Generator | *Use steam from the Steam Generators to drive the high-pressure turbine and the generator to produce electrical power.* | |
| | | | Main Steam Bypass (Dump) System | *Provide high pressure steam bypass to condenser for a controlled heat release from the reactor during startup, hot shutdown, cooldown, and reactor physics testing.* | | | |
| | | | Extraction Steam System | *Transport steam from the turbine extraction points to LP and HP feedwater heaters, and other miscellaneous process demands* | | | |

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| | | | Auxiliary Steam System | *Provide steam for the condensate system deaerator, sealing steam for the main turbine glands, and for blanketing of the Moisture Separator Reheaters.* |
| **18** | **Main Cooling Water System** | *Provide an ultimate heat sink for power plant loads.* | | |
| | | | Circulating Water System | *Remove the heat load rejected through the main condenser and the Closed Cooling Water System utilizing cooling water from seawater. Also provide cooling to the Aux Cooling System to minimize corrossion from sea water.* |
| | | | Condenser Air Extraction System | *Reduce the condenser pressure at plant startup to operating vacuum, maintain vacuum in the condenser during plant operation, increase the overall efficiency of the turbine generator and remove air and non-condensable gases from the condenser.* |
| **19** | **Auxiliary Cooling Systems** | *Remove waste heat from the reactor containment and support buildings via chillers, heat exchangers, cooling towers, pumps, piping and valves.* | | |
| | | | Chilled Water System | *Provide refrigerated water to* |

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| | | | | *the Auxiliary Cooling Systems* | | |
| | | | | | Chemical Injection Systems | *Provide a means to maintain chemistry in Auxiliary Cooling Systems* |
| | | | Component Cooling Water System | *Supply cooling water to the In-containment Cooling Water System heat exchangers.* | | |
| | | | | | Component Cooling Water Pumps | *Transfer cooling water to the Component Cooling Water System* |
| | | | In-Containment Cooling System | *Provide waste heat removal from the containment.* | | |
| | | | In-Containment Condensate Collection System | *Collect moisture from the In-Containment recirculation cooler cooling coils via five recirculation coolers and drain by gravity to a common collection tank.* | | |
| | | | Closed Cooling Water System | *Remove heat from equipment in the Turbine Building.* | | |
| **20** | **Service Water Treatment and Distribution System** | *Treat and distribute service water to plant systems.* | | | | |
| | | | Seawater Desalination System | *Desalinate seawater for supply to Demineralized Water Distribution System and Potable Water System* | | |

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| | | | Service Water System | |
| | | | Potable Water System | |
| | | | Make-up Demineralizer System | |
| | | | Demineralized Water Distribution System | |
| **21** | **Waste Water Treatment System** | *Collect, treat, recycle and dispose plant non-radioactive liquid wastes and tritiated water.* | | |
| | | | Waste Water Disposal System | |
| | | | Sewage Waste Water Treatment System | |
| | | | Common Waste Water Discharge System | |
| **22** | **Auxiliary Sodium Processing Systems** | *1) Receive, store, purify, sample and analyze sodium for the primary and intermediate Heat Transport Systems. 2) Provide motive force to fill the systems. 3) Provide equipment to receive sodium and NaK.* | | |
| | | | Primary Sodium Processing System | *Provide purification of the sodium in the primary loop.* |
| | | | Intermediate Sodium Drain and Processing System | *Provide purification and draining of nonradioactive sodium in the intermediate* |

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| | | | | *loop.* |
| | | | Ex-Reactor Storage Tank NaK Cooling System | *Remove heat from the ERST* |
| | | | Sodium and NaK Fill System | *Provide sodium and NaK storage for the ADHRS storage tank, the ERST, purification loop, and NaK cooling loop, to facilitate sodium and NaK filling and possible draining and removal.* |
| **23** | **Inert Gas Receiving and Processing System** | *Supply argon from liquid storage to plant systems.* | | |
| | | | Argon System | *Provide argon cover gas and penetration seal gas for the Primary Heat Transport System, Reactor Decay Heat Removal System, Ex-reactor Fuel Handling System, and the Auxiliary Sodium Processing System.* |
| | | | Cell Atmosphere Processing System | *Monitor and process plant gasses in contact with potentially contaminated environments as well as low vacuum high volume suction for inerted spaces.* |

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| | | | Primary Cover Gas Processing System | *Monitor plant gasses in contact with primary sodium and other selected argon atmosphere spaces.* |
| | | | Intermediate Cover Gas Processing System | *Provide clean argon for the intermediate cover gas sampling and analysis system as well as to the oil bubbler for discharge to the dedicated inert gas stack.* |
| | | | Intermediate Cover Gas Monitoring and Sampling System. | *Provide on-line analysis for impurities and gasses in the argon. Also provide sampling of gas for off-line lab analysis.* |
| | | | Plant Vacuum System | *Assist in inerting, initial fill and drain operation and subsequent sodium management activities for the primary, intermediate and ERST sodium systems as well as ADHRS and other NaK systems.* |
| **24** | **Plant Control and Data System** | *Provide overall control and coordination of the reactor, heat transport system, turbine and balance of plant for all operating modes. Integrate manual and automatic controls provided to maintain the plant at the desired power, temperature, pressure and flow.* | | |
| | | | Main Control Room | *Provide facilities for monitoring and control of the NPP* |

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| | | | Emergency Control Center | |
| | | | Information Management Center | |
| | | | Computer Rooms | |
| | | | Remote Shutdown Facility | |
| | | | Operations Support Center | |
| **25** | **Reactor Vessel Instrumentation System** | *Provide sensors to measure the temperature, flow and level of sodium within the reactor vessel.* | | |
| | | | Core Outlet Temperature Monitoring System | *Measure the primary sodium temperature in the sodium hot pool and transmit data to the Plant Protection System.* |
| | | | Assembly Temperature Monitoring System | *Monitor the primary sodium temperature at the outlet of selected fuel and control assemblies. This system Provide input signals to the Plant Control and Data System.* |
| | | | Primary Sodium Level Monitoring System | *Monitor the primary sodium level in the reactor vessel. Provide input signals to the Plant Protection System and also to the Plant Control and Data System.* |

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| | | | Assembly Flow Rate Monitoring System | *Monitor the flow rate of the primary sodium at the outlet of select assemblies.* |
| | | | Reactor Vessel Head Temperature Monitoring System | *Monitor the temperature throughout the reactor vessel head to verify acceptability of the temperature with prescribed limits.* |
| | | | Reactor Vessel Loose Parts Monitoring System | *Monitor for loose parts within the RV.* |
| | | | Assembly Power Monitoring System | *Monitor gamma flux at the open test assembly in the reactor vessel.* |
| **26** | **Primary Cover Gas and Fuel Failure Monitoring System** | *1) Provide sensors to measure the temperature, flow and level of sodium within the reactor vessel. 2) Detect fuel pin failures.* | | |
| | | | Primary Cover Gas Monitoring System | *Monitor the reactor vessel argon cover gas for significant changes of gaseous fission products and other compounds that would indicate fuel assembly failure, individual component failure, or degradation.* |

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| 27 | **Neutron Flux Monitoring System** | *Provide electrical signals proportional to neutron multiplication during subcritical operations and neutron flux during reactor power operation.* | | |
| | | | Low Level Flux Monitors | *Provide low level neutron flux monitoring below the reactor vessel.* |
| | | | Ex-reactor Flux Monitors | *Provide neutron flux monitoring outside the reactor vessel.* |
| | | | Neutron Source and Transport | *Provide stable and reliable initiation of the fission reaction at first reactor startup or new fuel load. Ensure constant minimal population of neutrons in the reactor core.* |
| | | | Neutron Moderator | *Reduce the speed of fast neutrons to produce thermal neutrons capable of sustaining a nuclear chain reaction.* |
| | | | Neutron Flux Monitoring System Wide-Range Signal Processor | *Provide operational process monitoring measurements and monitoring of the neutron flux density from start-up to 150% of reactor power.* |
| | | | Power Range Flux Monitors | *Provide sensors and instrumentation to monitor Power Range Neutron Flux.* |
| 28 | **Radiation Monitoring** | *Detect and record radiation levels in various plant areas, process* | | |

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| | **System** | *systems and effluents.* | | |
| | | | Process Radiation Monitoring System | *Provide sensors and instrumentation to monitor radiation at selected process locations.* |
| | | | Area Radiation Monitoring System | *Provide sensors and instrumentation to monitor radiation in selected plant areas.* |
| | | | Effluent Radiation Monitoring System | *Provide sensors and instrumentation to monitor radiation in plant effluent.* |
| **29** | **Reactor Protection System** | *Assures that the results of all postulated fault conditions remain within specified limits by sensing the need for and carrying out reactor scram, sodium pump trip, and containment isolation actions.* | | |
| | | | Reactor Shutdown System | *Ensure that the reactor is within the safe operating region by shutting down the reactor whenever established safety limits are approached.* |
| | | | Containment Isolation System | *Ensure that there are no uncontrolled releases of radioactive products from the containment during any event up to and including a DBA.* |

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| | | | Post Accident Monitoring System | *Monitor the plant safety-related functions during and following an accident situation.* |
| **31** | **Site Communication System** | *Provide on-site communications via public address, telephone, wireless telecoms, sound-powered comms and radio for normal as well as emergency conditions.* | | |
| **32** | **Plant Security System** | *Provide physical security of the plant according to rules and guidance established by the appropriate regulatory agency.* | | |