Advanced Nuclear Technology: Owner-Operator Reactor Technology Assessment Guide

2022 Version

2022 TECHNICAL REPORT

Advanced Nuclear Technology: Owner-Operator Reactor Technology Assessment Guide

2022 Version

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ABSTRACT

Owner-operators seeking to deploy new commercial nuclear power facilities must choose which technologies and designs to deploy. The decision will be a far-reaching one that will impact the organization financially and operationally for decades. Any decision must be well thought-out and backed by evidence.

This report contains guidance on selecting technologies for review, and then ultimately settling on a design to pursue. It provides a process framework for systematically reviewing the available reactor technologies to identify the ones that best fit an owner-operator’s goals, and then delving into more detailed review of individual designs. When the process is complete, an organization will have identified a primary design and alternative designs for comparison and potential backup, and it will have the information and data needed to stand by the evaluation.

Keywords

Advanced light water reactor
Advanced reactor
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PRIMARY AUDIENCE: Owner-operators looking to identify viable reactor technologies and specific designs that meet their mission and business objectives

SECONDARY AUDIENCE: Reactor developers that want to understand how their ultimate customers will evaluate their products

KEY RESEARCH QUESTION

With diverse business objectives to consider and numerous technologies and OEM-specific designs available or potentially available, how can an owner-operator identify viable reactor technologies and specific designs that meet their mission and business objectives and ensure that the final choice is (1) well founded and based on a repeatable process and collected evidence and (2) defendable to internal management, boards of directors, and public utilities commissions?

RESEARCH OVERVIEW

This report provides owner-operators and prospective owner-operators with a straightforward decision-making framework that helps the organization do the following:

- Define and understand their business objectives
- Evaluate general technologies and specific designs against those objectives
- Develop a defendable justification for a primary selection and alternatives
- Understand the inherent risk of technology and design selection and provide tools to manage that risk

There are other decision-making frameworks for reactor technology selection available in the public domain, and this report includes concepts based on them. However, there are two key distinctions between the available literature and this report. First, in terms of the intended audience, most of the available frameworks address technology selection in the domain of a nation-state program, whereas this report is intended to address a single owner-operator making a business decision. Second, a goal of this report is to provide an uncomplicated, repeatable process to evaluate complicated questions that, in most cases, have no quantitative answer, and, in some cases, no answer at all.

KEY FINDINGS

- The technology assessment procedure developed in this report consists of six primary process steps.
- In addition, the report identifies 31 specific criteria that should be evaluated at each step for each new technology or design being considered, aligned under five main categories.
- This report will help organizations navigate the process and address the ambiguities that will arise in a manner that provides for clarity and informed decision-making, even if *informed* means an affirmative declaration of “We just don’t know.”
- When the process is complete, an organization will have identified a primary design and alternative designs for comparison and potential backup. It will also have the information and data needed to support the evaluation.

EXECUTIVE SUMMARY

WHY THIS MATTERS

Owner-operators seeking to deploy new commercial nuclear power facilities must decide which technologies and designs to deploy. This decision will be a far-reaching one that will impact the organization financially and operationally for decades. Any decision must be well thought-out and backed by evidence.

HOW TO APPLY RESULTS

This report contains the step-by-step process and associated guidance for performing a technology assessment as well as many examples and pointers to helpful references. End-users should read the report in its entirety to better understand what is needed for an organization to perform the process. The evaluation will require a team and likely take anywhere from six months to two years. Appendix B, "Functional Roles in the Technology Assessment Process," provides guidance on building a team.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI maintains public- and member-facing advisory groups under the Advanced Nuclear Technology (ANT) Program that focus on advanced reactor R&D, demonstration, and commercialization topics. These forums provide opportunities to exchange information and obtain input on the direction and nature of EPRI's ANT programmatic focus to support deployment of advanced reactors.
- EPRI continues to look for and welcome collaborative opportunities to develop and apply tools and methods that support commercialization of advanced nuclear technology.
- EPRI has published an updated companion tool: *Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide)—2022 Revision* (3002023910). The *Siting Guide* is similar in form and function but can be used for the opposite purpose of this report—to find a site for a defined design (or range of designs).

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ACRONYMS AND ABBREVIATIONS

AE	architect engineer
ALWR	advanced light water reactor
ANL	Argonne National Laboratory
ANT	Advanced Nuclear Technology Program (EPRI)
AR	advanced reactor
ASME	American Society of Mechanical Engineers
BWR	boiling water reactor
CANDU	Canada deuterium uranium reactor
CFI	Corporate Finance Institute
CFR	U.S. Code of Federal Regulations
COL	combined operating license
CP	construction permit
DC	design certification
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-NE	Department of Energy - Nuclear Energy
D-RAP	Design Reliability Assurance Program
EAB	exclusion area boundary
EIA	U.S. Energy Information Administration
EPC	Engineering, Procurement, and Construction (organization)
EPRI	Electric Power Research Institute
EPZ	emergency planning zone
ESP	early site permit
FHR	Fluoride Salt-Cooled High-Temperature Reactor
FOAK	first-of-a-kind

ft	foot, feet (1ft = 0.3048 m)
GAO	U.S. General Accounting Office
GEN	Generation I, II, III, III+, and IV
GW	gigawatt(s)
ha	hectare(s) (1 ha = 2.47 acre)
HALEU	high-assay low-enriched uranium
HFE	human factors engineering
HTGR	high-temperature gas reactor
HWR	heavy water reactor
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IDA	International Desalination Association
IEA	International Energy Agency
INL	Idaho National Laboratory
ITM	inspection, testing, and maintenance
km	kilometer(s) (1km = .62 mi)
LCOE	levelized cost of electricity (or energy)
LFR	lead-cooled fast reactor
LLWR	large light water reactor
LPC	levelized product cost
LR	large reactor
LWR	light water reactor
lwSMR	light water small modular reactor
m	meter(s) (1 m = 3.28 ft)
mi	mile(s) (1 mi = 1.61 km)
M-MIS	man-machine interface system
Mo-99	molybdenum 99
MRL	manufacturing readiness level
MSR	molten salt reactor
MWe	megawatt(s) electric (1 MWe ~ 2.94 MWt based on current efficiencies)
MWt	megawatts(s) thermal (1 MWt ~ 0.34 MWe based on current efficiencies)

NEA	OECD Nuclear Energy Agency
NEI	Nuclear Energy Institute
NNL	U.K. National Nuclear Laboratory
NNSA	National Nuclear Security Administration
NPDPM	New Plant Deployment Program Model
NRC	U.S. Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OCC	overnight capital cost (also, overnight construction cost)
OECD	Organization for Economic Co-operation and Development
OEM	original equipment manufacturer
OL	operating license
ORG	Owner-Operator Requirements Guide (EPRI)
ORNL	Oak Ridge National Laboratory
PPE	plant parameter envelope
PR&PP	proliferation resistance and physical protection
PRA	probabilistic risk assessment
PWR	pressurized water reactor
QA	quality assurance
RO	reverse osmosis
ROI	return on investment
SCWR	supercritical water-cooled reactor
SFR	sodium-cooled fast reactor
SME	subject matter expert
SMR	small modular reactor
SPE	site parameter envelope
SSC	structure, system, and/or component
TEA	techno-economic assessment
TRL	technology readiness level
UNESCO	United Nations Educational, Scientific, and Cultural Organization
URD	Utility Requirements Document (EPRI)

USGS	U.S. Geological Survey
WBS	work breakdown structure
WNA	World Nuclear Association

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1
INTRODUCTION

Owner-operators seeking to deploy new commercial nuclear power facilities need to make choices about which technologies and designs to deploy. This decision will be a far-reaching one that will impact the organization financially and operationally for decades. Any decision must be well thought-out and backed by evidence.

This report provides guidance on selecting technologies for review and then ultimately choosing a design to pursue. It provides a process framework for systematically reviewing the available reactor technologies to identify the ones that best fit an owner-operator's goals, and then delving into more detailed review of individual designs. When the process is complete, an organization will have identified a primary design and alternative designs for comparison and potential backup, and it will have the information and data needed to stand by its evaluation.

Note: The target audience of this report is organizations pursuing nuclear systems intended for civilian commercial use. However, the process could easily be followed for other uses, such as making a choice to partner with an original equipment manufacturer (OEM) for a prototype or demonstration project.

Note: The guidance in this report follows a process like that developed in the 2015 version of *Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Power Generation Facilities (Siting Guide)* (EPRI, 2015), which also contains material referenced herein. An updated version of the *Siting Guide* has since been published; users of this report should be sure to refer to *Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide)—2022 Update* (EPRI, 2022).

1.1 Background

There is currently an increased global interest in deployment of nuclear, driven by several concerns that could differ globally by locale. Examples of these concerns are:

- Increased need for power
- Providing power to underpowered areas
- Clean air goals
- Carbon reduction goals
- Integration of renewables
- Increased need for flexibility and resilience
- Need for more distributed energy

Although there is still a global need and interest in large light water plants like those that have traditionally been deployed over the least 50 years, there is also a heightened interest in the deployment of advanced reactors (ARs). Today there are several large light water reactor (LLWR) designs available—some already licensed in the United States and other countries—and there are even more technologies, particularly AR technologies. AR technologies include light water and non-light water technologies (see Section 1.5) in various stages of development, ranging from concept to regulator design certification (DC). The nature of an owner-operator's goals for a nuclear energy system is also changing, with a newfound interest in reactors of varied (generally smaller) sizes (see Section 1.5.1.2) that address new and unique business objectives (see Section 2.2 and Appendix A). With the diverse set of designs available, identifying and, more importantly, justifying a final reactor design for deployment that best aligns with an owner-operator's goals can be difficult.

Until recently, the available technology choices have been between a small handful of technologies, primarily large light water pressurized water reactors (PWRs) or boiling water reactors (BWRs), from a limited number of OEM suppliers providing nearly the same end-product—firm, or baseload, electricity. An owner-operator considering deployment of a nuclear plant must evaluate the available choices and select a plant that meets their business objectives. With LLWRs, the decision is largely reduced to:

- What are the overall schedule and cost?
- What are the commercial requirements?
- Can the Engineering, Procurement, and Construction (EPC) organization(s) complete the task?
- Can the owner-operator's organization technically manage and operate the plant?

Today, with the diverse business objectives that must be considered, combined with the number of technologies and OEM-specific designs available or potentially available, the decision-making process of an owner-operator has been made much more complicated. This is especially true if the owner-operator's business objectives necessitate use of any technologies currently under development or not yet deployed because there are extended risks associated with these choices.

1.2 Purpose and Goals of This Report

The purpose of this report is to provide an owner-operator (or prospective owner-operator) with a straightforward decision-making framework, including an uncomplicated and repeatable process, that helps the organization:

- Define and understand their business objectives
- Evaluate general technologies and specific designs against those objectives
- Develop a defendable justification for a primary selection and alternatives
- Understand the inherent risk of technology and design selection and provide tools to help manage that risk

This framework and associated process will require the owner-operator to delve into and evaluate information that might be new to them and that might be incomplete or uncertain due to the current state of the nuclear industry. A goal of this report is to help the organization navigate the process and address the ambiguities that will arise in a manner that provides for clarity and informed decision-making, even if *informed* means an affirmative declaration of “We just don’t know”; this way, appropriate risk factors can be included. Risk is inherent in technology and design selection, any pre-deployment activities, and ultimate deployment. Risk cannot be removed from the process, but the framework presented in this report provides the owner-operator tools to help manage that risk (see Section 2.6).

There are other decision-making frameworks for reactor technology selection available in the public domain—for examples, see the International Atomic Energy Agency’s (IAEA’s) *Nuclear Reactor Technology Assessment for Near Term Deployment* (IAEA, 2013b); UK National Nuclear Laboratory’s (NNL’s) *SMR Techno-Economic Assessment: Project 3: SMRs Emerging Technology, Assessment of Emerging SMR Technologies Summary Report* (NNL, 2016); and *Program on Technology Innovation: EPRI Framework for Assessment of Nuclear Fuel Cycle Options* (EPRI, 2013); this report includes concepts based on them. However, a couple of key distinctions between the available literature and this report are:

- *Intended audience* – Most of the available frameworks address technology selection in the domain of a nation-state program, whereas this report is intended to address a single owner-operator making a business decision.
- *Straightforward process* – A goal of this report is to provide an uncomplicated and repeatable process to evaluate complicated questions that, in most cases, have no quantitative answer and, in some cases, have no answer at all.

1.3 Key Definitions

There are a few definitions used in this report that are important for the reader to understand because they have specific meanings here that could differ slightly from day-to-day parlance:

- *Technology* can mean both the general technology (for example, pressurized water reactor [PWR], gas-cooled reactor) or a vendor-specific design (for example, Company X’s Model N-100). This is important because the process defined herein uses both instances to settle on a general technology in the initial stages and then refine selection to a specific procurable *design*.
- *Design* specifically means a procurable (or at least advertised) vendor-specific reactor developed and marketed by an *original equipment manufacturer.*
- *Assessment* is the effort (and result) of performing the structured process defined in this report. It provides for a defendable comparison between different technologies and designs.
- *Selection* is the choosing (or ordering by ranking) of one or more technologies. By completing the assessment process as defined in this report, the *owner-operator* should have the information to make defendable choices.
- *Owner-operator* is the organization (utility, owner, or operator) that is pursuing a new nuclear reactor development project (that is, the organization performing the assessment exercise).

- *Original equipment manufacturer* (OEM) is an organization that owns a specific design; often referred to as the *developer*.
- *Suppliers* are any organization providing components or services to the OEM (or the *owner-operator* or *EPC* if they are responsible). Suppliers of specific interest are the architect engineer (AE) and the major component providers.
- *Engineering, Procurement, and Construction (EPC) organization* is intended to represent all organizations involved in the development project. This could be a single EPC entity, a consortium, or a looser collection of suppliers managed by a lead organization, such as the *owner-operator* itself.

1.4 Report Structure

It is recommended that users review this report in its entirety prior to using the process. A good understanding of the technical criteria and needs for each step in the process is necessary for maximum benefit:

- Section 1.5, End-User Considerations, covers several factors that provide additional context and definitions that readers should be aware of and understand.
- Section 2, Technology Assessment Procedure, presents an overview of the proposed technology assessment procedure, including the following:
  - A discussion of the phased approach in Section 2.1. The phases are:
    - Define an Owner-Operator’s Mission and Business Objectives
    - Identify Technologies of Interest
    - Screen to Candidate Technologies
    - Identify Potential Designs
    - Screen to Candidate Designs
    - Identify a Primary Design and Alternatives
  - The questions an organization must ask regarding its mission and business objectives in Section 2.2
  - Procedures for developing criteria importance weightings in Section 2.3
  - Procedures for scoring criteria in Section 2.4
  - An introduction to the assessment criteria in Section 2.5, which are organized in groups and defined in detail in Section 3
  - Guidance on understanding risk in the assessment process in Section 2.6

- Section 3, Assessment Criteria, provides a detailed list of assessment criteria and how they are applied in the technology assessment process, including the following top-level topics:
  - Basic Operations
  - Site Selection and Characterization
  - Maturity and Remaining Effort
  - Technology Capabilities
  - Cost and Commercial Related Factors
- Section 4, References, lists documents and other materials that are directly referenced or quoted in the report.
- Appendix A, Potential Nuclear Energy Missions, provides more detail on possible owner-operator missions that could be good choices for deployment of nuclear.
- Appendix B, Functional Roles in the Technology Selection Process, contains a primer on typical roles used in the technology assessment process.

1.5 End-User Considerations

1.5.1 Reactor Size and Type Designations

The global nuclear industry has many classifications for the size and type of a nuclear plant. Unfortunately, these classifications are more generalizations than specifications, which can lead to misunderstanding. Reactors are typically described by a subset of design attributes and features; these include:

- Neutron energy or speed (thermal or fast)
- Moderator (such as light water, heavy water, graphite)
- Coolant (water, gas, liquid metal, molten salt)
- Historical generation (I–IV)
- Fuel state (solid, liquid)
- Mission (such as electricity, heat production)
- Thermal/electrical output (MWt/MWe)

Classifications that are particularly relevant are detailed in the following.

1.5.1.1 Historical Generation

Generation (GEN) I, II, III, III+, and *IV*: These terms primarily refer to the historical development period of a nuclear reactor design. *GEN I* refers to the earliest prototype and demonstration reactors, of which there are none left operating today. Most reactors operating globally today are of the GEN II vintage, mostly light water reactors (LWRs), but they also include other coolant designs (outside of the United States). GEN III and III+ reactors incorporate evolutionary improvements in design over GEN II, targeting standardization, efficiency improvements, and advances in safety. All GEN III and III+ designs are water-based, and many plants are operating globally, with more under construction or planned. *GEN IV* specifically refers to a set of ARs currently under development and being studied by the Generation IV International Forum, with expectations to start operations in the 2030s. GEN IV reactors are expected to cover a broad range of plant sizes. Light water small modular reactors (lwSMRs), although often included in GEN III/III+, offer attributes that bridge the GEN III/III+ and GEN IV classes. At the time of this revision, EPRI includes lwSMR technologies under the AR designation along with microreactors.

1.5.1.2 Size

Large reactors (LRs): Most commercial nuclear plants operating today are GEN II, III, and III+ designs and would be considered LRs. Although some plants use different moderators and coolants, most are light water reactors, often referred to as *large light water reactors* (LLWRs) or *advanced light water reactors* (ALWRs) for later designs. Except for lwSMRs, GEN II, III, and III+ designs have historically been large reactors, operating on the order of 600–1500 MWe.

Medium reactors: The term *medium reactor* is not often used but is incorporated in this report to span the size gap between SMRs and LRs, on the order of 300–600 MWe. Historically, reactors in this size range have been avoided (except in the earlier years of nuclear development) due to economies of scale, being deemed too expensive to operate efficiently and leading to a proclivity for building ever larger designs. However, some proposed new reactor designs are re-evaluating this size range on the assumption that modern construction and operations technology, combined with higher thermal efficiency, can make them economically attractive.

Small reactors: Small reactors are often referred to as *small modular reactors* (SMRs), but *small modular reactor* is a rather ambiguous term that can easily cause confusion if not specified in more detail. At its simplest, this refers to a reactor generating a lower amount of electrical power as compared to more traditional large plants. SMRs are expected to be designed in a modular fashion, but this is not a requirement. The definition of *modular* can vary from one design to another, including multiple small units deployed on a single site, multiple reactor modules deployed on a single site, or a more typical design but where the plant is constructed from factory-built modules. In the United States, the U.S. Nuclear Regulatory Commission (NRC) considers light water designs of 300 MWe or less as SMRs (NRC, 2022), whereas U.S. Code 42 USC §18751 defines an SMR as being less than 300 MWe *and that can be constructed and operated in combination with similar reactors at a single site* (U.S. House of Representatives, 2021). However, those definitions are not globally standard, and varied sizes and non-water designs might be considered SMRs in different countries. The U.S. Department of Energy (DOE) uses the term *advanced small modular reactor* (U.S. DOE, 2021) to mean both water and non-water-based designs, and Canada uses the term *small modular reactor* for the same thing (CA SMR Roadmap, 2018).

Microreactor: Although there is no specific standard, this term typically refers to a small reactor generating a relatively low amount of power. A review of available literature will find the defining size of microreactors highly varied, ranging from about "10 MWe or less" up to "50 MWe or less." U.S. Code 42 USC §18751 defines a *microreactor* as being not greater than 50 MWe, whereas the U.S. General Accounting Office (GAO) noted in a 2020 report that "Nuclear microreactors are very small reactors usually generating less than 50 megawatts electric (MWe)" (U.S. GAO, 2020). As noted by the NRC in SECY-20-0093 (NRC, 2020b):

> There is not an agreed-upon definition for what constitutes a micro-reactor. Nevertheless, characteristics shared by the designs referred to as micro-reactors by stakeholders, industry, DOE, and DOD include low potential consequences in terms of radiological releases, small site footprints, and power levels generally on the order of tens of MWt or less, with increased reliance on passive systems and inherent characteristics used to control power and heat removal.

The low power levels, small site footprint, and strong safety features available to microreactors open many opportunities for siting versus the considerations for much larger plants. For the purposes of this report, a plant operating at 50 MWe or less is considered a microreactor.

1.5.1.3 Technology Generation

After size, the native attributes of the specific reactor technology are important to evaluating assessment criteria (as defined in Section 3). The proposed designs for new reactors under development implement innovative technologies that impart many positive attributes, primarily for safety, but also for construction and operations, which can open opportunities for deployment. It can be useful to characterize reactor technology into two groups:

Current generation: The current generation of nuclear plant technology encompasses all types of commercial nuclear reactors currently operating globally. As previously noted, this includes GEN II, III and III+ designs (including developed LR designs not yet built and those under construction but excluding lwSMRs).

Advanced reactor (AR): Much like SMR or MR, the term *advanced reactor* can be ambiguous, and many organizations have developed their own definitions. For example, the Nuclear Energy Institute (NEI, 2021b), the U.S. Congressional Research Service (U.S. CRS, 2019), and a recent U.S. DOE Funding Opportunity Announcement (U.S. DOE, 2020) all identify slightly different definitions of *advanced reactor* (one including fusion). A common theme is identified by the CRS as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors." Although the reactor types identified as GEN IV are generally considered ARs, the GEN IV designation is specific, so other reactors could be considered ARs as well.

The assessment process defined in this report is intended to be technology-agnostic, however, and the following definition of AR is used by this report:

> An advanced reactor (AR) is any (fission) reactor concept or design beyond Generation (GEN) III/III+ technologies and includes non-light water designs, light water SMRs, and microreactors.

1.5.1.4 Reactor Types and Designations

Since the beginning of the nuclear era, there have been many proposed, tested, demonstrated, and deployed nuclear plant designs. Going into the details of all these designs is beyond the scope of this report. However, the Nuclear Innovation Alliance has a detailed primer on some of the most current designs (NIA, 2021), the IAEA's additional references are *Advanced Large Water-Cooled Reactors* (IAEA, 2020) and *Advances in Small Modular Reactor Technology Developments* (IAEA, 2020b), and the organization Third Way manages a map of known AR OEMs and their designs (Third Way, 2022). Table 1-1 contains a summary of the various reactor types and their common abbreviations, which are often used in documentation and literature.

Table 1-1
Common reactor types

Type	Coolant	Abbreviation
Water	Light water	PWR
		BWR
	Heavy water	HWR
	Supercritical water	SCWR
Gas	Carbon dioxide	GCR
	Helium	HTGR
Molten salt	Molten salt (liquid fueled)	MSR
	Molten salt (solid fuel)	FHR
Liquid metal	Lead	LFR
	Sodium	SFR

1.5.2 Land Area

When assessing various technologies and designs, the size of the nuclear plant can be an important attribute; under any scenario, viable land space is a minimum requirement. It is best to have concrete knowledge of the land area needed for the chosen plant design. However, at early points in the assessment selection process, site selection might not yet be complete enough for a rigorous evaluation. Or, for example, in the case of an early site permit (ESP) that makes use of a plant parameter envelope (PPE, see Section 1.5.3), only general area size estimates may be known. At certain points in the assessment process (Section 2) and criteria evaluation (Section 3), it is best if the land area is known; in the absence of exact known values, the values in Table 1-2 can be used for guidance.

Table 1-2
Typical plant land area versus size

Size[1]	Operating (MWt)	Output[2] (MWe)	Typical Land Area Needed (acres [hectares])[3]		
			Plant Footprint[4]	Overall Site[5]	Additional Construction
Micro	<=150	<= 50	0.1–4 (0.04–1.6)	1–8 (0.4–3.2)	2–10 (0.8–4)
Small (SMR)	150 >=900	50 >= 300	25–200 (10–80)	50–500 (20–200)	50–100 (20–40)
Medium	900 >= 1800	300 >= 600	60–250 (25–100)	250–800 (100–325)	75–200 (30–80)
Large	> 1800	> 600	100–400 (40–160)	500–2000 (200–800)	100–500 (40–200)

Plant footprint refers to all area needed to support the operating plant and includes items such as parking, offices, permanent support buildings and warehouses, waste storage, the power block, switchyard, cooling towers, laydown and storage, and the protected area (over and above any previous items). Note that this can vary significantly based on the overall plant layout, including the compactness of the site (that is, distance between buildings and other infrastructure).

The *overall site* includes the plant footprint plus any additional area technically declared as part of the site. As with plant footprint, this can vary greatly. It could be not much larger than the plant footprint or could include significantly more area, depending on the overall characteristics of the site (for example, the orientation of existing property boundaries, location of water sources, environmental consideration, such as wetlands), the size of the NRC Exclusion Area Boundary (EAB), other site planning considerations, and future site plans (such as adding units).

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[1] The size and related values represent a single unit. Deployment of multiple units on a site is not necessarily a multiple of the numbers provided here and is highly dependent on reactor type, design, and overall layout. Consultation with an OEM or AE is highly recommended to obtain more accurate values. However, in the absence of specific info, you can add the unit sizes together to estimate the land area.

[2] The MWe values are estimated based on MWt.

[3] The values in Table 1-2 are typical ranges based on consolidated values from several sources, including the EPRI *Siting Guide* (EPRI, 2015); NRIC's 2021 report, *Advanced Nuclear Reactor Plant Parameter Envelopes* (NRIC/PNNL, 2021); and select recent COL (NRC, 2020) and ESP (NRC, 2020c) licensing submittals. These values are for approximating land use, which is not 100% proportional to plant size in MWt or MWe and cannot be explicitly defined without discussion with an individual OEM.

[4] As of publication time, the NRC has issued a draft *Generic Environmental Impact Statement for Advanced Nuclear Reactors* (NRC, 2021b), which "…assumes that the proposed plant site would be no larger than 100 ac (40.5 ha), within which site disturbance would affect no more than 30 ac (12 ha) of land permanently and no more than 20 ac (8.1 ha) of additional land temporarily."

[5] If a cooling water reservoir is needed, the overall site could be as much as 4000 acres (1600 ha) larger; see "Overall Site."

The anticipated size of the emergency planning zone (EPZ) is a unique aspect of SMRs and ARs that should be considered when determining the land area needed for the proposed project. Because it is conceivable that the EPZ for an SMR or AR could be within the site boundary, an applicant siting a new nuclear plant might want to ensure that the overall site footprint would encompass the anticipated EPZ size for the technology under consideration, or the bounding parameters contained in the PPE if a technology has not been selected prior to initiating the siting process.

When exact values are not known, there are a couple of criteria that can be useful for estimating at least the minimum site size. First, the plant footprint is the absolute minimum size for a site. Second, the size of the EAB can also be used as a reasonable proxy for at least a target lower end size. Although it is not mandatory that the overall site proper be contained within the EAB, the requirement that "…the reactor licensee has the authority to determine all activities including exclusion or removal of personnel and property from the area" (NRC, 1998) indicates that containing the EAB within the site would give the licensee greater control of the activities within the EAB, including potentially easing emergency management. These EAB requirements could limit the minimum land size needed, even for reactors with small facility footprints.

If a new plant or units are being constructed on or near an existing nuclear plant, the size of the overall site can be significantly reduced. On the other hand, if a new greenfield site is being developed and a cooling water reservoir is needed, the overall site could be significantly larger, and adding as much as 4000 acres (1600 ha) in additional area would be a good estimate.

The *Additional Construction* area is additional temporary area needed for construction. It may or may not end up being part of the site (for example, nearby leased property), but it must be accounted for in an environmental review for U.S NRC licensing (NRC, 1996).

When first starting a siting project, particularly greenfield siting where no potential sites have been identified, it is recommended that the process begin with areas on the higher end of the spectrum. For example, for typical large reactors, sites of as much as 6000 acres (2400 ha) are often defined, although favorable sites as small as 2000 acres (800 ha) might be considered if land constraints preclude the larger site size or especially restricted favorable areas exist. The nominal 6000-acre (2400-ha) area is consistent with facility land requirements for large plant facilities plus a cooling water reservoir and potential temporary construction space, thereby providing a consistent basis for comparison of potential sites while allowing flexibility for ultimately locating plant components within the evaluated area. This flexibility makes it possible to refine detailed plant locations as more information (such as environmental and geotechnical considerations, land availability) is developed regarding the site in subsequent steps in the siting process. The flexible approach avoids the need to re-evaluate the site as locational refinements are made. Land requirements for smaller plants might be less than those for large plants (depending on the number of units proposed). The nominal 6000-acre (2400-ha) initial basis for potential site identification will likely still be appropriate for multiple-unit SMR deployment with similar total site electrical supply capacity as larger designs. Owner-operators may wish to reduce the nominal site size for lower project capacities (such as in the case of very few SMR units or a microreactor) in proportion to the associated cooling water reservoir size requirements (note that microreactors and SMRs may use air cooing, significantly reducing water needs).

Owner-operators requiring larger site acreage or wishing to provide additional flexibility (for example, for construction facilities, such as staging, laydown, and storage) should adjust the nominal site size and use the modified area as a consistent basis for site evaluations.

1.5.3 Plant Parameter Envelope and Site Parameter Envelope

The terms *plant parameter envelope* (PPE) and *site parameter envelope* (SPE) are often used when siting a new nuclear plant. Although the terms sound similar, they are distinct in their definition and purpose. These concepts can be useful when assessing technologies and designs.

The purpose of a PPE is to allow for the identification of potential sites when a specific plant design or technology has not yet been selected. In the United States, this can be beneficial when developing an ESP in accordance with 10 CFR 52 Subpart A (NRC, 2007c). A PPE is a detailed set of plant parameters reflecting bounding values for required site conditions. It is used when an applicant has identified one or more reactor designs for consideration and vendors have developed sufficiently detailed site requirements for their reactor designs. The PPE reflects bounding values across all designs being considered for each plant parameter and combines them into a single set of bounding conditions. Thus, sites meeting the bounding values would be considered suitable for any of the designs reflected in the PPE. The PPE then defines the envelope of the facility/site interface, conditions that if not satisfied by the site could preclude locating a nuclear plant there. Consider the simple example shown in Table 1-3.

Table 1-3
Simplified example of plant parameters reflecting bounding values for required site conditions

Attribute	Plant A	Plant B	Bounding Condition	Bounding Plant
Min. Land Area	1000 acres (400 ha)	2000 acres (800 ha)	2000 acres (800 ha)	B
Cooling Water Flow Rate	700,000 gal/min (2,650 m^3/min)	600,000 gal/min (2,270 m^3/min)	700,000 gal/min (2,650 m^3/min)	A
Operating Staff	400 people	300 people	400 people	A

As individual parameters from each design are compared, the most bounding (nominally the most conservative value for siting purposes) is taken as the value used for the siting process, with the understanding that any site that meets all bounding conditions should then be able to support any of the reactor designs under consideration. Organizations developing an ESP can use NEI 10-01, *Industry Guideline for Developing a Plant Parameter Envelope in Support of an Early Site Permit, Revision 1* (NEI, 2012), for guidance on developing a PPE, which the NRC confirmed in 2003 as a valid methodology (NRC, 2003).

Note: At the time of this publication, the NRC has issued a Draft Regulatory Guide (NRC, 2021c) on the use of a PPE, and NEI has issued a draft revision 2 of NEI 10-01 (NEI, 2021).

It is important that plants considered under the PPE approach be relatively similar in most attributes, particularly in major attributes such as size, water usage, and ecosystem impact, or the overall bounding conditions may become overly conservative for some of the subject designs. Technically, if the bounding values meet the mission and purpose of the projects, the PPE approach would still work, but the resulting sites identified for consideration might be limited, possibly leading to a site selection that is not optimal for the final chosen design.

Whereas the PPE is developed by the owner-operator during the siting process to identify potential sites that could support several designs, the SPE is developed by the reactor designer for their specific design. Like the PPE, it identifies bounding parameters, but in this case, only for one specific design. The purpose of the SPE is to allow identification of a potential site of which the owner-operator can be relatively assured that the plant under consideration will be able to be sited with minimal changes to both the site and plant. Once a plant design is selected, a SPE can be a powerful tool to help screen potential sites during the siting process as defined in the EPRI *Siting Guide* (EPRI, 2015). The SPE can also be used to bound environmental impacts, easing the effort to develop environmental reports (NRC, 2007b).

These two concepts can play a part in the technology assessment process. For example, if an ESP based on a PPE exists, several technologies, and possibly full designs, will likely have been developed, and the PPE parameters can be used as specific inputs into the assessment process. Although it is likely that an owner-operator will already have put significant effort into understanding technologies and designs in the creation of a PPE for an ESP, the assessment process can still be used to select a final design. Additionally, if enough time has passed, innovative technologies might be available, or previously identified designs might no longer be available.

If no PPE exists but a site has been identified, the output of the assessment process (the selection of a primary design and alternatives) can be used to create one where the PPE bounds the primary and one or more of the alternatives. On the other hand, on selection of a primary design, that design's parameters (or possibly including alternatives for bounding) can inform the creation of an SPE, which can provide input into the site selection process (see the EPRI *Siting Guide*).

1.5.4 End-User Applicability

This report is intended to be applicable to any owner-operator regardless of locale and is intended to be as regulatory-neutral as possible. The actual technology assessment procedure identified in Section 2 is regulatory-agnostic and valid for almost any nuclear plant technology assessment and selection activity. Where reference to regulations is deemed needed, U.S. regulations are used for reference. Any noticed regulatory requirements will likely be necessary in any region because the activities themselves are largely necessary to ensure nuclear, personal, and environmental safety. End-users outside of the United States are encouraged to follow the process and use the references and examples provided to help guide them under their own regulatory requirements.

2
TECHNOLOGY ASSESSMENT PROCEDURE

This section describes suggested elements of an overall technology assessment procedure. It is a general guide to help owner-operators assess various nuclear technologies and specific plant designs, and then come to a defendable conclusion. Although there are some differences due to a limited number of choices for assessment and potentially a lower amount of quantitative (or at least clearly verifiable) information, this process is based on the one used in EPRI's *Siting Guide* (EPRI, 2015). It also serves as a comprehensive checklist of technology assessment issues and methods for addressing them in selecting a final design for a new nuclear plant.

The technology assessment procedure consists of the following six primary process steps (see Figure 2-1):

1. Define mission and business objectives
2. Identify the technologies of interest
3. Screen to candidate technologies
4. Identify potential designs
5. Screen to candidate designs
6. Identify proposed and alternative designs

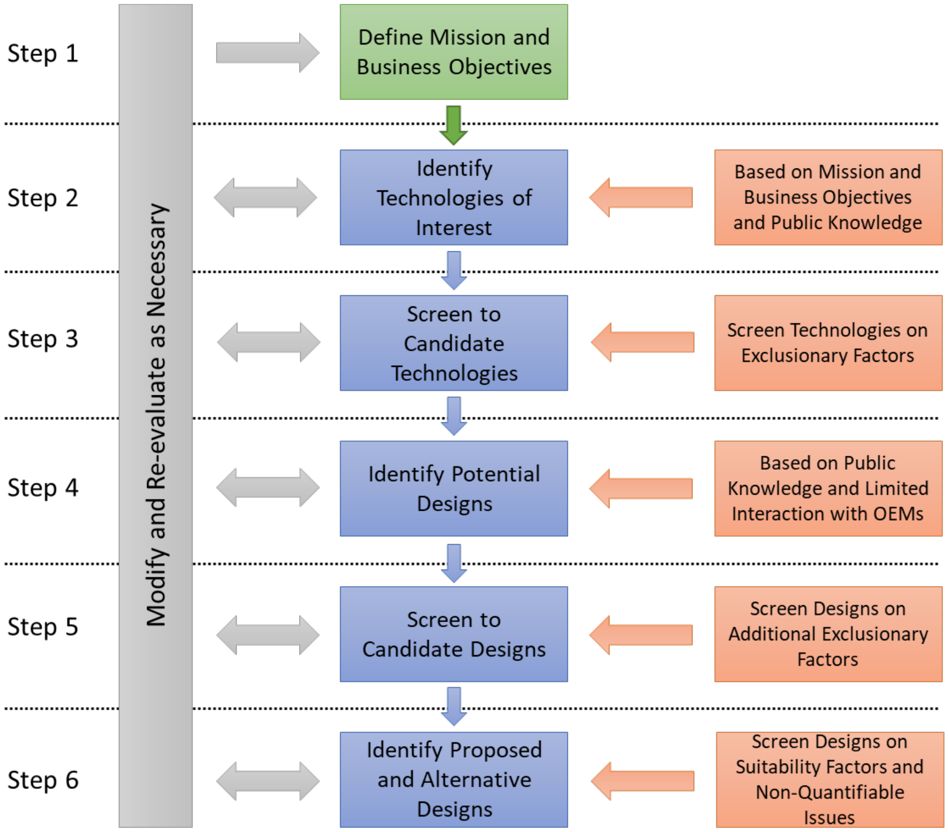


Figure 2-1
Technology assessment process steps

Each of these process steps is covered in Section 2.1, "Technology Assessment Procedure Overview."

Four analytical processes are applied in executing the procedure, as follows:

- *Mission and Business Objective* (Section 2.2) – Guidance for the owner-operator on developing their mission and business objectives, a required input into the process
- *Criteria/Importance Weighting* (Section 2.3) – Development of weighting factors that reflect the relative importance of individual criteria in the assessment and development of a composite suitability value that reflects tradeoffs among criteria
- *Criterion Scoring* (Section 2.4) – Development of utility functions that quantify the relative suitability of a design with respect to a single criterion
- *Technology Assessment Criteria* (Section 2.5) – Application of criteria that represent facility design, safety, siting, operations, and maintenance requirements, which affect plant suitability and are considered in technology selection

The discussion that follows requires some forward referencing because concepts are introduced before they are formally defined (for example, assessment criteria are referenced in Section 2.1 and then defined in Section 3). It is strongly recommended that readers first review Sections 2 and 3 in their entirety to become familiar with assessment concepts, and then review them a second time to fully understand the overall technology assessment procedure.

2.1 Technology Assessment Procedure Overview

Figure 2-1 is an overview of the steps executed in nuclear plant technology assessment and selection as defined in this report.

The process is applied starting with the defining of the owner-operator's *Mission and Business Objectives,* which are used to guide the rest of the process and evaluation. This is followed by identifying the *Technologies of Interest*, which are underlying reactor technologies such as PWRs, BWRs, molten salt reactors, and fluoride salt-cooled high-temperature reactors that, based on limited inspection, could meet the mission and business objectives. These technologies are then evaluated on an exclusionary basis to narrow the field to a more limited number. Once a smaller set of technologies is identified, *Potential Designs* based on the underlying technologies are identified. These are a selection of OEM-specific designs that appear to meet the owner-operator's mission and business objectives. Like the technologies, these potential designs are evaluated on an exclusionary basis to narrow the field to a more limited number of *Candidate Designs.* Finally, these candidate designs are evaluated for their suitability for the mission and business objectives, resulting in *Proposed and Alternative Designs.*

The assessment process outlined in this report is designed to provide effective resource utilization in characterizing technologies and designs under consideration. Starting with the technologies of interest, the technologies and designs under consideration are successively reduced so that an increasing level of detail is applied to those found to be more favorable in the earlier stages of the process. This application of the process steps (see Figure 2-1) allows an owner-operator to thoroughly screen for potentially suitable technologies and designs while they devote more attention and resources to the more favorable alternatives as the number of technologies and designs under consideration is reduced. This aspect of technology assessment and selection is conceptually portrayed in Figure 2-2.

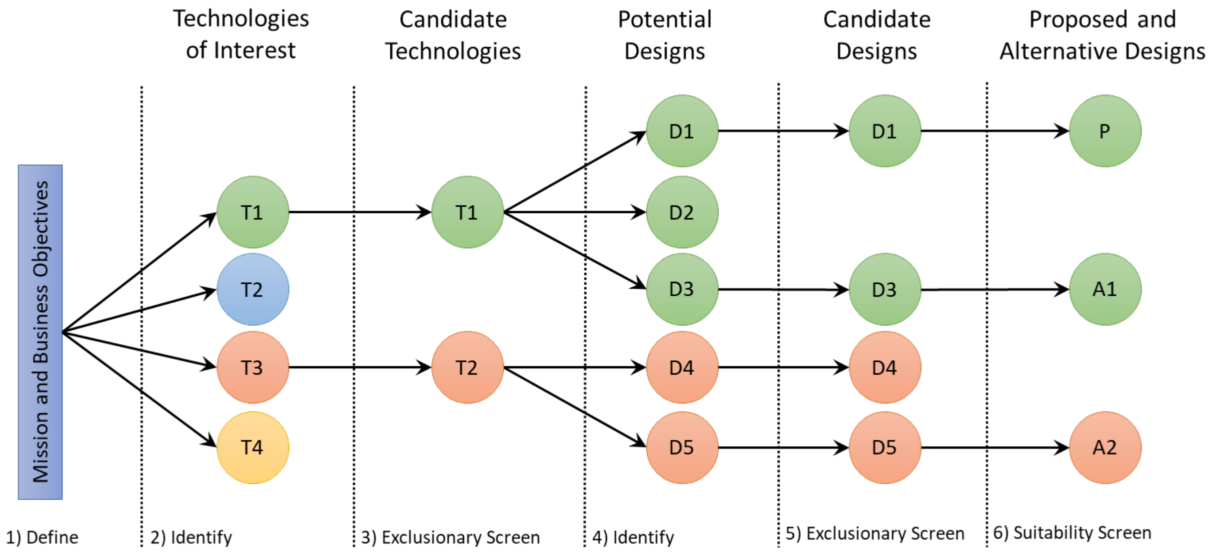


Figure 2-2
Conceptual technology assessment and selection process

The selection of the technologies of interest (Step 2) is based on the owner-operator's mission and business objectives for the new nuclear plant (Step 1). Steps 3–5 of the process are limited in nature because screening is performed only to identify several designs for detailed evaluation.

Comparison of individual designs based on their relative suitability is the focus of Step 6. This portion of the process begins with the use of published and unpublished information and concludes with detailed information collected through various investigations, as necessary, culminating in the selection of a proposed design for which an owner-operator can be reasonably sure meets their mission and business objectives. As the assessment process unfolds, the level of information detail and the corresponding level of confidence in the assessment increase. Accordingly, previous conclusions should be re-evaluated at each step of the process to ensure that they remain valid considering new data. If necessary, steps can be repeated using revised criteria evaluations and/or new data and information—for example, when the results of a step yield insufficient results (such as when there are too few technologies to carry forward) or unacceptable uncertainties.

Note: Organizations are encouraged to follow the process as defined; however, it is recognized that they might have performed the equivalent of earlier steps on their own prior to taking up this guidance. Organizations should review these steps against the work they have completed to date to find the most appropriate starting point, and then document their rationale.

Several terms must be understood before performing the assessment process:

- *Assessment Criteria* – Technical and business-related **conditions and benchmarks** against which the various technologies and designs will be examined. Individual criteria might have clear, measurable standards based on required business objectives or regulatory requirements to reflect on. Or an individual criterion will simply identify information the owner-operator should know and understand about the technologies and designs being considered such that an informed decision-making process can be completed. Examples of measurable criteria include objective items, such as output steam temperature or refuel period, and examples of subjective criteria include the design of the fuel handling system or construction techniques to reduce schedule. See Sections 2.5 and 3 for an explanation of the criterion types included.
- *Exclusionary Factors* – Criteria examined based on exclusionary factors include those that can be evaluated based on **requirements**, and they may be identified as minimums, maximums, needs, or other qualifying language that indicates compliance is mandatory. Exclusionary factors provide a binary go/no-go decision on a technology or design. An example of an exclusionary factor is a requirement for a minimum electric output of 500 MWe. Any technology or design that does not supply that is excluded.
- *Avoidance Factors* – Criteria examined based on avoidance factors include those that can be evaluated based on goals; they might be identified as wants, preferences, aims, or other qualifying language that indicates that compliance is not mandatory but so highly desired as to use an exclusionary screening to provide a binary go/no-go decision on a technology or design. An example avoidance factor is a preference for plants that can go five or more years without refueling to avoid outage time. Although this is not a requirement, and a plant that refueled more often could be acceptable, it is a significant preference and therefore excluded.

- *Suitability Factors* – Examining criteria based on suitability factors is done to find the **best** result, not necessarily to exclude any design. Suitability factors are evaluated using criterion weighting and scoring to obtain quantitative results from a qualitative process. For example, there is a requirement for a minimum electric output of 500 Mwe; Design A provides 850 MWe and Design B provides 875 MWe. Both designs are acceptable. Each design is scored separately based on a utility function (see Section 2.4), resulting in Design B receiving a higher score because it could provide for more revenue.
- *Issue Comparison Analysis* – The three preceding factors should be evaluated on a single technology or design for each criterion in isolation without comparison to any other. Issue comparison analysis, however, compares unique designs based on qualitative issues. For example, both Design A and Design B are determined to be acceptable based on criteria analysis, and Design B is ranked the highest numerically. However, Design B uses more water than allowed under standard permitting. Although there are processes for submitting a deviation request for a special permit, this could add schedule and risk to the project. This is documented in an issue comparison analysis (see Table 2-2) and used to finalize the choices for proposed and alternative designs.

Summary descriptions of each step follow.

2.1.1 Step 1 – Define Mission and Business Objectives

The process is applied starting with the defining of the owner-operator’s *Mission and Business Objectives.* This first step is crucial because many of the following steps and actions, including criteria evaluation, will be based on these inputs.

The mission and business objectives will derive from the owner-operator’s pre-existing fundamental business decisions on the need for power or other product, the market for the facility’s output (electricity or otherwise), the currently assumed economic viability of a nuclear facility, and other organization-specific requirements, goals, and issues.

Mission and business objectives are intended to help specify the purpose of and need for the project, including identification of items such as the following:

- End-product (such as electricity, heat, hydrogen)
- Required output (MWe or MWt)
- Target location for the plant (such as service territory for electrical generation, near industrial facilities for heat)
- Service requirements (firm or flexible generation, black-start capabilities, weather resiliency)
- Target budgets (such as overnight capital cost or overnight construction cost [OCC], levelized cost of electricity or energy [LCOE])
- Need dates or other relevant time frames (such as from 20-year plans)
- Longer-term goals (such as the number of units over time, intent to provide other services, desire to be a first mover)

See Appendix A for detailed descriptions of possible missions and business objectives related to electricity generation, process heat, cogeneration, other product generation (such as hydrogen production and desalination), and other missions.

For regulated electrical utilities, mission and business objectives are typically driven by the utility's need for power, the type of power needed (firm or flexible), and the total MWe needed to service its territory or the combined service territory of participants in a jointly owned project. Those developing a merchant plant, or for other missions, must define their mission and business objectives based on the overall goals of the project. For example, for a steam heat mission, attributes such as thermal output, temperatures, and volumes will need to be defined. Some owner-operators might need to meet state, local, or even self-imposed carbon reduction strategies, and therefore have goals to increase their deployment of carbon-free energy generation.

See Section 2.2 for details on defining mission and business objectives.

2.1.2 Step 2 – Identify Technologies of Interest

After the mission and business objectives are complete, the next step is to identify the *Technologies of Interest*. These are the base, underlying reactor technologies, such as PWRs, BWRs, lwSMRs, molten salt reactors, or fluoride salt-cooled high-temperature reactors (see Section 1.5.1.4). This selection is based on the general knowledge of the defined business objectives and public information on the available technologies. Owner-operators should remove technologies from their technologies of interest pool they know with certainty will not be adequate. However, where there is uncertainty, technologies should remain in the pool for Step 2.

Note: If a specific technology is already identified or prescribed (for example by a national program requirement), this step could be skipped.

Two initial considerations that can easily affect choices for the technologies of interest include energy output requirements and need date. At this stage, fundamental nuclear technologies are often intermingled with output size, and output size requirements can be an easy initial screening option. For example, if the desired energy output is large (that is, requiring a GW-sized plant), technologies focused on smaller sizes, such as microreactors, can likely be excluded; however, a small fleet of SMRs could be a viable option and included here. The need date is also a viable attribute for initial selection; if the need is soon, the inclusion of only more mature technologies is appropriate, but if the need date is later or flexible, additional technologies should be included.

Additional considerations at this point may also include longer-term goals. For example, the number of reactors expected to be deployed over time may be a consideration, where initial deployment assumes a more mature technology, with consideration of advanced designs later.

In any event, owner-operators should ensure that their pool of technologies of interest is large enough such that it does not exclude viable technologies that can meet their mission and business objectives. Also, at this point, try not to let size be too great a constraint; almost any technology can be provided in any size, or multiple units can be deployed, but some technologies are likely better candidates than others.

Note: Any organization considering the deployment of nuclear should also consider alternative energy sources other than nuclear. In the United States, this consideration must be documented in the Environmental Report of an ESP, COL, or CP (NRC, 2018). This report does not specifically address this and is intended only for use in comparison of nuclear technologies.

2.1.3 Step 3 – Screen to Candidate Technologies

The next step is to screen to *Candidate Technologies*. This screening is a limited, exclusionary-based process to eliminate technologies from the technologies of interest pool. In this step, each technology is evaluated on select criteria (see Table 2-1 and Section 3) against the mission and business objectives (Section 2.2) to see if the criteria can be met; if not, the technology is removed from the pool (or the mission and business objectives are modified). In this step, criteria can be evaluated based on publicly available information. The output of this step is a set of candidate technologies.

Table 2-1
Technology assessment criteria and typical screening activity

Section	Criteria	Candidate Technologies Screening	Candidate Designs Screening	Proposed/ Alternative Designs Screening
3.1	**Basic Operations**			
3.1.1	Plant Energy Output	Yes	Yes	Yes
3.1.2	General Operations & Maintenance	No	No	Yes
3.1.3	*Fuel and Used Fuel Management*			
3.1.3.1	Fuel Selection	Yes	Yes	No (see note)
3.1.3.2	Used Fuel Storage and Disposal	Limited	Yes	No (see note)
3.1.4	Good Neighbor	No	No	Yes
3.2	**Site Selection and Characterization**			
3.2.1	Site Evaluation	Limited	Yes	Yes
3.3	**Maturity and Remaining Effort**			
3.3.1	*Design Maturity and Remaining Effort*			
3.3.1.1	Design Completion	Limited	Limited	Yes
3.3.1.2	Reactor Systems	Limited	Limited	Yes
3.3.1.3	Reactor Non-Safety Auxiliary Systems	Limited	Limited	Yes
3.3.1.4	Engineered Safety Systems	Limited	Limited	Yes
3.3.1.5	Fueling, Refueling, and Fuel Handling Systems	Limited	Limited	Yes
3.3.1.6	Other Systems or Critical Plath Components	Limited	Limited	Yes

Table 2-1 (continued)
Technology assessment criteria and typical screening activity

Section	Criteria	Candidate Technologies Screening	Candidate Designs Screening	Proposed/ Alternative Designs Screening
3.3.2	Regulatory and Licensing	Yes	If data are available	Yes
3.3.3	Reactor OEM Capability and Capacity	No	If data are available	Yes
3.3.4	Supply Chain Maturity, Remaining Effort, Capability and Capacity	Yes	If data are available	Yes
3.3.5	Owner-Operator Capability and Capacity	No	If data are available	Yes
3.4	**Technology Capabilities**			
3.4.1	Design Philosophy	No	No	Yes
3.4.2	Design Processes and Tools	No	No	Yes
3.4.3	*Safety, Reliability, Availability, and Sustainability*			
3.4.3.1	Safety	No	No	Yes
3.4.3.2	Structures, Systems, and Components (SSCs)	No	No	Yes
3.4.3.3	Human Factors, Instrumentation and Control, and Cybersecurity	No	No	Yes
3.4.3.4	Operations and Maintenance	No	No	Yes
3.4.4	Flexibility and Resiliency	No	No	Yes
3.4.5	Fuel, Fuel Cycle, and Waste Management	No	No	Yes
3.4.6	Proliferation Resistance and Physical Protection	No	No	Yes
3.4.7	Licensing	No	No	Yes
3.4.8	Constructability	No	No	Yes
3.5	**Cost and Commercial Related Factors**			
3.5.1	OCC	No	No	Yes
3.5.2	LCOE and Levelized Product Cost (LPC)	No	No	Yes
3.5.3	Other Costs	No	No	Yes
3.5.4	Commercial Considerations	No	No	Yes

Note: The detailed evaluation for these two fuel-related items in Step 6 should be according to the more detailed criteria noted in Sections 3.3 and 3.4.

In this stage of the process, the technologies of interest are screened using exclusionary and avoidance factors to eliminate unfavorable technologies and identify candidate ones that will be reviewed in the next step to identify potential designs. The technologies of interest are first screened using exclusionary factors to eliminate those that are considered not feasible to develop due to business, regulatory, institutional, facility design, and other specific constraints. Exclusionary factors are those that clearly identify a technology as non-viable—for example, output temperature might be an exclusionary factor if a specific minimum temperature of steam is required for an industrial process.

However, it is likely that factors considered to be more about avoidance will also be included. Avoidance factors will include judgment calls about issues such as fuel forms and availability, number of units that might need to be deployed, desire to be involved in development, or other more open-ended business objectives.

If this screening process results in too few technologies remaining to identify an adequate number of potentials, the avoidance factors can be relaxed, and the process repeated. Conversely, if the technologies remaining are too many and additional avoidance factors can be defensibly applied, the criteria may be made more stringent, and the process repeated. The avoidance screening process is repeated until the candidate technologies identified are adequate (not unreasonably large or small) to present multiple options or until no more restrictive, or more relaxed, avoidance factors can be justifiably applied.

2.1.4 Step 4 – Identify Potential Designs

The next step is to *Identify Potential Designs*. The selected designs are based on the output of Step 3; a selection of OEM-specific designs based on the candidate technologies that meet the owner-operator's business objectives are identified. Like Step 2, exclude designs that are known with certainty to be inadequate; however, where there is uncertainty, designs should remain in the pool for the next step. This selection can be made with publicly available information but might include information gathered through meetings and discussions with various OEMs.

Potential designs are identified by reviewing the candidate technologies identified in Step 3 to then identify discrete designs that are favorable to the mission and business objectives. Professional judgment should be incorporated in defining potential designs to ensure that they are feasible to develop and meet the objectives of the project.

A typical process for conducting this review to identify potential designs is as follows:

- Use easily available information (public or not) to identify and list the assorted designs that classify themselves as being based on the candidate technologies. Note that some designs are hybrid and may partially fit under a technology or span more than one. Also, some OEMs offer more than one design, usually under differing base technologies.
- Quickly compare the selected designs against the mission and business objectives to exclude those that can be easily discarded.
- At this point of the process, it is best to err on the side of inclusion because a more formal review of criteria for exclusion will be done in the next step.

The output of this step is a set of potential designs.

2.1.5 Step 5 – Screen to Candidate Designs

Step 5 is to screen to *Candidate Designs*. Like Step 3, this is an exclusionary screening to eliminate designs from the pool of potential designs. In this step, each design is evaluated on select criteria against the mission and business objectives to see if the criteria can be met, and if not, the technology is removed from the pool (or the mission and business objectives are modified). Like Step 3, a limited set of criteria is evaluated (see Table 2-1 and Section 3), but in this step, additional criteria are included. Also, like Step 3, this screening includes avoidance factors that might need to be modified if the number of candidate designs is too small or large.

Although publicly available information can be used in this step, it is at this point where the owner-operator might need to engage OEMs more proactively to ensure that all selected criteria are evaluated fully. The output of this step is a set of candidate designs, and the goal is to end with three to five available designs. However, note the following:

- If there are no designs remaining at the end of this step, the mission and business objectives will need to be modified or avoidance factors will need to be relaxed, or the process halted because there are no adequate designs at this time (see Section 2.1 for more information on avoidance factors).
- If there is only one design remaining at the end of this step, care should be taken. At the end of this step, a single remaining design should not be considered an acceptable proposed design. Step 6 will still need to be completed to ensure that the remaining design is adequate, and performing Step 6 on only one design raises concerns because it removes any options from future decision-making, significantly increases risk if the design later proves to be an inadequate choice, and does not allow for a foil for comparison, which could cause bias in the detailed criteria evaluation. Modifying the mission and business objectives should be considered, or avoidance factors can be relaxed if defendable. As a minimum, consider moving the best of the rejected designs forward as well, to function as a comparator.
- If there are more than about five designs output from this step, it is possible to move forward with them all, but the overall process will take more time. There are two viable options to reduce the number. The review team can repeat the exclusionary exercise using more or refined criteria, particularly for avoidance factors, which may or may not reduce the number, or the team can simply choose based on the information gathered to date. At this point, the team will have collected much information and evaluated many criteria, and as explained previously, much of the information and criteria might still be open-ended. A decision to choose must be done methodically, be well documented and supported, be a team decision, and, most important, be able to stand up to scrutiny if challenged. Nonetheless, it can be acceptable at this point in the process.

The resulting set of candidate designs should be of sufficient number and diversity such that the owner-operator can show that the results represent the major tradeoffs that exist with respect to the mission and business objectives and reflect the best designs that can reasonably be found.

2.1.6 Step 6 – Identify Proposed and Alternative Designs

The objective of Step 6 is to rank a relatively small number of candidate designs (the output of Step 5) for a more detailed study and to identify the *Proposed and Alternative Designs*. The goal of this step is to identify a proposed design and at least one or two alternative designs. Unlike Steps 2 and 5, which evaluated a subset of criteria and only on an exclusionary or avoidance basis, for this step, all criteria (as noted in Table 2-1) are evaluated for suitability, and done so with criteria weighting and scoring, providing for a numerical ranking for all designs. There are several substeps that need to be completed in order:

1. *Develop Weighting Factors for Criteria* – The importance of this substep cannot be overstated. The values used as weighting factors will directly impact the results, and an improper foundation for their development will skew the results. The values for weighting factors are organization-specific and cannot be supplied in this report—they must be developed by the owner-operator's project team performing this exercise. Weighting factors should be developed for all relevant criteria, and users are advised to review Section 2.3 of this report and Appendix C of the EPRI *Siting Guide* (EPRI, 2015) on best practices. The project team might want to examine for insight the publicly available references, including the UK's *Nuclear National Laboratory Review of Metrics Relevant to Reactor Systems* (NNL, 2012b) and its *Addendum* (NNL, 2012), that examine development of weighting, explicitly and implicitly.
2. *Develop Criterion Scoring Metrics* – To evaluate the suitability of each design, each relevant criterion is first evaluated independently. This requires a scoring metric, or utility function, for each individual criterion. Criterion ratings are typically created by assigning each potential or primary technology a rating (for example, 1–5, where 1 = least suitable, 5 = most suitable) for each of the criteria being evaluated. See Section 2.4 of this report and Appendix B of the *Siting Guide* for more information on criterion scoring.
3. *Analyze and Evaluate the Criteria* – Unlike the previous screenings that have been exclusionary, this screening is inclusionary in that it seeks to not just eliminate designs that are unsatisfactory for the business objectives, but to identify the design(s) that are most suitable. For this substep, all relevant criteria (as noted in Table 2-3) should be investigated, analyzed, and evaluated. At this point of the process, and depending on the development stage of subject designs, information on the various criteria might be vague, incomplete, insufficient, or otherwise lacking. In these cases, the project team should gather what is known, methodically document what is unknown, and make a best estimate judgment on the risks implicated by the incomplete information. See Sections 2.5 and 3 for the assessment criteria.
4. *Scoring and Ranking* – Once weighting factors have been developed, the relevant criteria are individually scored, multiplied by their weighing factors (see Table 2-2), then summed for each individual design to create a composite suitability ranking for each design. The output is a list of designs ordered from most favorable to least (see Figure 2-3).
5. *Issue Comparison Analysis* – Theoretically, the ordered results from the previous step, from highest score to lowest, should identify a primary design and alternatives in order of preference. However, there could be other issues, such as an organization's larger business plan, existing knowledge of nuclear energy and operations, various level of confidence, and

other organization-specific but subjective topics, that need to be addressed, particularly when compared to the other designs. To support this, a table of issues is created that compares these issues across all designs (see Table 2-3).

6. *Identify the Proposed and Alternative Designs* – On completion of scoring, ranking, and issue comparison analysis, the assessment team will have enough information and data to make informed choices for a proposed design and alternatives.
7. *Establish Alignment with the Business Objectives* – Because all criteria have been evaluated with the organization's mission and business objectives in mind, this step is not specifically required. However, some organizations might find value in aligning the results against their objectives. The previous assessment activities were all bottom-up, whereas this activity provides a top-down review.

Table 2-2
Detailed design criteria rating: sample results

Criterion*	Weighting Factor	Design D1		Design D3		Design D4		Design D5	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
Plant Energy Output	9.6	2.5	24	3	28.8	3	28.8	3	28.8
General Operations and Maintenance	3.9	5	19.5	1	3.9	2	7.8	2	7.8
Fuel Selection	4.2	4	16.8	3	12.6	4	16.8	3	12.6
Used Fuel Storage and Disposal	4.6	3	13.8	3	13.8	3	13.8	2	9.2
Reactor Systems	7.4	4	29.6	4	29.6	5	37	4	29.6
Engineered Safety Systems	6.4	5	32	4	25.6	4	25.6	4	25.6
Human Factors Engineering (HFE) and Instrumentation and Control (I&C)	5.6	4	22.4	3	16.8	2	11.2	4	22.4
Operations and Maintenance	5.2	4	20.8	2	10.4	3	15.6	4	20.8
Overnight Capital Cost	4.8	5	24	2	9.6	2	9.6	2	9.6
Commercial Considerations	6.7	3	20.1	4	26.8	3	20.1	1	6.7
Composite Rating			223		178		186		173

*The general assessment criteria set (and resultant composite rating) has been abbreviated; the weighting factors, ratings, and scores are for illustration purposes only.

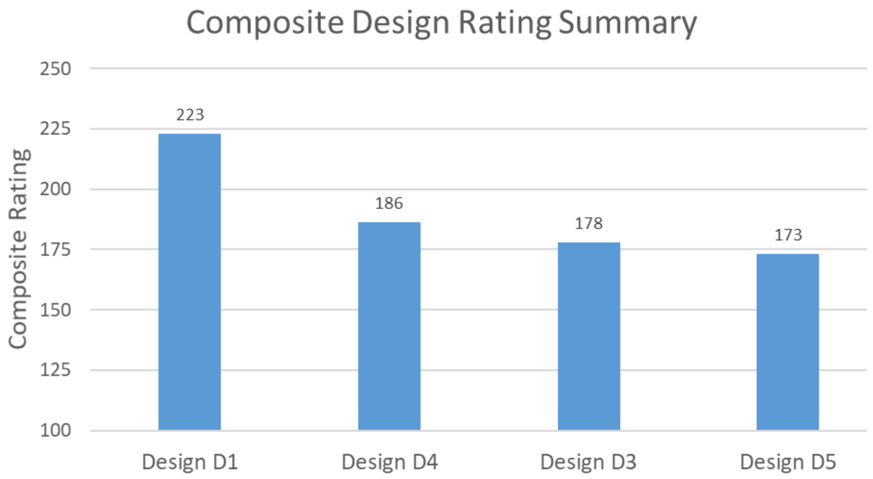


Figure 2-3
Technology suitability ratings: sample results

In the example in Table 2-2, the Step 6 screening has been completed, and all four designs have been deemed technically qualified, meaning that based on the owner-operator's mission and business objectives, there are no remaining exclusionary or avoidance factors. The Step 6 suitability ranking in Table 2-3 shows that some score better than others, but there are nuances that must be examined.

The detailed criteria described in Section 3 have been designed to provide a basis for evaluating a spectrum of issues affecting the suitability of a nuclear plant design. Accordingly, owner-operators should apply the full criteria set (as noted in Table 2-1), omitting only those criteria that clearly cannot differentiate between designs, are clearly not applicable, or for which data cannot be obtained to allow a reasonable consideration. In practice, all the criteria should be considered, with any deviation specifically noted.

The overall process for applying the full detailed criterion set is analogous to that previously described for exclusionary and avoidance criteria. Because the number of technologies under consideration at this stage is small, ratings should reflect data and information at the most detailed level available. The data used in the evaluations should also be as reflective of design-specific characteristics as feasible so that ratings accurately reflect real differences in a design's suitability to meet objectives.

Once designs have been evaluated using the full set of detailed criteria, owner-operators might wish to verify the conditions of the top-ranked designs (those under consideration as final proposed or alternatives) by conducting more detailed investigations with OEMs.

Table 2-3
Candidate design issues analysis comparison: sample*

	Design Suitability Issue (Basis for Evaluation)			
	Fuel Selection (Review of the fuel form, fuel suppliers and technical capability to produce, and regulatory and technical ability for storage and disposal.)	**Site Selection (Review of targeted site, an existing coal plant, and its characteristics against the designs.)**	**Design Maturity (Review of the design, how much is completed overall and for subsystems and components, and remaining effort.)**	**Flexibility (Review of the plant's ability to be flexible on the grid, particularly based on the impact of renewables coming on and off the grid.)**
Design 1	Uses fuel-like existing LWR fuels, but with a higher enrichment. Should be able to acquire from existing suppliers; storage and disposal will require additional qualification.	The plant will fit on the site, but there is little additional room for construction. A review of nearby properties indicates that we should be able to lease land during construction.	The design is based on existing technology already in production and use. Although there are some novel issues, there are few concerns.	The plant will meet flexibility goals today and as expected in the next 20 years. Beyond that time, the penetration of renewables and flexibility needs have not been studied, and there is little margin.
Design 3	Uses solid high assay low enriched uranium (HALEU) fuel. Physically capable of being manufactured, but no existing in-country suppliers at this time. Disposal will require additional qualification.	The design fits the site well with no significant issues identified.	A significant amount of design work is completed, and license applications have been filed but not yet awarded. Exchanges with the regulator to date have not demonstrated issues with the design.	The plant will meet flexibility goals today and has margin to meet most future needs.
Design 4	Uses solid HALEU fuel. Physically capable of being manufactured, but no existing in-country suppliers at this time. Disposal will require additional qualification.	Significant below- grade construction is required. Site is known to be bedrock at a shallow depth, potentially increasing construction costs.	License application has been approved by a regulator in another country. However, the design specifics for a few important SSCs not required to be defined for licensing are not completed, and there seem to be hurdles to overcome.	Because it was designed for another country, the design includes a control system that can be externally dispatched as needed. It is intended that the plant would start without this capability, but it could be turned on as circumstances allow.
Design 5	Uses liquid fuel; no in-country suppliers; currently no known or qualified method for storage or disposal.	Although enough water is available, air cooling significantly reduces water usage.	The design, if made real, has great potential, but it exists solely on paper and is at least a decade away from being deployable.	The plant would meet flexibility goals today and have margin to meet most future needs.

*Table and contents have been abbreviated and are intended only as a process example.

As a quality check, information can be examined to ensure that no exclusionary or avoidance factors are present that were not identified during application of the previous steps. For example, while gathering more detailed information, new data could reveal a criterion that was not previously considered exclusionary but now is because the OEM has since changed the design, which was not reflected in publicly available information, or, more likely, simply because more detailed information has been gathered. This quality check is part of considering the designs under review as integrated units that must, finally, demonstrate that they meet the owner-operator's mission and business objectives.

This approach is used as a resource optimization technique in which the full set of candidate designs is analyzed using all screening criteria and comparison of other issues. The output of this step is a proposed design and at least one or two alternative designs. It is not required that all candidate designs effectively pass through the screening process. Some might not meet expected criteria, or, at the end of this process, the lowest-ranked designs may be dropped from further consideration.

The processes described in the preceding yield numerical composite ratings for each technology being analyzed. The ratings can be used to rank them in order of their relative overall suitability as nuclear plants. However, the final proposed design and the alternatives are not required to be based wholly on the calculated ranked scoring. Accordingly, the selection of designs to be carried forward as proposed and alternative designs should reflect all that is known about issues affecting them and so should not be based on numerical scoring results alone; rather, the numerical scoring results are used as a guide and one of multiple decision factors, including issue comparison analysis. The results of the issue comparison analysis can have a significant impact on the results, but organizations are cautioned to clearly document and defend the results of their issue comparison analysis to ensure objectivity.

The more detailed data and information used during Step 6 should allow the owner-operator to identify a suite of designs (such as the highest-ranked ones) that, based on the data and information, are acceptable development candidates (that is, any design that survives this step should be capable, or at least potentially capable, of obtaining a license to construct and operate as a new nuclear plant that could meet the owner-operator's mission and business objectives).

See Table 2-2 and Figure 2-3 for examples of detailed scoring and the composite summary, and see Table 2-3 for an example of issue analysis comparison.

As noted in the foregoing, organizations might want to align the results with their mission and business objectives. This can provide a top-down review of the final selections that makes sure that that all objectives have been accounted for and that the spirit of the objectives was not lost during the assessment process. To perform this activity, each objective is evaluated for the primary design and each alternative as shown in Table 2-4, in which each of the final designs is qualitatively scored against the original business objectives. For demonstration purposes only, the highlighted rows align the results from Table 2-1 (Fuel Selection, Site Selection, Design Maturity, and Flexibility) against specific objectives (Long-Term Goals, Target Location, Need Dates, and Service Requirements, respectively). For example, Design 1 requires the purchase of additional land for siting, so it is evaluated to partially meet the Target Location objective.

Table 2-4
Alignment with business objectives

Objective	Design 1	Design 3	Design 4	Design 5
Technology and Design Assessment Envelope	*M**	*M*	*P*	*M*
End-Product	M	M	M	M
End-Product Rationale	*M*	*M*	*M*	*M*
Required Output	E	M	E	M
Target Location of Plant (or Plants)	P	M	P	E
Service Requirements	M	E	E	E
Operating Life	*M*	*M*	*M*	*M*
Need Dates and Time Frames	E	M	P	N
Target Budgets	*M*	*M*	*P*	*P*
Owner-Operator's Long-Term Goals	E	M	M	N

*Alignment scoring: E – Exceeds, M – Meets, P – Partially Meets, N – Does Not Meet

The review is a qualitative evaluation and should be based on all the data and information collected as part of the assessment; each design should be assessed independently. Although it might be expected that the primary design exhibits the best alignment with objectives and that all designs at least meet objectives, that is not necessarily the case. Some objectives may carry different priorities than others within any organization, and it is possible that no design can completely meet a specific objective to an organization's ultimate satisfaction. Therefore, it is possible that one of the final designs might not meet all objectives fully. In these cases, the project team should review their objectives and clearly document the rationale for their final decisions.

2.2 Mission and Business Objectives

The success of any technology assessment process requires that the assessment team have a clear understanding of the organization's mission and business objectives for the project. This input is foundational to the process, and failure to adequately vet the mission and business objectives with all stakeholders can result in a final selection that, in the end, is not actually viable. At best, this results in wasted time and resources for performance of the assessment; at its worst, it could result in the development and construction of a plant that does not meet the goals.

Owner-operators are cautioned to take as much time as needed to thoroughly answer the questions below. Some are quantitative and might be simpler to answer. Others are qualitative, and organizations should ensure that all needed stakeholders are provided an opportunity to offer input. Many of the criteria that will be assessed will be done so based on reflection against the organization's business objectives. Therefore, failure to adequately complete this first step can taint the results of the entire process. When defining the mission and business objectives, use of words such as *minimum, maximum, range, must, need, requirement, should, want, preference,* and *goal* should be used whenever possible but accurately (for example, do not specify a desire as a requirement when it is not, and vice versa).

The following is a listing of typical mission and business objectives that impact technology selection. If an item is clearly not applicable, it can be removed, but users are cautioned to err on the side of including more. It is not possible to cover the goals of every organization in this report, so the addition of supplementary mission and business objectives might also be warranted. However, users should ensure that any item added specifically affects technology selection. Every organization has many issues that are important to them, but only include those where the definition could specifically affect the choice of a technology or design. Note that there are two opportunities in the process to identify goals and requirements that were not previously identified. The first is thorough evaluation of avoidance factors, which can uncover previously unidentified organizational or project-related goals or desires, and issue comparison analysis, which provides for comparison of other objectives not identified earlier.

- *End-Product* – Define the desired end-product or mix of end-products desired for the project. Typical end-products include electricity generation (such as firm or flexible), process heat (such as for district heating or industrial processes), cogeneration (that is, electricity and heat), other products (such as hydrogen production or desalination), or products from other missions. See Appendix A for more details on these end-products.
- *End-Product Rationale* – Describe the business case for the need, or desire, for the defined end-product. For a U.S. utility looking to fulfill a typical electrical mission, this would be equivalent to the “Purpose and Need” definition in NRC licensing documents (NRC, 2007b). For other missions, such as process heat or desalination, additional description might be needed, including a discussion of markets and other end-product needs, and includes items such as desired revenue generation and profit (see Appendix A for descriptions of various missions).
- *Required Output* – Identify and describe the required product output of the plant, based on its mission (for example, MWe, MWt, kg of hydrogen/day; see Appendix A for descriptions of various missions), that is required to meet the objectives of the end-product rationale. This is an important constraint and will be used as a specific exclusionary criterion throughout the process. Owner-operators looking to deploy a new nuclear facility are reminded of the option, with the advent of SMRs and microreactors, of deploying multiple smaller, more modular units to achieve the required output. Also, being able to be flexible and respond to grid changes might prove to be more beneficial for some missions, and depending on the local pricing models, could even be more financially beneficial.
- *Target Location of Plant (or Plants)* – Identify the target location of the future facility or facilities. For utility-based electrical generation, this might be based on service territory or could be a predefined choice (such as based on an ESP or targeting a defined location, such as next to an existing nuclear facility or as a fossil plant replacement). However, for other products, such as providing a direct electrical connection to a facility, providing process heat, or making hydrogen, the target location could be something different. Note that in some cases, the target locations could be a set of discrete pockets across the country. For example, the first reactor built for process heat for a petroleum company could potentially be sited at several facilities around the United States near existing refineries, the final choice being made based on factors such as cost or community acceptance.

If a specific site is identified, the characteristics of that site now become attributes of mission and business objective because any new plant must be compatible. As an example, if a site has been licensed in the United States under an NRC early site permit based on a PPE, now the PPE becomes an input to which criteria will be evaluated. In this case, it is likely that specific OEMs were consulted about their designs to develop the PPE and any of those would still likely be appropriate. But if enough time has gone by, new innovative technologies could now be on the market, the OEM could have changed their design, or the OEM or their design might no longer be available.

- *Service Requirements* – Identify and describe the service requirements for the plant. This includes items such as the need and priorities for flexible or firm generation, reliability, weather resiliency, and black-start capabilities. For non-electricity products such as process heat or hydrogen production, the identification of production schedules might be necessary. For example, if steam is the primary objective, perhaps more is needed during the day than at night; if steam heat is a byproduct of a primarily electrical generation plant, the maximum output that a client could take might need to be identified.
- *Operating Life* – The minimum as well as the desired operating life of the plant should be identified. These values would be based on a long-term understating of the product need as well as estimated times needed to recoup a desired return on investment (ROI). The minimum might be calculated as the ROI for a purely merchant activity but could be based on long-term energy planning for a regulated activity. The desired life should consider that innovative technologies will become available and that the costs to operate and maintain will increase as the facility and its equipment age.
- *Need Dates and Time Frames* – It is extremely important to identify the need date (if there is one), or perhaps more general time frames, for not only the in-service date, but also preceding milestones. If a specific need is not yet identified, a review of a utility's 20-year plan, for example, can provide guidance. For a non-electrical mission, a company's overall strategic plan can be reviewed. This is a good place to review company, state, and federal carbon reduction goals, requirements, and time frames. Other issues may drive need dates for different milestones, for example, construction might need to begin by a certain date to receive certain financial investments, or production might need to start by a certain date to receive tax credits. The need date is an important constraint and may be used as an exclusionary criterion throughout the process.
- *Target Budgets* – Identify the target budgets that the owner-operator is willing to take on for the project. These are normally reviewed as exclusionary criteria because, in general, any project that exceeds the budgets would be disqualified (unless the budgets are refined). The budgets should be expressed not as costs, but as true maximum budgets, of which projects that are expected to be under can continue and those that are over will need to be remediated, the budgets changed, or canceled. Budgeting can be a difficult process and might need to be iterated on as one moves through the assessment steps of this procedure. It is not uncommon to revise a budget when costs are determined to be higher than expected, but if that is done, the change should be described and defended. In early steps, the budgets might be based on simple criteria and information from long-term business plans, but by the end of the process, more detailed budgets are required. Owner-operators should ensure that budgets include the following costs broken down into at least these five groups:

  - *Exploration* – This includes all the preliminary engineering work, including items such as performing this technology assessment exercise. This effort is normally an internal organization exercise with a small team and a small portion of an organization's overall nuclear deployment costs. However, these efforts are often taken up before a full project is approved by management or, if needed, by a utilities commission as required for explicit project budgeting, financing, and cost recovery; therefore, available funding might be low.
  - *Engagement with Potential Suppliers* – This covers detailed engagement with potential suppliers post-exploration, through the development of an RFP and receipt of bids and a final agreement. It is important to note that the engagement with potential suppliers may include more than what is noted in the preceding but could, in the case of technologies with lower technology readiness levels (TRLs), include more explicit partnership and support through the design and early licensing process. For example, some early advanced reactor organizations will need financial support to finalize design and licensing. Owner-operators should clearly specify the budgets available for these activities. This input can be reviewed against exclusionary criteria, screening out technologies or designs that exceeded this budget.
  - *Facility Licensing* – This includes budgets for all activities related to the licensing of the specific plant(s) that the owner-operator is looking to build. In the United States, this would include the costs for an ESP, COL, CP, and/or OL, and included costs for engineering, site characterization, supplier engineering and support, and regulatory review costs.
  - *Construction* – This includes all costs related to construction activities for the plant. OCC is a common reference here, but that excludes the cost of financing, which has been shown by recent history to be a major contributor to total costs. The owner-operator should ensure that the budget accounts for both the OCC and financing, and that there is a clear understanding of the organization's risk tolerance, which should be plainly identified.
  - *Operations* – This includes all O&M and fuel budgets, any other fixed and variable operating costs, and includes the budgets for construction financing during operations.
- *Owner-Operator's Long-Term Goals* – The long-term goals of the owner-operator should be identified and described. For example, is the goal to build only one plant to meet a specific electrical capacity need or is there a longer-term plan to build out a fleet? Other examples include a goal to replace an entire fleet of retiring fossil plants or start a new nuclear program in a country where none currently exists. Other questions to ask are:
  - Is there an intent to expand the business, perhaps becoming a technology service provider or operator to other organizations?
  - Is there a desire or motivation (financial or otherwise) to be an early adopter and a technology leader?

- Is there a desire or willingness to partner with OEMs and supply chain providers to help define and refine the technology, or does the organization simply want to purchase a readily available product with minimum technical input?
- If long-term goals include fleet deployment, is there a need or desire for technology or design standardization, or is there an affinity for using different technologies or designs over time as technologies mature?

Note that some OEMs might offer only a limited portion of the plant, for example, only the nuclear island. Others might partner with AEs and other suppliers to offer a larger package. It is incumbent on the owner-operator and review team to ensure that they are comparing like-for-like systems, which might require the review team to seek out their own information from other suppliers. Also, it is possible that the bounds could expand or contract during the review, for example, only the nuclear island in Steps 1–3, and more of the plant in Steps 4–6.

Therefore, as part of their project objectives, the owner-operator might want to define the overall bounds (that is, SSCs) for which the assessment process will be performed. This report is intended to cover the major SSCs of a full nuclear plant producing electricity or heat. However, an owner-operator might want to limit their review to a smaller bounding envelope, such as the nuclear island only, or they may want to extend the bounds to include external systems not specifically covered herein, such as those for external product generation use in a hydrogen or desalination plant. For the former, the review team should carefully remove items from the criteria in Section 3 when developing their review plan; for the latter, the team will need to add their own criteria carefully.

As noted previously, it is of the utmost importance that the organization’s mission and business objectives be adequately defined and that all stakeholders have input into the process.

2.3 Criteria/Importance Weighting

In evaluating the inevitable tradeoffs between assessment criteria, it is necessary to assign a relative importance to each criterion in selecting a nuclear power technology; the relative importance should be reflected as a numerical weight value. In a simple example, if flexibility requirements are twice as important as the ability to provide constant firm power, the former criterion might be assigned a weight twice as large as that for the latter. Assignment of weights is a sensitive issue in studies because the opinions and value judgments about the relative importance of individual criteria vary with the perspectives of the individual stakeholder or group (such as the owner-operator, regulators, OEMs, and public interest groups).

After determination of the criterion weights, these normalized weights are multiplied by the utility scores (1–5) for each of the criterion-weight pairs and these products summed to get an overall weighted score (composite suitability value) for each design. These composite suitability values can then be used to rank or compare designs in terms of their overall suitability.

A possible variation on the use of a single consensus weighting for each criterion is the determination of separate technology rankings using the consensus weightings of various stakeholder groups. These groups and their resulting rankings can be brought together in an open, moderated group discussion to find common ground for an agreed-on identification of the top designs to be analyzed in Step 6.

Sensitivity studies using different criterion weight sets (thereby reflecting different viewpoints) can be conducted to assess their effect on the composite rating of a primary or alternative design and thereby lend additional credibility to the decision process.

There is a variety of methods for developing criterion weight values (for example, the nominal group technique, modified Delphi, and Kepner-Tregoe). Although detailed discussion of these techniques is beyond the scope of this report, a summary of one (the modified Delphi technique) is provided in the weighting workshop handbook in Appendix C of the EPRI *Siting Guide* (EPRI, 2015). Also, the Nuclear National Laboratory report *Addendum to NNL(11)11491—Review of Metrics Relevant to Reactor Systems* (NNL, 2012) has a good discussion on criteria definition and the rationale that they used for weighting factors.

2.4 Criterion Scoring

To evaluate the suitability of each primary and alternative technology in Step 6, each criterion is first evaluated independently (that is, not an ordered ranking). This evaluation is accomplished by defining a utility function that translates design characteristics into a common suitability scale expressing preferences for one technology over another. A typical suitability scale ranges from 1 to 5, where the scale value of 1 is the lowest level of suitability (least preferable) and the scale value of 5 is the highest (most preferable). An example of this utility function translation might be the number of staff needed to operate and maintain the plant under normal operating conditions (in which increasing preference is associated with decreasing staff). In this example, “x” staff (in number of people) could be assigned a suitability of 2, and “y” staff (where $y < x$) would be assigned a suitability of 3. Using this utility function, designs requiring “y” staff are preferred to those requiring “x.”

Many utility functions relate attributes to the suitability scale using a linear function. However, nonlinear functions are appropriate for other situations and would be defined based on the professional judgment of the discipline specialist. Functions can be continuous when the suitability attribute can be represented by a quantitative continuum or can be discrete when the suitability attribute is grouped into classes or groups and scored by the professional according to increased suitability. It is important for owner-operators to ensure that utility functions defined in their technology assessment plan accurately reflect the conditions and technical concerns unique to their technologies and designs of interest. Further discussions on criterion scoring as well as examples using several types of utility functions can be found in Appendix B of the EPRI *Siting Guide* (EPRI, 2015).

Note: Multiple criteria are defined in Section 3, and, in many cases, multiple attributes are noted for evaluation in each criterion. To keep the screening process as manageable as possible, only the top-level criterion is provided for “official” consideration and scoring. However, it is possible that one or more of the attributes can significantly drive the evaluation. For example, the failure of a single attribute to meet owner-operator requirements may, in effect, provide the basis for an exclusionary screening of the technology for that whole criterion. Or, in the case of suitability screening, a single attribute could lower the score of the entire criterion. The review team can approach evaluation of the attributes and subcriteria in two separate ways: the overall criterion could be based on the evaluation of the limiting attribute, or the evaluation could consider the overall combination (that is, an averaging). The choice made by the reviewer is ultimately based on the mission and business objectives of the owner-operator and could differ between individual criteria. In general, evaluations considered for suitability screening are more amiable to a collective score, whereas those used for pure exclusionary screening tend to favor consideration based on the most limiting factors. It is in the case of avoidance factors that a judgment call will most likely need to be made, with the results used as feedback to determine if modifications to the mission and business objectives should be made. In all cases, good documentation of the reviewer's justification for their decision making is important.

2.5 Technology Assessment Criteria

The criteria used in evaluating the suitability technologies and designs for a new nuclear power plant are listed in Table 2-1. A detailed description of the siting criteria and their application follows in Section 3.

As noted in Table 2-1, the various detailed criteria in Section 3 are aligned into five groups, based on the characteristics and issues addressed, as follows:

- Basic Operations
- Site Selection and Characterization
- Maturity and Remaining Effort
- Technology Capabilities
- Cost and Commercial Related Factors

These criterion groupings are further subdivided to enable separate consideration of the specific aspects of new plant development, as follows:

- *Basic Operations* highlights several important high-level, and likely exclusionary, criteria such as energy output, fuel selection, including storage and disposal, and operational requirements. Technologies and designs that do not meet these criteria would normally be excluded unless mission and business objectives are changed.
- *Site Selection and Characterization* identifies that state of site selection and characterization, surfacing factors that are important to technology assessment. In most cases, technology assessment and selection would be done in parallel and iteratively with site selection because the selected site will have measurable impacts on the assessment criteria for a technology, but, in turn, the final technologies must be suitable for the site. If a site is already chosen, a PPE can provide significant input into the assessment process. Conversely, if the technology assessment process is followed all the way through, including the selection of alternatives, the development effort for a PPE will be eased (see Section 1.5.3).
- *Maturity and Remaining Effort* are measures of the technical and nontechnical issues that affect risk to the project. From a technical perspective, this could include evaluation based on the common standard of technical readiness level (TRL) or from other methods for evaluating maturity—not only from the design perspective, but through the entire supply chain. From a nontechnical standpoint, this includes an evaluation of the OEM, suppliers, and the owner-operator's team themselves, for the skills, acumen, willingness, and financial wherewithal to meet the needs of the project.

- *Technology Capabilities* are the specific features of a nuclear plant that provide for safety, reliability, flexibility, resiliency, and efficiency, for not only operations, but also construction and ongoing maintenance. This is likely the most objective criteria for which data will be available.
- *Cost and Commercial Related Factors* include an evaluation of internal development and project management costs, costs supporting an OEM or suppliers through development and licensing (if applicable), site selection and licensing, construction and operating licensing, EPC costs, operations and maintenance (O&M) costs, fuel costs, and decommissioning costs.

Individual criteria are characterized in a three-tiered hierarchy of exclusionary, avoidance, and suitability factors, based on the severity of the constraints imposed by underlying requirements.

Exclusionary factors represent requirements that, if not satisfied by the technology conditions, would preclude nuclear plant development. Examples include technology characteristics that would not support the business objective requirements (such as electrical output in MWe or steam output temperature). Exclusionary factors are used to eliminate technologies based on consideration of go/no-go situations and are normally based on regulatory or plant design factors.

Avoidance factors have the same technology screening effect as exclusionary factors but are more flexible in their application. They are used to identify broad areas with more favorable than unfavorable conditions, for example, the TRL. Because the distinction between favorable and unfavorable areas is not well defined and can differ from one organization to another, applying avoidance factors can help ensure that the technology assessment approach is effective. For example, one of the goals of an effective approach is to strike a balance between having a sufficient number and diversity of potential designs for further study and having too many to practically consider in Step 6. This balance is achieved in Steps 3 and 5 by applying avoidance factors. If a suite of avoidance factors combined with exclusionary factors in Steps 3 and 5 results in too few or too many potential designs for use in Step 6, the application of the avoidance factors can be refined accordingly.

Finally, suitability factors represent characteristics that affect the relative suitability to business objectives or cost of development, but they do not represent unacceptable criteria, severe licensing problems, or excessive additional cost. Examples of criteria typically evaluated based on suitability factors are General Operations and Maintenance, Site Evaluation, Fueling, Refueling and Fuel-Handling Systems, Flexibility and Resiliency, and Commercial Considerations. The evaluation of designs with respect to suitability factors requires assessing tradeoffs among the various criteria, as described in Section 2.4.

Table 2-1 also identifies the typical level of screening activity for each step in the process (as defined in Section 3). Note that there are no specific requirements: more or less screening activity can be done at any step of the process. However, the following patterns should provide a reasonable level of effort for efficient and qualified results:

- Yes – there is typically a significant amount of robust screening activity
- No – there is generally no screening activity performed
- Limited – only a subset of the criterion’s attributes is normally evaluated
- If data are available – limited screening is done using data that can be easily identified

The individual assessment criteria covered in Section 3 can be applied as several factor types at various stages of the process. For example, the plant output might be applied as shown in Table 2-5.

Table 2-5
Example: applying the plant output criterion

Condition	Factor Type	Process Stage
Output in MWe meets requirements.	Exclusionary	Steps 3 and 5
Output in MWe meets requirements, but overall efficiency is low, or multiple units are required.	Avoidance	Steps 3 and 5
Output in MWe meets requirements, but steam temperature is too low for potential future, but not yet specifically defined, use as a heat source.	Suitability	Step 6

In the example in Table 2-5, the second row indicates that multiple units being required is an avoidance factor based on the owner-operator's hypothetical mission and business objectives. If the owner-operator had different drivers or constraints, the need for multiple units could have perhaps been regarded as a suitability factor instead.

2.6 Understanding and Managing Risk

The selection of a new technology or design for deployment inherently comes with significant risk. Although methods can be used to understand, manage, and perhaps limit this risk, ultimately, all the risk cannot be removed—there are just too many unknowns that could impact the project.

For the purposes of this report, it is useful to consider risk in the following three ways:

- *Selection risk* – This is the risk inherent in the process of selecting the "best" technology and design. The proper method for addressing and mitigating this risk is through:
  - *Rigorous use of this process* – This process does not cover all scenarios and issues. However, the owner-operator and review team will have a good foundation for decision-making if they follow the process; do their due diligence to address the criteria within by collecting data and information; and ask probing questions of their potential partners, suppliers, and themselves.
  - *Well-developed mission and business objective* – This cannot be overstated; improper or underdeveloped goals and objectives cannot lead to the most robust solution, and could lead to a solution that, in the end, is not a good fit for the owner-operator (see Section 2.2).
  - *Proper weighting factors* – These must be well considered and aligned with the organization's mission and business objectives. There might be a tendency to try to include risk in the assignment of weighting factors (that is, increasing the weighting for a criterion that is deemed a higher risk), but this is improper. Weighting factors are about understanding the importance of any criteria to meeting the mission and business objectives (see Section 2.3).

- *Pre-deployment risk* – This is the risk that a chosen technology or design will be available, licensable, technically capable, and have a supporting supply chain, for deployment on the schedule identified in the mission and business objectives. The proper method for addressing and mitigating this risk is through avoidance factors and criterion scoring:
    - *Avoidance factors* – These can be used to screen technologies and designs that, based on the criteria and in the view of the owner-operator, are too risky. Care should be taken because being too risk-averse could easily result in too few final designs for consideration (see Section 2.1).
    - *Suitability scoring* – This is the best place to account for this type of risk. A criterion that is considered to have a considerable risk for one technology or design should be scored lower than the same criterion for another design evaluated to carry a lesser risk (see Section 2.4).
- *Deployment risk* – This is the risk of the actual plant deployment (that is, construction and operations). This is inherently a financial risk and should be accounted for under cost and commercial related factors (see Section 3.5). Through performance of this assessment process, the owner-operator will have collected significant information to help better evaluate the schedule and cost of construction and operations.

  The development of a financial risk model is beyond the scope of this report. Most organizations with the financial capability to consider the deployment of a new nuclear plant likely have their own internal processes for evaluating the financial risk of large capital projects. If not, a report from Booz | Allen | Hamilton to the U.S. DOE, *Nuclear Mega Project Risk Analysis Model*, can provide insight (Booz, Allen, Hamilton, 2009).

Note: The owner-operator and review team should be aware that the risk management techniques described in this report as noted in the preceding do not quantify risk. This is especially true for selection 3.1 and pre-deployment risk, of which the tools and guidance herein provide only risk reduction techniques. Financial risk analysis tools for deployment risk can be used to provide quantitative risk evaluation, but those tools are beyond the scope of this report.

3
ASSESSMENT CRITERIA

This section provides a detailed description of each technology assessment criterion and its application in the process. These criteria descriptions have been designed to be generic so that they can be applied to technology selection for any new nuclear plant. Depending on the availability of data for the technologies and designs under consideration, some customization of criteria and utility functions might be appropriate for specific projects, and some criteria might not be applicable for some technologies (for example, some technologies might not have features or functions that are impacted by a criterion).

Each owner-operator should review the material in this report, their own business objectives, and the design features and regulatory status of the various technologies as the first steps in the assessment process. Based on this review, the owner-operator will be able to design a detailed assessment plan that details both the process steps and the criteria to be used in evaluating various technologies and designs.

As stated in Section 1, one objective of the technology selection process is to ensure that the selected technology satisfies applicable technical suitability requirements, those established by the owner-operator as well as those promulgated by relevant regulators or other external stakeholders. Technologies and designs not capable of meeting these requirements cannot (generally) be considered for a new nuclear plant, and some technologies or designs might be considered more favorable than others because they provide additional margin in meeting these requirements (for example, one technology may provide more flexibility options than another).

It is important to understand that depending on the owner-operator's business objectives, some requirements can likely be modified, tabled, or converted into wants. This can be particularly true if the owner-operator's business objectives include the pursuit of less mature technologies. For example, to deploy a nuclear reactor, it will be required that the design be licensed in some manner. An owner-operator could have an exclusionary requirement that a design must have a license, such as an NRC Design Certification (DC). Alternatively, they could choose to consider licensing status through a suitability utility function, with a DC receiving a score of 5, a DC application a score of 4, and an evaluation of licensability scaled from 1 to 3.

Individual criterion discussions are organized by the relevant process steps identified in Section 2, so that criterion descriptions reflect the level of detail needed at each step.

Candidate Technologies – In this stage of the process, the technologies of interest are screened using criteria with exclusionary and avoidance factors to eliminate unfavorable technologies and to identify candidates that will be canvassed in the next step to identify potential designs. Criteria for which data are generally available to support this early screening are identified in Table 2-1.

Because the evaluation at this point is based on general technologies, not specific designs, and generally public summary data, it might be possible for one specific design under a technology to meet goals and another to not. Therefore, targeting output ranges instead of specific numbers and using relaxed avoidance factors in this step are appropriate because additional and more specific screening will be completed later.

Candidate Designs – In this stage of the process, the potential designs are screened using criteria with exclusionary and avoidance factors to eliminate unfavorable designs and to identify candidates that will be canvassed in the next step to identify proposed and alternative designs. Criteria for which data are generally available to support this mid-level screening are identified.

Because the evaluation at this point is based on more specific designs for which more information and data are available, more specific attribute targets are warranted. However, at this point, information and data would still be largely publicly available or gained through early conversations with OEMs. Obtaining the data and information needed at this stage could require nondisclosure agreements with the subject OEMs. However, this should not be a deterrent—erring on the side of inclusivity in this step is important because additional, more specific screening will be completed later.

Proposed and Alternative Designs – This section of each criterion description provides the full level of detail for application of each criterion. Typically, all, or almost all criteria are used at this stage of the analysis, using the most detailed design information available via direct and specific engagement with OEMs so that the selection of proposed and alternative designs is supported by the most current, accurate information available.

This step of the decision process for selecting a proposed and multiple alternative designs from the candidates includes not only an algorithmic rating/weighting/ranking process, but also an issue-by-issue evaluation of the advantages and disadvantages of sites under consideration. Accordingly, individual criteria are not discussed in the context of issue evaluation. Owner-operators might wish to use previously developed ratings at this stage and/or develop additional detail on issues reflected in the evaluation criteria.

Once the candidate designs have been scored and ranked, the process of selecting a proposed design is unique to the owner-operator's business plan for the new nuclear plant, existing knowledge of the designs under consideration, level of confidence required to make a management decision on a proposed design, and the characteristics of the candidate designs.

Whereas previously executed steps in the selection process use discrete criteria for exclusion purposes, a comparison of candidate designs typically takes on a more issue-based focus. Accordingly, the decision-making process becomes one of balancing (often unquantifiable) relative advantages, disadvantages, and risks associated with the candidate designs. Issues such as reliability, uncertainty, regulatory acceptance, public acceptance, and the overall level of risk to the project's purpose and need factor into these evaluations.

Because they have not been subject to previous nuclear plant development, these considerations become especially important in the consideration of new or untested designs; owner-operators need to be confident that they can ultimately demonstrate that their proposed design is licensable and deployable.

3.1 Basic Operations

Basic operations criteria include fundamental, top-level, technical, and operational attributes that generally must align with the owner-operator's mission and business objectives. The criteria listed in Sections 3.1.1–3.1.4 are purposely not identified in an exact one-to-one orientation with the mission and business objectives as defined in Step 1 (Sections 2.1.1 and 2.2). They are instead high-level topics that should be evaluated with respect to their alignment with the mission and business objectives (that is, do they, or can they, coincide with and support the goals of the organization and new plant development project?).

As an example, the type of fuel used, the design of fuel-handling equipment, and specific used fuel disposal methods are not likely part of any owner-operator's mission and business objectives, but they can go to costs, ease of use, alignment with existing expertise, desire to be a leader, and regulatory requirements. The owner-operator will want to evaluate the criteria and ask probing questions to verify that their objectives can be nominally met, and if so, to what extent.

Some of the topics in this section are evaluated in much more detail, often with a slightly distinct perspective, in later sections. This is by design; these topics in Section 3.1 are intended to be evaluated at a high level, particularly where exclusionary or avoidance determinations can be made easily or early in the process.

3.1.1 Plant Energy Output

Plant Energy Output is a measure of the output of the plant from an energy perspective but in a form that meets the mission and business objectives. At its simplest, for a firm power electricity mission, this could be nothing more that size in MWe. For other missions, such as producing process heat, which could in turn be used for producing other products such a hydrogen, heat output in MWt might be the appropriate measure. However, there are other considerations that could (and perhaps should) be evaluated based on the plant's mission. Typical energy output attributes would include:

- *Nominal Energy Output* – Electrical, thermal, or both, depending on mission. For thermal missions, this might include the grade of heat (such as the degree of saturation or extent of superheat for steam, or simply hot water or another thermal fluid).
- *Nominal Product Output* – An optional criterion for the product generated for missions other than electricity or heat (such as kg of hydrogen/day), if part of the assessment bounds (see Section 2.2).
- *Number of Units or Modules* – If multiple units or modules are needed to meet the required energy output.
- *Energy Efficiency* – At its simplest, this is the energy produced per unit of fuel. However, depending on the ultimate application, the need for operating flexibility, or the end-product, this could also include heat rates and the heat rate efficiency across the range of operations.

- *Minimum and Maximum Output* – The minimum amount of energy the plant can supply and still operate effectively, as well as the maximum if peaking is needed.
- *Ramp Rates* – Rates for increasing or decreasing production to generate energy flexibly to meet demand as needed. This is intended to be a high-level evaluation of basic flexibility early in the process. A more detailed evaluation will be done according to Section 3.4.4 in Step 6.

Although the subattributes noted in the preceding are discrete, for the purposes of criterion evaluation, they are considered in aggregate. For exclusionary screening (Steps 3 and 5), failure of any one of the attributes to meet goals would indicate exclusion for the overall criterion. Unlike the other bullets that can easily be based on exclusion factors, the evaluation for the number of units or modules would likely be based on avoidance factors, depending on the owner-operator's mission and business objectives. For suitability screening (Step 6), a defined utility function could incorporate all attributes.

Candidate Technologies – Plant energy output is normally included in the exclusionary screening performed in Step 3. Technologies that **clearly** do not meet requirements would be excluded. Note that several potential AR technologies allow for multiple units or modules that, if considered, can change the evaluation and might allow for potential inclusion where a single unit or module might be excluded.

Candidate Designs – Plant energy output is normally included in the exclusionary screening performed in Step 5. Designs that **clearly** do not meet requirements would be excluded. Note that several potential AR designs allow for multiple units or modules that, if considered, can change the evaluation and might allow for potential inclusion where a single unit or module might be excluded.

Proposed and Alternative Designs – Plant energy output is included in the suitability screening performed in Step 6. At this point in the process, the subattributes would be included in a utility function analysis. This could be in the form of a simple "overall rating," or the function could include a more detailed calculation.

3.1.2 General O&M

The *General O&M* criterion includes two top-level attributes related to the number of personnel on site and O&M practices.

- *Number of People On-Site* – the number of people on site during operations
  - *Standard O&M* – the number of people needed to operate and maintain the plant on a day-to-day basis, excluding outages (planned or unplanned)
  - *Outage O&M* – the number of people on site to perform a planned refueling or maintenance outage

- *Planned Availability* – This is the amount of time that the plant will be available for production of electricity or other services. It is a function of all normal operating time, accounting for:
  - *Refuel Outage Period and Outage Time* – This is the period, normally in months or years, between refueling outages (if online refueling is not an option). Assuming that there is a refueling outage, this would include the critical path refueling time.
  - *Maintenance Outage Period and Outage Time* – This attribute represents any time needed for scheduled maintenance outages that might be necessary and that do not fit within a refueling outage window.
  - *On-Line Maintenance* – This covers the capabilities, complexity, and risk for performing on-line maintenance, if such maintenance is needed. A review of this attribute includes issues around both planned and unplanned maintenance.

Candidate Technologies – Because these attributes tend to be design-specific, this criterion is not normally evaluated in Step 3's screening for candidate technologies.

Candidate Designs – Because there are generally no specific right or wrong values for these attributes, and because any evaluation will need to be based on the owner-operator's mission and business objectives, this criterion is not normally reviewed in Step 5's screening for candidate designs.

Proposed and Alternative Designs – General operations is included in the suitability screening performed in Step 6. At this point in the process, the subattributes would be included in a utility function analysis. This could be in the form of a simple overall rating, or the function could include a more detailed calculation. In Step 6, this evaluation will likely consider various tradeoffs and alignment with the mission and business objectives.

3.1.3 Fuel and Used Fuel Management

This section covers two related criteria—fuel selection and used fuel storage and disposal. Whereas these two criteria are covered in detail in Sections 3.3 and 3.4, they are covered at a high level here for two reasons:

- Many ARs will be using novel fuels and fuel designs that will impose different fabrication, procurement, storage, handling, and waste disposal requirements from those well established for LWRs.
- An owner-operator will want to vet these considerations against their mission and business objectives as early as possible in their evaluation to include or exclude novel technologies and designs prior to detailed assessment in step 6, where the criteria in Sections 3.3 and 3.4 are nominally evaluated.

Therefore, it is generally intended that Sections 3.1.3.1 and 3.1.3.2, "Fuel Selection" and "Used Fuel Storage and Disposal," be evaluated only in Steps 3 and 5, and that the detailed evaluation take place in Sections 3.3 and 3.4 during Step 6.

3.1.3.1 Fuel Selection

Fuel selection includes an evaluation of the type of fuel that the plant will be using, including its mechanical design and license status, and its current or future availability. Fuel selection is generally evaluated against factors that affect the fuel's availability, either through regulations or unsolved technical issues, and the ability to be easily handled during operations. Typical fuel selection attributes would include:

- *Enrichment* –The fuel enrichment needed (or useable) by specific technology or design. It is typically expressed as a percent of U^{235} but for ARs could be identified as a different isotope.
- *Fuel Form* – The mechanical fuel form (which, in this case, includes liquid fuels) and the ease or complexity of fuel handling during operations, which could require more novel approaches.
- *License Status* – The current license state for the fuel or, more importantly, for unlicensed fuels, an evaluation of the time and resources needed to license the fuel.
- *Availability* – An identification and evaluation of the capability to obtain enough fuel to start and operate the plant over its lifetime, which could include an evaluation of not only licensing, but manufacturing complexity, capability and capacity, and ability to obtain materials internationally (and other import/export control issues).

Candidate Technologies – Fuel selection is normally included in the exclusionary screening performed in Step 3. Technologies that **clearly** do not meet requirements would be excluded. However, in this step, exclusion would typically be based on regulatory constraints prohibiting use or time constraints that do not meet the owner-operator's mission and business objectives.

Candidate Designs – Fuel selection is normally included in the exclusionary screening performed in Step 5. Technologies that **clearly** do not meet requirements would be excluded. However, in this step, exclusion would typically be based on regulatory constraints prohibiting use or time constraints that do not meet the owner-operator's mission and business objectives. Information gathered in Step 3 might be adequate for screening candidate designs, requiring minimal additional data, and information gathering.

Proposed and Alternative Designs – Fuel selection as noted in this criterion is not normally evaluated in Step 6; instead, the criteria identified in Sections 3.3.1.5 and 3.4.5 would be evaluated in much more detail.

3.1.3.2 Used Fuel Storage and Disposal

Used Fuel and Disposal evaluates the regulatory requirements, operational impacts, and available disposal (or reprocessing) pathways. Although congruent with selection (Section 3.1.3.1), proliferation resistance and physical protection (PR&PP) concerns are also considered here. As noted in *Owner-Operator Requirements Guide (ORG) for Advanced Reactors, Revision 1* (EPRI, 2019b) in the Waste and Used Fuel Management policy, both the OEM designer and the owner-operator should:

- Not assume the availability of off-site facilities for used fuel storage
- Not assume any outside entity taking possession of used fuel during the life of the plant to allow for continued operation of the reactor

Also, the ORG states:

> The criterion for on-site storage of used fuel reflects the importance of decoupling reactor operations, including waste management, from external factors such as availability of off-site interim storage and permanent disposal facilities.

Several attributes are covered under this one criterion:

- *On-Site Storage* – The requirements for fuel pool or other on-site storage (or the equivalent based on the fuel form), which might require more novel approaches.
- *Interim Off-Site Storage* – If interim off-site storage is available, the capacity requirements for fuel pool or other on-site storage (or equivalent) could be reduced. As noted in the ORG, off-site storage should not be assumed, but the viability of off-site storage can differ in different locales.
- *Ultimate Disposal (or Reprocessing)* – If an ultimate disposal repository (or reprocessing) is available, the capacity requirements for the fuel pool, on-site storage, and interim off-site storage (or their equivalents) could be reduced. As noted in the ORG, off-site disposal and reprocessing should not be assumed, but the viability of these options can differ in different locales. The global experience for handling the fuel form across its lifetime should be considered.
- *PR&PP* – The EPRI ORG Threat Protection policy notes that the plant must protect against internal and external physical threats. In addition, the ORG Tier I requirement, Physical Protection and Proliferation Resistance, notes that the plant must have and maintain both physical and administrative controls to prevent against sabotage and theft and to ensure that nuclear materials are controlled and accounted for to impede their diversion or misuse. The intent of this attribute is to evaluate it at a high level based on the reactor technology, fuel types, and general design. A more detailed evaluation will be considered in Section 3.4.6.

Candidate Technologies – Because most of these attributes under this criterion are design-specific, they are not normally evaluated for candidate technologies, with one exception being proliferation resistance and physical protection, centered primarily on the fuel form. For this specific attribute, there are a few key questions to ask (University of Manchester, 2016):

- Does the fuel cycle involve the production of high-grade fissile materials at any stage?
- Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal?
- Are the nuclear materials produced in the fuel cycle difficult to access?

As examples, high-temperature gas reactor (HTGR) fuel is difficult to break down, making it difficult to access the fissile material. By contrast, the fissile material in a liquid fuel molten salt reactor (MSR) is relatively easily separated by reprocessing.

Owner-operators constrained by laws or regulations should evaluate candidate technologies on a specific exclusionary basis. If there is significant uncertainty in how to manage these concerns or any other attributes, they can be excluded on an avoidance basis. (For example, an owner-operator might prefer not to engage with a specific fuel design due to its perceived complexity and risk.)

Candidate Designs – Although the issues around used fuel storage and disposal are design-specific, this criterion is not normally evaluated in Step 5. Designs can be excluded if they do not meet requirements, but it is unlikely that any viable OEM design would not meet the basic minimum requirements; issues based on the overall technology will have been addressed when evaluating candidate technologies. However, avoidance factors can be reviewed at this stage.

Proposed and Alternative Designs – Used Fuel Storage and Disposal as noted in this criterion is not normally evaluated in Step 6. Instead, the criteria identified in Sections 3.4.5 and 3.4.6 would be evaluated in much more detail.

3.1.4 Good Neighbor

It is important that any nuclear plant be a "good neighbor" in the community in which it sits. As noted in the EPRI ORG (EPRI, 2019b), a new nuclear plant should:

> Provide an overall benefit to the surrounding community through protection of the environment and other benefits, while providing a dependable source of economic well-being. The design and siting of the reactor should consider the needs and objectives (economic, social, etc.) specific to the community in which the reactor is deployed.

And as noted in *Advanced Nuclear Technology: Advanced Light Water Reactor Utility Requirements Document, R13* (the URD) (EPRI, 2014), any new nuclear plant should have minimal impact on the surrounding environment and community by minimizing radioactive and chemical releases.

The good-neighbor criterion is effectively a measure of how the individual SSCs, along with construction process, ongoing O&M, and even future decommissioning, can impact the local community. This criterion is a combination of several discrete issues, many of which might be covered technically in other criteria below, and more specifically, when performing a siting review (EPRI, 2015). The purpose of this criterion is to focus the review on the impact to the local community, including the people and ecology, and other considerations for economic and environmental justice.

Candidate Technologies – The good-neighbor criterion is dependent on specific design and implementation attributes and therefore is not normally evaluated for candidate technologies.

Candidate Designs – OEMs are generally aware of the need that their offerings be considered as good neighbors for them to be of value to owner-operators. Therefore, it is normally assumed that any viable OEM design would meet the minimum requirements for this criterion; it is not normally evaluated for candidate designs.

Proposed and Alternative Designs – The good-neighbor criterion is most appropriately evaluated based on suitability. It is expected that any viable OEM design would meet the minimum requirements, so it is appropriate to evaluate this criterion based on a utility function or scaling factor.

Note: If a design does not appear to meet the minimum requirements of a good-neighbor policy on any basis, it should be excluded or more due diligence done by the owner-operator to understand the design and its details.

3.2 Site Selection and Characterization

Site selection and characterization identifies the status of any site selection and associated characterization, surfacing factors that are important to technology assessment. The relationship between site selection and technology selection can become intertwined and confusing. On one hand, having an identified target site can speed the technology selection process because the properties of the site will provide constraints on technology selection that will likely provide for clear exclusionary evaluations of some criteria. On the other hand, identifying a specific design before site selection can speed the site selection process in the same way. A key point regarding these two scenarios is that although the process might have been streamlined, the result is likely to be less than optimal. If the overall process between site and technology selection is performed in an iterative, systems-engineering-style analysis, optimizations can be made that might provide a better solution.

With the preceding noted, there are examples for which identifying a target site first could make sense. For example, an electrical utility with a known need for increased generation capacity might already own viable property, such as land next to an existing nuclear plant or the site of a retiring coal plant—in both cases, near transmission lines and reliable sources of cooling water.

Similarly, there are good examples where identifying a technology or specific design first could make sense, such as a nation-state starting a nuclear program to deploy several reactors across the country over the next several years to support rural electrification goals. Although sites have not yet been identified, the selection of a single design for deployment could make sense overall for O&M purposes.

If a site is already chosen, it might have a PPE defined specifying criteria that can be used to evaluate designs. An SPP developed by an OEM can provide significant input into the assessment process, verifying whether a design can be used on the identified site. Conversely, if the technology assessment process is followed all the way through, including the selection of alternatives, the development effort for a PPE will be eased.

The reality is that most cases will follow the path of an iterative process, with the technology assessment and selection completed in parallel with site selection. This is because the selected site will have measurable impacts on the assessment criteria for a technology, but in turn, the final technologies must be suitable for the site.

The EPRI *Siting Guide* (EPRI, 2015) provides a detailed process (on which this process is based) for identifying appropriate sites. It is not explicitly noted in the Siting Guide as a formal step in the process, but the Siting Guide does assume that the organization has evaluated and understands their mission and business objectives for the process. The criteria and resulting information developed in Step 1 (see Sections 2.1.1 and 2.2) can easily be used by both processes and is indeed used as a basis for criterion analysis in both cases.

Unlike the assessment criteria evaluations done in other portions of this report, the siting criteria evaluations are a bit unique in that they can vary based on the status of site selection. If a site is defined, there are clear criteria that must be met; if not, the criteria might be open-ended or perhaps not applicable. Likely, as an iterative process is performed, the situation will swing back and forth as analysis is completed.

Therefore, the criteria and attributes presented in the following, and how they will be evaluated, are left largely to the owner-operator to define under their own circumstances. It is highly recommended that more time and attention be invested in the development of weighting factors and scoring utility functions for the items in this section.

If a target site (or sites) is identified, the specific known attributes of that site should be clearly identified, documented, and used in the evaluation of the site characteristics criterion below. See the EPRI *Siting Guide* for a detailed description of site characterization.

If no specific target site is identified, the owner-operator might want to ensure that their business objectives include any required criteria. For example, a utility might note that they have several fossil plants retiring, and although no sites are specifically identified, their goal is to potentially site a new nuclear unit on one of those sites. Owner-operators can find that if a large site is not already identified, available land may be limited in their target location(s), limiting the available site size and potentially the access to resources such as cooling water; therefore, the technology choices could be limited.

3.2.1 Site Evaluation

Owner-operators are directed to the EPRI *Siting Guide* for in-depth descriptions of the characteristics and attributes important to siting a new nuclear power plant. The criteria and attributes presented here are identified as being those most related to technology and design selection considerations, presented from the point of view of plant requirements or capabilities. If a target site is identified, the evaluation would be based on the ability to meet site requirements. However, if a site is not identified, the evaluation would be based on the ability to meet the owner-operator’s business objectives while complying with all federal, state, and local requirements, regulations, and laws. When identifying a technology, owner-operators should consider that local communities might have preferences for different technologies potentially being sited nearby and include that in their evaluation. As a minimum, the review team should consider the following siting attributes when evaluating this criterion:

- *End-Product Transmission* – an assessment of the capability for the nuclear technology or design to transmit its end-product from the site to the end-user. Do the mission and business objectives, along with the plant capability, support the needed transmission distance?
- *Land Use* – an evaluation of the land required to site the plant, compared against any known limitations. Smaller reactors will take less land, but at the same time, multiple smaller reactors could be placed on the same site.
- *Seismic Requirements* – an evaluation of seismic capability. If a site is identified, this would be to ensure that the design fits in the site’s seismic profile. If a site is not identified, this would be an evaluation of the design’s ability to meet a minimum profile.
- *Water Requirements* – an evaluation of water needs, if needed by the design, with respect to any potential site’s ability to provide it. This includes all water needs, such as cooling water, service water, fire water, demineralized water, and fresh water, as well as the ability to obtain water rights.

- *Discharge Requirements* – an evaluation of all potential discharges from the plant. This includes cooling water discharges and related thermal effects as well as any other liquid or gaseous discharges that could contain chemical or radioactive contaminants.
- *Flood Resistance* – an evaluation of the capability to be deployed in areas prone to flooding and safely operate, or at least safely shut down if flooded.
- *Extreme Weather Conditions* – an evaluation of the capability, if needed, to operate in extreme cold, heat, wind, precipitation, or other extreme weather conditions.
- *Population* – an evaluation of the capability to be deployed in denser population areas. Note that in the United States, the NRC is evaluating the ability to deploy ARs in denser population areas; however, as of publication, the requirements and guidance are not yet completed (NRC, 2022).
- *EPZ Size* – an evaluation of the plant's capability to support a reduced-size EPZ.
- *Ecological Criteria* – an evaluation of the plant's potential impact on the ecology. Unless a site is specifically identified, this would primarily be an evaluation of impacts due to construction, overall potential land use, and impacts to waterways.
- *Engineering and Construction Requirements* – an evaluation of the engineering and construction effort needed to deploy a plant. This would include an evaluation of the ability to do so on an existing site (for example, deploying a design that requires deep embedment in a low-lying area) or perhaps the potential costs for engineering and construction of novel systems (such as air cooling).
- *Infrastructure for Construction and Operations* – an evaluation of the existing and potentially needed infrastructure for construction and operations. This would include transportation infrastructure, such as road, rail, and waterway access, and labor availability.

The status of site selection and characterization can be varied, with the possibilities including:

- *No sites or regions selected* – This would be uncommon because most organizations will have some sense of where they want to deploy a new plant. However, this might be the case if performing an exploratory exercise, in which case, this criterion should be skipped.
- *Regional areas identified* – Examples might include a utility's entire service area, remote northern areas, a dry desert area, or a resource-constrained island chain. Although specific sites have not been characterized, important constraints can be understood, such as the need to operating in extreme weather, potential availability of water, and general seismic conditions.

- *Targeted sites identified* – This could include candidate and potential sites identified through the EPRI *Siting Guide* process, or perhaps desired sites such as a series of fossil plant replacements. If the Siting Guide process has been followed, a significant amount of characterization data should be available to support the technology assessment. If sites are only identified, much of the preceding information should still be available with reasonable effort.
- *Identified and characterized site (or sites)* – A fully identified and characterized site will provide constraints for the technology assessment that can easily be evaluated on an exclusionary or suitability basis.

Candidate Technologies – Unless a specific site is identified that clearly excludes a technology, this criterion is not normally evaluated as in Step 3. If a site is identified, the only attributes likely to prove exclusionary from a technology perspective are land use. However, use caution because most technologies come in many sizes.

Candidate Designs – Some of the attributes under this criterion are design-specific, and several can be evaluated on an exclusionary or avoidance basis, depending on the status of site selection or mission and business objectives. For example, a design that requires substantial amounts of cooling water might be excluded for deployment in desert environments, whereas a design that uses dry cooling would not.

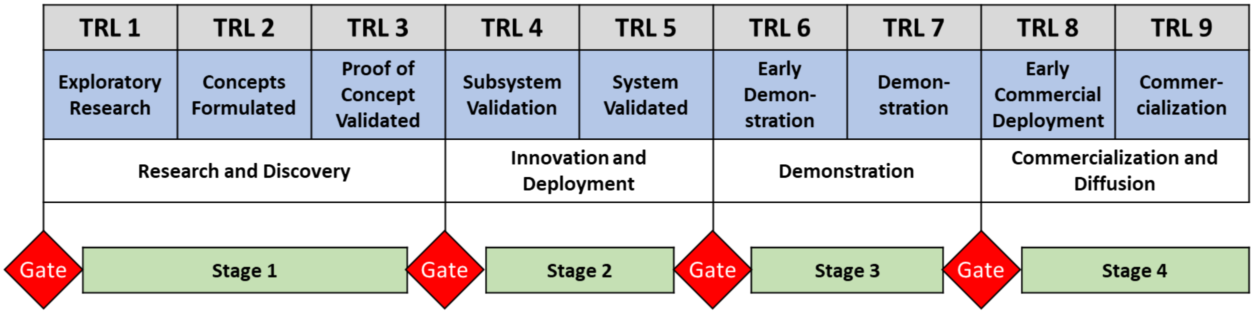
Proposed and Alternative Designs – Although some of the attributes under this criterion can be treated as exclusionary, such as a plant's ability to meet seismic requirements, others, such as engineering and construction requirements, are likely best evaluated based on suitability in Step 6. At this point in the process, the subattributes would be included in a utility function analysis. This could be in the form of a simple overall rating, or the function could include a more detailed calculation.

3.3 Maturity and Remaining Effort

Maturity and *remaining effort* are measures of technical and nontechnical issues that affect risk to the project. The two terms can be considered as two sides of the same coin. Maturity is a measure or description of the current state, whereas the remaining effort provides a gauge on the resources needed and timing. This difference is important because the two concepts, although loosely tied, can also be quite independent of each other.

Maturity describes the current level of completeness, qualification, or suitability for adequately meeting requirements or goals. *Remaining effort* describes the time and activities needed to meet a desired maturity level. As a simple example, consider the design, engineering, and qualification for a component that is 50% complete; that would be a measure of its maturity. Its remaining effort is a measure of the outstanding design, engineering, qualification, and testing needed to move to 100% complete, including the time to complete those activities. Both concepts must be understood because the time it takes to increase the maturity from one level to another is not necessarily dependent on the maturity level, but instead on the activities required.

One of the most common methods used to measure maturity, particularly technical maturity, is the TRL. The concept was initially conceived by the U.S. National Aeronautics and Space Administration but is often used by the U.S. Department of Defense (DOD) and the DOE (including DOE-NE). A previous review of literature showed no fewer than 16 different scales for measuring TRL. EPRI synthesized those into a proposed TRL scale suitable for ARs, as shown in Figure 3-1 and defined in *Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability* (EPRI, 2017).



TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Exploratory Research	Concepts Formulated	Proof of Concept Validated	Subsystem Validation	System Validated	Early Demon-stration	Demon-stration	Early Commercial Deployment	Commer-cialization
Research and Discovery			Innovation and Deployment		Demonstration		Commercialization and Diffusion	

Figure 3-1
TRLs and development stages

The methods used to determine the TRL of any system, structure, component, process, or overall design are beyond the scope of this report. Readers are directed to the EPRI report (EPRI, 2017) for a description of the TRL scale and its underlying elements, as well as *Program on Technology Innovation: EPRI Framework for Assessment of Nuclear Fuel Cycle Options* (EPRI, 2013) for a technology readiness assessment process.

As can be seen from Figure 3-1, an evaluation can be completed to identify that a subject reactor design is, for example, at TRL 6, Early Demonstration. However, this does not provide any information on what is needed in the form of effort (financial resources, labor, and time) to get to the desired state of TRL 9, Commercialization. This remaining effort evaluation must be approached separately, and after the maturity evaluation. The determination of maturity, particularly as a TRL, has a unique process to follow, but the determination of effort is, from a process perspective, a relatively simple project budgeting and estimating endeavor, albeit with considerable uncertainty.

For owner-operators assessing technologies and designs for potential deployment, the evaluation of maturity and remaining effort are crucial and dependent on the mission and business objectives defined in Step 1 of the process, particularly those around need date, time frames, and long-term goals. For example, if the mission and business objectives indicate an urgent need and there are no long-term goals beyond deployment of a single plant to meet generation needs, perhaps only those designs evaluated to be at high TRL would be acceptable. If the time to deployment is a bit longer and the long-term goals include multiple deployments and a desire to be a technical leader, perhaps those designs evaluated at a lower or mid-range TRL would be acceptable, but they would still need an effort evaluation to determine if the resources and time required meet the organization's goals. If the goal is a long-term plan (for example, for a utility or country developing the plan for their overall nuclear program), the evaluation might include two or more time frames. In this case, it is recommended that different time frames be treated separately (that is, creating two or more sets of business objectives and working the assessment process separately for each).

The maturity and remaining effort evaluations will take place not only from a technical basis, but a nontechnical basis as well. Although concepts such as TRL are normally used to measure technical maturity, the overall idea can be used to evaluate manufacturing readiness as well as organizational readiness. The manufacturing readiness level (MRL) (Wikipedia, 2021) is a measure developed by the DOD to assess the maturity of manufacturing readiness, which can be used in an assessment of the general industry or, more specifically, the capabilities of possible suppliers, which is important to this process (U.S. DoD, 2018). Similarly, organizational readiness can be defined as the preparedness of an organization to take on a significant new project. It asks the question:

> Does the organization have the capability, or at least the willingness and resources, to obtain the capability, to accomplish its goals effectively (I.S. Partners, 2019)?

When evaluating the criteria in this section, the review team should assume that the technology will be adequate for its purpose **when** it is available. An evaluation of the technology based on **what** it is capable of will take place in Section 3.4. This difference is by design for two reasons: First, the information needed for the maturity and remaining effort evaluation is intended to be more readily available, thus allowing for screening in Steps 3 and 5 based on exclusionary and avoidance factors. This is based on the idea that if the technology will not be ready on time, it does not matter how good it will eventually be. Second, the information needed for the technology capabilities evaluation is quite detailed and likely not available until Step 6.

3.3.1 Design Maturity and Remaining Effort

Design Maturity and Remaining Effort is a key criterion for assessment because it includes for most prospective owner-operators highly weighted attributes. It is tempting to assess a single technology or design as whole. However, except for existing and commercially available OEM designs, it is not likely that all facets of the plant design are at the same maturity level or require the same effort, particularly time, to get to the desired state. Therefore, the various SSCs must be evaluated separately.

For the purposes of the assessment process defined in this report, it is not expected that all SSCs will be addressed, only the ones identified as major or critical path for timing. One might consider that the result for the overall design is based on the lowest common denominator of any SSCs, but that is not practical. SSCs with low maturity might be able to be moved up in level quickly with little effort. On the other hand, some single component, perhaps a sensor that is already commercially available in another industry, is nearly ready in all ways but needs a new material identified and qualified to meet temperature and corrosion requirements, which could take considerable time.

The EPRI ORG (EPRI, 2019b) states in its *Innovation and Proven Technology Policy* that:

> Innovative features will be used where justified to meet the mission but should be demonstrated where necessary prior to commercial deployment to reduce licensing and investment risk… [and that] … immature technologies should be used only where they provide a clear competitive advantage and manageable risk.

The maturity evaluation should include an understanding of the current state of the art and the level to which the identified (or planned) technologies have been researched, validated, and demonstrated (see TRLs, Figure 3-1). As noted in the ORG, there are cases where technologies used in other industries might be more advanced than those currently used in the nuclear industry. Although this may make them more mature from a technical perspective, their adoption for use in nuclear applications may take additional effort.

The remaining effort evaluation should include the design, engineering, testing and qualification, and demonstration work needed to move the maturity to the desired next level, which would typically be some level of commercialization, or perhaps demonstration, depending on the owner-operator's goals.

Both the maturity and remaining effort evaluations should be completed against the owner-operator's mission and business objectives, not against the promise of an overall technology or the specifications of the OEM's design. It is possible that these evaluations could reveal gaps between the owner-operator's requirements and the OEM's design that need to be accounted for. For example, consider an OEM that has selected a material that, based on research, validation, testing, and demonstration, is verified to their planned operating temperature (that is, at a commercial level), but the owner-operator's goals require a slightly higher temperature. In this case, the maturity might be set back a bit and effort required to move it forward again.

The SSCs identified in the following should be considered when performing this evaluation. These SSCs are taken from the EPRI URD (EPRI, 2014) and ORG, but not all major SSCs are represented because some are expected to differ little from what is already commercially available. There are several technologies and novel AR designs moving forward globally. It is important that the owner-operator understand the makeup of the systems that might have features and SSCs that differ from LWRs. It is incumbent on the owner-operator to ensure that all relevant SSCs are evaluated.

Unless otherwise noted, the criteria in the following sections should be evaluated:

Candidate Technologies – The design maturity and remaining effort criteria are generally not evaluated when evaluating technologies in Step 3, except for an exclusionary screen where the needed time frames are too short for any technology that is not already (or very nearly) commercially available. The remaining effort is generally not evaluated at this step due to the effort and design-specific information required.

Candidate Designs – As with candidate technologies, candidate designs are generally not evaluated on remaining effort at this stage due to the effort and design-specific information required. Candidate designs can be screened on an exclusionary basis based on avoidance factors that may be present due to the maturity level. For example, an owner-operator may be willing and able to shepherd a design from demonstration to deployment but have no desire to participate in early R&D or validation.

Proposed and Alternative Designs – In Step 6, the detailed maturity and remaining effort assessments are completed using the most specific design information obtainable from the OEMs and likely require significant interaction to gather the right information. It is highly likely that the information will be incomplete, vague, or at risk of changing later. The review team will simply need to make their best estimates with the information available and account for risk. Because designs were eliminated based on any maturity avoidance factors in Step 5 and remaining effort is the critical factor, criteria evaluation based on maturity suitability factors is not necessary. Instead, the remaining effort is the critical attribute that should be evaluated for suitability based on developed utility functions (note that a detailed maturity assessment is still required as input into the remaining effort determination).

3.3.1.1 Design Completion

There is fairly clear evidence that the level of design completion has a direct impact on the outcome of a new reactor development project. For reference, see the World Nuclear Association's (WNA's) *Lesson-learning in Nuclear Construction Projects* (WNA, 2018), NEI's *Strategic Project Management Lessons Learned & Best Practices for New Nuclear Power Construction* (NEI, 2020), and IAEA's *Project Management in Nuclear Power Plant Construction: Guidelines and Experience* (IAEA, 2012). All things being perfect, any new reactor project would start with a plant that has been 100% designed and engineered. Historically, this has not been the case. In fact, even a fully designed plant will likely need some level of customization to align with its siting. (Note that some OEMs are looking at design concepts that could reduce this level of customization, but these concepts have not yet been fully tested; see the following sections.)

Currently, there are no known fully completed designs for more novel technologies and designs, such as ARs, and full designs are not specifically necessary. What is necessary is that the level of design completion be in alignment with the mission and business objectives, most importantly to those relating to timing, but also to those related to the level of support, partnership, and risk with which the owner-operator wishes to engage.

The WNA report notes the following four stages in the design and engineering of a nuclear power plant:

- *Conceptual* – adequate for developing a site license, such as an ESP in the United States
- *Preliminary* – adequate for obtaining a design license, such as a DC in the United States
- *Basic* – adequate for obtaining a construction license, such as a CP or COL in the United States
- *Detailed* – adequate for procurement activities and limited site work

Additionally, a forthcoming Plant Systems Design standard from the American Society of Mechanical Engineers (ASME) called "PSD-1" is intended to address the stages of design. PSD-1 also has four stages that loosely align with the preceding:

- *Preconceptual* – Design concepts based on mission and business analysis are complete
- *Conceptual* – Design of the overall plant functional concept is complete
- *Preliminary* – Design of allocated systems is complete
- *Final* – Design of products like components and construction materials is complete

Although the two concepts are similar, they have some differences. The WNA description is simple and does not contain much more detail than previously noted, but it does include all three legs of typical project management—scope, schedule, and cost—and is intended to include licensing status. On the other hand, PSD-1 is intended to be an extremely detailed design standard, typically developed in conjunction with the buyer. It is about the actual physical design, only includes the scope, and does not include licensing status. The review team might find that the WNA concept is better suited for early steps in the assessment process or early designs, and the PSD-1 concept better aligned for Step 6, when reviewing more mature designs, or when working with their final chosen development partners during actual development.

Note: The PSD-1 standard is expected to be completed in late 2023. However, those interested can contact the ASME Codes & Standards PSD Executive Committee or review a preliminary presentation by the chairperson of the committee (Hill, 2020).

An owner-operator should establish an understanding of the current design stage and evaluate whether it is adequate for the next activities that need to be completed. If it is not, what is needed to bring it into alignment? Finally, what is the overall remaining effort to get to the desired level for the project (which could differ from one project to another—for example, a demonstration reactor as compared to a commercial reactor)?

The review team might want to consider breaking the design into major systems to better understand the state of design completion. For example, a novel design might be only partially complete at the nuclear island level but expected to use a common and available balance-of-plant design that needs finalization only at the interface.

3.3.1.2 Reactor Systems

All plants, regardless of type, will have some type of reactor system meant to generate thermal power sufficient for the end-product needs, serve as a radioactive material boundary and possibly a pressure boundary, provide a flow path or other methods for coolant to remove heat generated under all operating conditions and remove decay heat after shutdown, and provide for control of reactor core reactivity.

When evaluating the maturity and remaining effort for reactor systems, the key areas for review include:

- *Materials* – use of new or unproven materials to support higher temperatures and coolants other than water (such as molten salts)
- *Fuel and Core Designs* – novel approaches for fuel, such as innovative fuel designs and in-reactor fuel arrangements, or use of liquid fuel
- *Reactivity Control* – different approaches for reactivity control (such as other than light water chemistry and control rods)
- *Reactor Coolant System* – the methods, forced or natural, for circulating the reactor coolant and transporting the heat to the power generation system (or other end-use system), either directly or through steam generators or other heat exchangers, as well as novel overpressure protection and coolant transport systems (if applicable)

3.3.1.3 Reactor Non-Safety Auxiliary Systems

This area typically encompasses several subsystems that might be included in all technologies or designs or might function in slightly different ways. Reviewers will need to understand the following features and functions of the technologies and designs under consideration:

- *Heat Exchanger System (as applicable)* – Typically, a steam generator in a PWR and not included in a BWR, but could be provided in other forms of heat exchange in advanced reactors.
- *Coolant Cleanup and Volume Control System* – Typically found in light water designs, but ARs might have equivalent systems. For example, an MSR or liquid fuel reactor will likely include systems with equivalent functions.
- *Process Sampling Systems* – Used to collect liquids and gases and transport them to sampling stations.
- *Reactor Shutdown Cooling System* – Provides normal (non-safety) reactor shutdown cooling.

When evaluating the maturity and remaining effort for reactor non-safety auxiliary systems, key areas for review include use of new or unproven materials to support higher temperatures and fluids other than water (such as molten salts) within the heat exchangers and other system components, and novel coolant cleanup and volume control systems, particularly those used to clean molten salt or liquid fuel technologies.

3.3.1.4 Engineered Safety Systems

Engineered safety systems are largely technology- and design-specific, with functions and systems that generally fall into the following two categories:

- *Core Damage Prevention* – Some AR technologies (for example, liquid fuel reactors) will not experience core damage in the traditional sense (that is, melting of the fuel resulting the release of radioactive material). However, depending on the technology and ultimate design, there could be other operationally similar failure scenarios that need to be prevented. Key functions and related systems for core damage prevention include (as applicable) those for safe shutdown, coolant inventory control, decay heat removal, reactivity control, and pressure control.
- *Accident Mitigation* – These functions can differ across technologies and designs based on postulated accidents and failure mechanisms, but the requirement to prevent release of radioactive fission products will exist nonetheless. Key functions and systems for accident mitigation include (as applicable) those for maintaining post-accident containment integrity (leakage prevention and testing, heat removal, isolation, combustible gas control) and fission product control (both inside and outside the primary containment).

For common PWR and BWR light water (and similar) designs, the maturity and remaining effort are generally well known. LwSMRs are taking some novel approaches to these functions and systems, but key issues, such as material compatibility and plant physics and operations, are well known and understood. However, for many new AR technologies and designs, a deeper investigation into these systems will be needed to understand their level of maturity and remaining effort needed.

3.3.1.5 Fuel, Refueling, and Fuel-Handling Systems

For common PWR and BWR light water (and similar) designs, the maturity and remaining effort of *Fueling, Refueling, and Fuel Handling Systems* are generally well known. In their novel approaches to these functions and systems, lwSMRs are generally targeting standard fuel designs; therefore, the major issues are well known and understood. However, new AR technologies and designs are using incredibly unique designs for fueling, refueling, and fuel-handling systems. The owner-operator will need to perform due diligence on these systems and related processes to understand their level of maturity and remaining effort needed.

For all practical purposes, each different reactor technology will have a different set of equipment, processes, and procedures for managing fuel. In general, though, all the following functions must be accounted for: receipt of new fuel, new fuel storage, fuel handling and inspection, spent fuel storage, reactor disassembly/assembly, cask handling, and preparation for spent fuel shipping (as applicable).

When evaluating the maturity and remaining effort for reactor fueling, refueling, and fuel-handling systems, key areas for review include:

- Use of new fuel designs and configurations
- Fuel form and design qualification
- New types of disassembly and fuel-handling equipment or significant use of robotics or automation
- Equipment and processes for handling non-light water coolants during refueling
- Chemical separation techniques for liquid fuel reactors
- Storage of novel geometries, fuel forms, or high assay fuel in casks, including qualification of fuel storage containers

Note that some potential fuel designs might be more resilient from a safety perspective, exhibiting novel features that reduce the need for safety-related SSCs for storage and cooling.

3.3.1.6 Other Systems or Critical Plath Components

The following SSCs should be included as criteria on an as-needed basis, depending on the technology or design.

- *Power Generation System* – Typically included only if not making use of a typical Rankine cycle turbine and condenser system (for example, Brayton cycle or critical CO_2 systems).
- *Plant Cooling System* – Typically included only when not using once-through cooling (not likely in the United States due to fish protection requirements (U.S. EPA, 2014)) or cooling towers (natural or forced draft). Although hybrid and air-cooling systems already exist commercially, these might be included for evaluation to ensure that their use meets the mission and business requirements.
- *Waste Processing Systems* – Typically included only for non-light water-based (or similar) systems. The waste processing systems for water-based reactors are well understood and commercially available, but those for many AR designs are not yet proven.

- *Control Rooms* – Due to increased digital systems and automation characteristics, new reactor designs are likely to have more novel control rooms, including new types of controls, displays, and human interface designs. Additionally, some designs may use single control rooms for multiple reactors and plan for fewer control room personnel than have been typically used. These innovative designs may require additional design, testing, and qualification for regulatory approval.
- *I&C Systems* – Due to the pace of digital technology and software development, modern plants might use novel technologies and designs that potentially push technical and regulatory boundaries. If so, these technologies and designs should be evaluated.
- *Shared Systems* – The deployment of multiple units on a single site, such as several SMRs, could result in several shared systems. Typically, these are straightforward and have few novel characteristics (that is, water systems). However, novel designs might use innovative shared systems for safety (or other important) functions, which could require additional review.
- *Non-Electric Loads* – The interaction of any non-electric loads (that is, hydrogen production or desalination, if applicable) and their impact on the plant should be evaluated because they can be at least a partial heat sink for the plant (see Appendix A). The design and control systems should be evaluated for their overall maturity.
- *Other SSCs* – Depending on the technology or design under consideration, there might be other relevant but novel SSCs that should be included for evaluation. For example, novel technologies could require different methods for fire protection, which could require SSCs atypical to current nuclear plants, possibly imposing additional licensing considerations.
- *Critical Path Components* – When evaluating the technology or design, a determination should be made if there are any critical path components that, while perhaps representing a small portion of the total set of plant equipment, are critical for operation and low on the maturity scale or require significant remaining effort. An example might be a high-temperature sensor that must be compatible with a molten salt fluid, which has not yet been identified, validated, or demonstrated.

3.3.2 Regulatory and Licensing

The EPRI URD (EPRI, 2014) is specifically intended to provide a framework that supports (as much as possible, and particularly in the United States) a risk-free regulatory and licensing basis for plants based on its requirements. Licensing is required to build and operate a nuclear plant in any locale, and any difficulties in obtaining the required licenses will only add cost and schedule to the project. The URD notes in its *Economics Policy* (emphasis added):

> Implementing this policy necessitated that design requirements be specified which assured control of construction and operating costs. Therefore, great emphasis was placed on constructability, simplicity, design margin and other ***requirements which provided confidence*** that the construction schedule can be met, ***that licensing approval will be obtained***, that operating costs will be controlled, and that the plant design availability can be achieved.

On the other hand, the EPRI ORG (EPRI, 2019b) recognizes that the global regulatory and licensing status for ARs is largely in flux. The ORG notes in its *Licensing Preparation Policy* that modern designs must (emphasis added):

> Address current applicable regulatory expectations and provide, at a minimum, equivalent safety provisions appropriate to the technology. Design feature unaddressed by or inconsistent with current regulatory expectations may be made practical with advanced reactors (e.g., remote operation). ***These should be noted as increasing regulatory risk and should have a carefully developed rationale and justification*** to present to the regulator.

And the ORG further notes:

> - It is important for potential owner-operators of advanced reactors to ***consider regulatory issues early in development*** so that time and money are not wasted developing a design that cannot be reasonably expected to be licensed to operate.
> - ***Pre-application discussion with regulators is essential*** to identify expectations.

This criterion addresses plant licensability, licensing engagement status, path to licensing, and the regulator's capability. It covers evaluations of:

- *The OEM's interaction and progress with the regulator* – Are conversations taking place and going well? Is the relationship productive?
- *The regulator's ability to license the technology* – Are the regulations for licensing the technology or design adequately defined and mature? If not, does the regulator have the technical expertise and processes in place to meet the goals of the project?
- *The design against regulatory requirements* – Is the design pushing the boundaries or taking novel approaches with respect to the regulator's current licensing paradigm (see following note)?
- *Formal licensing actions to date* – Are topical reports and other licensing documents submitted? Is there a design certification submitted or approved (see following note)?

Note: For the latter two bullets covering the design against regulatory requirements and formal licensing actions to date, the specific goal for this criterion is to evaluate the maturity and, most importantly, the remaining effort. Technical aspects are covered in Section 3.4.7. When evaluating this criterion, the review team should assume that the regulatory process will evolve with the design and licensing, leading to an ultimate success, but it may take some time. In Section 3.4.7, the approach will be slightly different, comparing the technical aspects of licensing against currently known regulatory requirements.

As with design, this is a measure of maturity and remaining effort. Where is the design with respect to licensing? What is required to get to the desired state?

For existing water-based designs typical of those operating today, regulations are fully in place for countries with existing nuclear programs. In those cases, review of this criterion may be straightforward, even for designs that have not yet been fully licensed. More novel water-based designs, such as lwSMRs, may bring new considerations and more project risk that needs to be evaluated in further detail. Although there are many efforts in place to update regulations, globally, the regulatory frameworks for non-water reactors are currently immature, and evaluations will require considerable consideration and risk assessment. For development in countries with no or limited regulatory framework, careful assessment of schedule—not just of the project, but of the activities of other stakeholders (such as government entities)—should be incorporated into the evaluation of the criterion.

With respect to ARs, because regulatory frameworks are in flux, care should be taken to not assign too much certainty to proposals and draft regulations that could change or never materialize. Innovative design concepts that rely on potential future changes in the regulations themselves or the regulator's evaluation processes can be promising and exciting, but they carry significant risk.

Two additional considerations might be applicable: 1) the licensing of a design that was previously licensed in a different country (under a different regulator) or 2) updating the license for design modifications (or possibly both, because the different regulations might require design changes). Although the previous licensing should help expedite the process, this relicensing process is effectively a step backward in the maturity and will require additional time and effort that must be accounted for.

Candidate Technologies – The regulatory and licensing criterion is generally assessed in Step 3 for candidate technologies based on two attributes. First is an exclusionary factor evaluation of whether the project timeline supports novel approaches or if regulatory certainty is required (that is, working with a certified design) to meet the schedule. The second is an avoidance factor evaluation of whether the owner-operator has the desire and ability to take on the risks of new concepts, based on a basic understating of the technology and the current state of regulations and regulatory acceptance of those new concepts.

Candidate Designs – Licensing regulatory activities are very design- and OEM-specific. Although Step 5 is an evaluation with respect to individual designs, this step assumes limited specific knowledge, not much more than is available in the public domain or limited engagement with the OEM. Fortunately, in most countries, engagements with regulators are public activities; much can be inferred from public interactions. In cases where regulatory engagement is limited for early, more conceptual projects, there might be little information available. Evaluation of this criterion based on exclusionary or avoidance should be limited to designs for which real and accurate information is available. Designs that do not have enough specific information and data available would not necessarily be removed at this stage because they were not removed in Step 3 and no additional data one way or another are available.

Proposed and Alternative Designs – In Step 6, detailed maturity and remaining effort assessments are completed using the most specific licensing and regulatory information obtainable from the OEMs. The assessments likely require significant interaction to gather the right information and could require direct interaction with the regulator to assess their capability and capacity to support licensing efforts. At this point, collected data and information should be complete (that is, all information should be able to be collected and what is collected accurately assessed). However, the results might not be satisfactory due to unknowns in the design, licensing approach, and regulator activity. The review team will simply need to make their best estimates on time frames and risk. Based on the many levels of uncertainty, exclusionary and avoidance factors are not expected to be evaluated here, focusing the evaluation on suitability based on developed utility functions.

3.3.3 Reactor OEM Capability and Capacity

The development and deployment of any new reactor are done with the effort of a large team—the owner-operator, an EPC team if applicable, the OEM, an architect engineer, and an extensive list of other suppliers. But the reactor technology and design belong to the OEM, and, therefore, they are the critical organization for a new reactor project.

The OEM must be capable of rising to the occasion to meet the needs of the project. An OEM's ability to meet the challenge depends on several foundational factors:

- The owner-operator's mission and business objectives
- The OEM's mission and business objectives
- The current state of the design and the remaining effort needed
- The roles and responsibilities expected of the OEM in the project

With an understanding of these factors, the OEM's capability and capacity can be evaluated. *Capability* is a measure of the OEM's culture, business processes, and technical wherewithal to meet the requirements of their expected roles, most importantly, completing and licensing a design. *Capacity* is a measure of the OEM's ability to execute over the course of the entire project engagement. At best, the project will take several years, and potentially a decade or more, and it might require the OEM to grow significantly over time. This means that the evaluation will need to project out into the future, which involves much uncertainty. However, several indicators can be examined:

- *Executive Leadership* – Does the OEM's executive team have the capability to lead the company through the project, particularly through large growth if applicable?
- *Technical Capability* – Are the technical leaders and key technical talent capable of moving forward with the design, particularly in addressing currently known open issues with the design and how their capability applies to systems beyond the nuclear island?
- *Relevant Experience* – Does the OEM (and, more importantly, key staff) have timely and relevant experience in the development and deployment of nuclear facilities, including design and fabrication experience or expertise with the major components of their design?
- *Business Processes* – Does the OEM have business processes in place to support their required roles, including managing potential growth?
- *Project Management* – Does the OEM demonstrate capability in large-scale project management?
- *Culture* – Does the OEM demonstrate an understanding, belief, and practice of nuclear safety culture (including quality assurance)? As important, does their general culture align appropriately with the owner-operator's general culture?

- *Financial Status* – Does the OEM have the financial capacity or backing, over time, to execute adequately on the project, not only for development and deployment, but also the capacity to be a long-term service partner over the life of the plant? If there is an intention that the owner-operator provide financing, is the owner-operator capable and prepared to do so?
- *Multiple Clients* – Does the OEM have both the capability and capacity to handle multiple clients and projects simultaneously?

The roles and responsibilities of the OEM can differ greatly based on the starting point of the design, the status of identified major suppliers, site selection status, and a project's commercial structure. The owner-operator should ask questions such as:

- Has the design been certified, or is it a conceptual design? How much involvement will be needed by the owner-operator?
- Have an AE and large component supplier been identified, and how involved are they in the project?
- Has a site been identified? If so, how might that impact design? If not, what is the OEM's role in site licensing?
- Is the project being run under an EPC construct where the OEM is part of the team?
- What other services will the OEM be responsible for providing, such as operator or inspection and maintenance training? Will these services be only for deployment or over the operating life?

Expected roles and responsibilities should be evaluated against the indicators in the preceding list.

One last attribute to evaluate is the OEM's need for support and engagement from the owner-operator and how that aligns with their goals.

Candidate Technologies – OEM capabilities are dependent on selection of a specific design and an associated OEM; therefore, they are not evaluated in Step 3 for candidate technologies.

Candidate Designs – Although OEMs can be identified in Step 5 for candidate designs, the level of engagement with an OEM needed to make an evaluation on this criterion may exceed that which is available at this stage. Therefore, individual OEMs are evaluated only in Step 5 for candidate designs if the data and information are available.

Proposed and Alternative Designs – In Step 6, detailed engagement with OEMs is necessary, and development of the information and data to make an evaluation on this criterion can begin to take shape. Much of the information desired might be limited and vague because substantially detailed information may require significant commercial engagement that has not yet taken place. The review team will simply need to make their best estimates. Based on the qualitative nature of this criterion, exclusionary and avoidance factors are not expected to be evaluated here, focusing the evaluation on suitability based on developed utility functions.

3.3.4 Supply Chain Maturity, Remaining Effort, Capability, and Capacity

Although there has been significant development of new nuclear plants in some countries, overall global development is less than the new construction that took place in the 1970s–1990s. This is particularly true in some countries that were once leaders in new nuclear development, such as the United States and France.[6]

Also, as noted in the American Nuclear Society's *Nuclear News* in April 2019 (Tannenbaum, 2019):

> …established nuclear suppliers have mentioned a noticeable decrease in orders for safety-related items, that is, items controlled under the auspices of a supplier's 10 CFR Part 50 Appendix B–compliant quality assurance program. This decrease is consistent with curtailment of new nuclear construction, market pressures, and efforts to reduce generating costs while maintaining nuclear safety.

The effect of fewer orders for new plants, combined with a reduction in orders from the global operating fleet, has over the past two decades put significant pressure on suppliers' ability to keep a trained and qualified nuclear workforce and operating procedures, with some vendors, particularly large component vendors, leaving the business entirely. The current rate of new plant construction is already straining the nuclear supply chain, and expectations are that current climate change and carbon reduction considerations could significantly increase new plant development, further exacerbating the supply chain.

Currently, new plants under construction are primarily large light (or heavy) water designs, based on technology, materials, and manufacturing techniques that are well known; however, there are clear constraints in the supply chain. Although these designs are familiar, most still exhibit first-of-a-kind (FOAK) or first-in-a-while properties, resulting in poor economies of scale, additional costs for learning curves, and risk and profit premiums (WNA, 2014). In addition, providing materials and components for new construction can even stress long-time, well-qualified suppliers due to the sheer volume needed. A supplier that has been providing a limited number of high-quality parts to the operating fleet for years could find itself overwhelmed with a large order in support of a new reactor, resulting in poor output due to bringing on inexperienced staff who do not fully understand nuclear safety culture and reduced quality management due to the total volume of work. The same effect can happen when attempting to take components that are well-developed and understood in other industries and use them in a nuclear capacity, which can have additional requirements and standards unfamiliar to current suppliers.

The potential development of ARs adds new constraints to the supply chain: new components, new materials, and new designs. Additionally, because there is real promise in advanced manufacturing and construction methods, such as additive manufacturing and modular construction, many new plant OEMs are planning to make use of these methods. And, although there is promise, many of these concepts are yet untested.

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[6] As of July 2022, there were 55 new nuclear plants under construction globally, with China leading development at 20 new units and India in second place with eight. The United States has two units under construction, and France has one (WNA, 2022).

At this time, it is highly unlikely that all components of any new reactor can be procured in a single home country. This necessitates international procurement, which often leads to significant technical, commercial, and regulatory complexity. On the other hand, many countries see new nuclear development as a key driver for increasing their own manufacturing and supply chain base, such that there might be pressure (regulatory or commercial) to procure materials at home. This can lead to using suppliers that are unfamiliar with the unique requirements of nuclear production.

As an owner-operator considering the procurement of a new nuclear plant, it can be enticing to consider the supply chain the responsibility of the OEM or the EPC organization and attempt to cover risks through commercial means. Recent experience in new nuclear plant construction shows that even for relatively known technologies, this is likely a mistake; in the end, the owner-operator cannot contract away all their risk. For example, having to rework a critical path component could lead to months of construction delays, impacting the owner-operator's bottom line through extended carrying costs on financing.

An owner-operator should understand the status of the supply chain for the major (nominally large) components for their potential new-construction project. For relatively known technologies, an understanding of the supply chain's capacity and capability (see the following) may be sufficient. When it comes to reactor technologies with novel components and manufacturing techniques, the owner-operator will want to understand the technical maturity (for example, the MRL) and remaining effort required to reach the production stage.

For this criterion, the terms *maturity* and *remaining effort* should be considered analogs to those described in the preceding, with the exception being that this consideration is not about the capabilities or qualities of the component itself (that is considered under design), but rather the maturity of the manufacturing processes needed to fabricate the component, including the availability of qualified materials. As examples, EPRI released three advanced manufacturing roadmaps for manufacturing methods (EPRI, 2021b), additive manufacturing (EPRI, 2021), and AR materials (EPRI, 2021c) that explicitly define the current state of the art and the time likely needed for full nuclear commercialization.

The term *capability* represents the supply chain's ability to manufacture the component at a commercial quality in a reasonable time. An evaluation of capability would include the availability of production machinery, trained and qualified workers, and fully developed and implemented processes. Capability could differ depending on locale and sourcing requirements. For example, a home country might not have the capability, but a foreign country might.

The term *capacity* represents the supply chain's potential throughput. One or more suppliers could have the capability to manufacture a component, but not the capacity to manufacture hundreds of components on a reasonable schedule. Capacity should include a consideration of the overall supply chain's ability to meet throughput, including current backlog, not just any one supplier. Capacity might also include an evaluation of the supplier's long-term ability to provide support over the life of the plant.

Early in the assessment process (Steps 3 and 5), capability and capacity should be considered on an industrywide basis because specific suppliers are likely unknown. The evaluation is simply based on what is potentially feasible. Later in the assessment processes (Step 6), identification of large-component and critical path suppliers might be possible. Evaluation of suppliers that engage in new nuclear deployment and construction now should be straightforward. For a novel design with novel component requirements, further consideration of key suppliers is likely needed. For a large organization, such as an AE, considerations such as those noted in Section 3.3.3 for an OEM's capabilities should be addressed.

Due to the differences in all available and potential technologies and designs, it is impractical to specify here the exact components and suppliers that should be considered under this criterion. The selection might also be different for different technologies or designs, for example, if evaluating both an HTGR and an MSR. When evaluating this criterion, it is not necessary to evaluate all components or supply chains. The goal is to find the ones for which the supply chain poses significant risk to the overall success to the project.

To find key components, the evaluation team should evaluate many of the systems found in Section 3.3.1 and look for other unique systems or novel components expected to be used by the technology or specific design, for example, safety-related components, such as rebar, piping, embeds, ductwork, and electrical.

Key suppliers include the AE, EPC, large-component manufacturers, and craft labor suppliers.

One supply chain pathway that should be explicitly considered is that for fuel. This is particularly true for non-light water designs that are expecting to use HALEU fuel. The fuel supply chain should be addressed across the entire fuel cycle over the life of the plant.

Candidate Technologies – The evaluation of the supply chain criterion in Step 3 for technologies is normally done only at the capability and capacity levels for mature technologies (for example, those currently used in large LWRs or other already deployed designs). For less mature technologies, such as ARs, capability and capacity can likely be ignored, with the focus on maturity and remaining effort. At this stage, there are no fully identified components with specific designs, but a review of publicly available information can easily identify components that have been problematic in more recent experience and novel components that will likely be used in ARs. Because Step 3 is an exclusionary screening, the primary attributes for consideration are the results related to timing and schedule (fully exclusionary) or overall project risk (avoidance).

Candidate Designs – The review of candidate designs in Step 5 might not be much different from that completed in Step 3 because, at this point in the assessment process, there might not be much more information available. Preliminary reviews of designs and initial interactions with OEMs can surface more details, particularly if the OEM had initiated any public licensing processes or selected key suppliers. Ultimately, the evaluation team should determine if enough new information is available to warrant another exclusionary screening, or if it can be skipped at this stage.

Proposed and Alternative Designs – By the time Step 6 is reached, the evaluation team should have significant information on specific designs obtained through specific interactions. Conversations with the OEMs on key component and supplier issues should be taking place. The detailed maturity and remaining effort assessments are completed using the most specific design information obtainable from the OEMs. As with design maturity, it is highly likely that supply chain information will also be incomplete, vague, or have a risk of changing later. The review team will simply need to make their best estimates with the information available and account for risk.

Although specific designs were not likely eliminated based on any supply chain maturity or remaining effort exclusionary or avoidance factors in Step 5, now that more detailed information is available, this can be done to exclude any specific designs. Once the exclusionary screen is complete, remaining effort is the critical factor, and additional criteria evaluation based on maturity suitability factors is not necessary. Instead, the critical attributes are the remaining effort and suitability of key suppliers, which should be evaluated for suitability based on developed utility functions (note that a detailed maturity assessment is still required as input into the remaining effort determination).

3.3.5 Owner-Operator Capability and Capacity

This criterion is an evaluation of the owner-operator's ability to execute on the project over the long term. The ability for an owner-operator to adequately perform is dependent on several foundational factors:

- The owner-operator's mission and business objectives
- The current state of the design and the remaining effort needed
- The roles and responsibilities that the owner-operator is expected to have on the project

Upon understating these factors, the owner-operator's capability and capacity can be evaluated. Capability is a measure of the owner-operator's culture, business processes, and technical wherewithal to completely meet the requirements of their expected roles. Capacity is a measure of the owner-operator's ability to execute over the course of the entire project engagement, which at best will take several years (and potentially a decade or more) and could require the organization to grow and change significantly over time. This means that the evaluation will need to project out into the future, which involves significant uncertainty. However, there are several indicators that can be examined:

- *Executive Leadership* – Can the owner-operator's executive team lead the company through the project, particularly through large growth, if applicable?
- *Technical Capability* – Can the technical leaders and key technical talent move forward with the design, particularly in addressing currently known open issues?
- *Business Processes* – Does the owner-operator have business processes in place to support their required roles, including managing potential growth?
- *Project Management* – Does the owner-operator demonstrate capability in large-scale project management?
- *Culture* – Does the owner-operator's culture allow for an effort that is potentially significantly different (such as unique processes, procedures, metrics, and goals) from the normal course of business to take place effectively?
- *Financial Status* – Does the owner-operator have the financial capacity or backing, over time, to adequately execute on the project?

A few critically important attributes must be examined for alignment, or the project will have a significant risk of failure:

- Is the current state of design maturity and remaining effort in alignment with the owner-operator's mission and business objectives?
- Is the level of required partnership and engagement with the OEM, suppliers, regulators, and other stakeholders in alignment with the owner-operator's mission and business objectives?
- Are the risks with this design, particularly financial risks, in alignment with the owner-operator's mission and business objectives?

At first glance, it might seem that an evaluation of this criterion would produce the same result for any design, which is not the case. Foundations of the owner-operator's mission and business objectives do not change, but the level of effort and engagement will change with each design based on the specific design's maturity and remaining effort, and the level of engagement in the form of labor and financing, needed to support the project.

Candidate Technologies – The criteria under Basic Operations (Section 3.1) should have screened out any basic technologies that do not meet the owner-operator's business objectives. Therefore, this criterion is not evaluated in Step 3.

Candidate Designs – For the evaluation of this criterion in Step 5 for candidate designs, the level of engagement with an OEM needed to make a fully formed evaluation on this criterion could exceed that which is available at this stage. Therefore, this criterion is evaluated only in Step 5 for candidate designs if the data and information are available.

Proposed and Alternative Designs – In Step 6, detailed engagement with OEMs is necessary, and development of the information and data to make an evaluation on this criterion can begin to take shape. The information gathered from the detailed engagements to date should be reviewed with internal stakeholders to understand and verify alignment and determine if changes in mission and business objectives are warranted. Information might be limited and vague because detailed information could require significant commercial engagement that has not yet taken place. The review team will need to make their best estimates. Based on the qualitative nature of this criterion, exclusionary and avoidance factors are not expected to be evaluated here, focusing the evaluation instead on suitability based on developed utility functions.

3.4 Technology Capabilities

Technology Capabilities are the specific features of a nuclear plant and its design that provide for safety, reliability, flexibility, resiliency, and efficiency, not only for operations, but also construction and ongoing maintenance. These are the key features and design principles for each technology or design.

Because this report is intended to be technology-agnostic, this section defines criteria at a high level. It is incumbent on the review team to perform the technical due diligence on the specific technologies and designs being assessed.

The technical areas covered in this section were derived and synthesized from several reference sources—the EPRI URD (EPRI, 2014), the EPRI ORG (EPRI, 2019b), the NNL *Review of Metrics Relevant to Reactor Systems* (NNL, 2012b) and its *Addendum* (NNL, 2012), the *Generic Feasibility Assessment for SMRs* (University of Manchester, 2016), and IAEA *Nuclear Reactor Technology Assessment for Near Term Deployment* (IAEA, 2013b). These references go into specific and low-level detail, and it is recommended that the review team peruse them as part of their assessment process. The documents not only provide significant insight into various technical details, but they also include discussion into the thought processes behind those details as well as general information on performing such assessments.

The technical areas covered in the rest of this section include:

- Design Philosophy
- Design Processes and Tools
- Safety, Reliability, Availability, and Sustainability
  - Safety
  - SSCs
  - Human Factors, I&C, and Cybersecurity
  - O&M
- Flexibility and Resiliency
- Fuel, Fuel Cycle, and Waste Management
- PR&PP
- Licensing
- Constructability

For criteria evaluation purposes, each of these subsections is considered a single entity. However, there are, in fact, several subcriteria in each. The evaluation team must make the assessment based on all pertinent information.

The amount and level of detail of the information and data available can be different for different technologies and designs (see Section 3.3, “Maturity and Remaining Effort”). For example, the information available for a licensed PWR design is significant, but the available information will be much less for an AR design of lower maturity.

For fully finished designs that are licensed in some way (for example, a DC, CP, OL, or COL in the United States), the evaluation is straightforward because there is significant information and data and, probably, operational experience to draw on.

For low-maturity technology designs, it is important that the evaluation of the criteria in this section assume that the technology will meet the designer’s intention on complete development. This can be a difficult concept for the review team to grasp because of the tendency to assume that the lack of information is a risk. Much of this risk is captured in Section 3.3, and the goal is to not double down on that risk assessment. The review team should constantly ask this question:

If the technology or design is completed as planned and advertised, what is our rating for these criteria based on the ability to meet the owner-operator's mission and business objectives?

Where information and data are missing, the review team should make their best assessment and document their assumptions. It is possible for a criterion in this section to receive a high score because if completed as planned, it would fit the goals of the project perfectly; however, a related criterion in Section 3.3 might score very low because of the uncertainty in maturity and remaining effort. Where limited information such as drawings and design data are available, the IAEA's *Nuclear Reactor Technology Assessment for Near Term Deployment* contains an extensive list of questions that a potential owner-operator could ask regarding the criteria in this section (see the IAEA report for details).

Although the review should assume that the final product is as planned or advertised, including proposed time frames, the review should include an evaluation of expected performance. The following are three examples that should help provide context to this consideration:

- *Example 1*: There is uncertainty in the specification of a critical material for the reactor system. The OEM is performing testing on a specific material that they believe will work for their process. The review team should assume that the material tests satisfactorily for the OEM and that they will include it in the design. The review team can assess the capability for that material to last the life of the plant, be inspected and repaired, and react appropriately to transients.
- *Example 2*: The OEM has specified a highly automated I&C system that is currently undergoing development and testing. The review team should assume that the I&C system is completed as planned but should then evaluate its ability to perform in the specific regime of which the plant will operate.
- *Example 3:* The proposed fuel form has not yet been fully designed and tested. The OEM is actively performing work on their plan. The owner-operator should assume that the final fuel form evaluated by the OEM will be adequate but should evaluate the technical ability to manage fuel storage, refueling, used fuel-handling, and any PR&PP concerns.

During review of the criteria in this section, it is possible that one result will be a better understanding of the maturity and remaining effort as defined in Section 3.3. The review team might want to iterate on their evaluations as needed.

Unless specifically noted in individual sections, the evaluation and screening of the criteria in the Technology Capabilities section are as follows:

Candidate Technologies – The criteria under Technology Capabilities are generally specific to a particular OEM's design and are not normally evaluated for exclusionary screening of candidate technologies in Step 3. Very novel technology concepts will likely be screened in or out at the start based on the owner-operator's mission and business objectives in Section 3.1 or through the maturity and remaining effort criterion in Section 3.3. Beyond that, the review team is cautioned to not make decisions on perceived concerns taken from potentially insufficient information gathered for this step.

Candidate Designs – Although the criteria under Technology Capabilities are generally specific to a particular OEM's design as previously noted, the owner-operator is not likely to have gathered sufficient information to make a valid exclusionary assessment on this criterion in Step 5 because significant engagement with the OEM is likely required.

Proposed and Alternative Designs – In Step 6, detailed engagement with OEMs is necessary. Development of the information and data to make an evaluation on the technology capabilities criteria can begin to take shape. The information gathered from the detailed engagements to date should be reviewed to ensure that the OEM is embracing the concepts in the criterion to the level expected by the owner-operator. For existing designs for which significant data are available such as an already operating design or based on a DC, CL, or COL in the United States), screening on exclusionary or avoidance factors is possible. However, by that point in their design, they would likely meet minimal requirements, making a suitability screen more applicable. For low-maturity designs, the review team will need to gather the best information possible and screen on suitability using developed utility functions.

3.4.1 Design Philosophy

This criterion encompasses the goals of simplification, standardization, and use of proven technology. The primary objective is to design, build, and operate a nuclear plant that is as free of complexity as possible and uses SSCs that are well known and understood for ease of operations and maintenance. As noted in Section 3, this does not preclude technology that is innovative to nuclear energy, but the use of truly novel technologies should be limited. If used, there must be a compelling case that any innovations are required or add significant value to the plant.

The following items provide more detail:

- *Simplification* – Both the EPRI URD (EPRI, 2014) and the EPRI ORG (EPRI, 2019b) note simplification as a top-level policy statement. Both documents use similar language to describe simplification and emphasize that the concept should be a high priority and carry significant importance in design and expected operations of the nuclear plant. Simplification efforts must be focused on a few key goals: increased safety, reduced costs, and reduced burden on operators with reduced opportunity for human error. The ORG states in its Simplification policy that the design should:

  > Minimize the number of SSCs (including interconnections, such as conduit, cable, piping, etc.) to reduce complexity of operation and to reduce capital, operating, and maintenance costs. Emphasis should be placed on limiting the complexity and number of safety-related components.

  Simplification undoubtedly comes with tradeoffs that must managed by the designer and evaluated for this criterion by the review team. Many new reactor technologies offer remarkably simple and low-complexity primary systems that rely on natural physical properties for operation and safety, but they can introduce complexity in other areas of the plant. For example, molten salt or liquid fuel reactors offer low-pressure systems of simple, basic design, but they potentially require complex chemical cleanup and off-gas systems. TRISO fuel offers the potential to build a nuclear plant without a primary containment structure and all that is involved with constructing and maintaining it, but it might require complex fuel-handling systems. A simplified human-machine interface that embraces automation can reduce human error, but complex software that is difficult to maintain could be hiding behind the scenes. Even fully licensed, modern, advanced PWRs and BWRs that embrace simplification in their designs include new SSCs that are novel and present potential issues for future inspection and maintenance.

One other thing that should be considered is that simplification in the overall design can potentially reduce flexibility in operations, maintenance, and future modifications—for example, limiting future power uprates or ability to be differently flexible due to changes on the grid.

- *Proven Technology* – As with simplification, both the URD and ORG stipulate the use of proven technology. In the case of advanced light water designs, the URD focuses on making use of operating experience with previous light water plants to select SSCs that have a good history and limit novel technologies to addressing areas known to need improvement. The URD notes in its Proven Technology policy:

> The proven technology policy encouraged the use of advanced technology, e.g., digital man-machine interface systems, where there [is] a need to solve known LWR problems or an opportunity for simplification, and where the advanced technology [is] proven. Assuring that advanced technologies [are] sufficiently proven typically [requires] testing and/or proven successful use in other applicable industries, e.g., fossil-fired power plants, process industries, etc.

With ARs, the ability to use proven technology might offer unique challenges due to limited operating experience, particularly through use in nuclear energy. But that does not preclude the use of proven technology if the field of operating experience is widened to include other industrial uses as previously noted. For example, large solar farms currently use molten salts operating at high temperatures, and operating experience and lessons learned can be taken from there. Another area ripe for “nuclear innovation” is digital control systems, which are fully embraced by the fossil power industry, aviation, transportation, and the military.

When evaluating this criterion, the reviewer should consider two slightly contradictory outcomes of proven technology. The first is that using subpar SSCs in an over-embrace of the concept. The second outcome is the extension of something used in another industry too far beyond its operating experience and knowledge base, such that it is effectively no longer “proven.”

- *Standardization* – The goals of standardization are twofold. A key request by the utility industry during the development of the URD in the late 1990s and early 2000s was plant standardization. The URD notes in its Plant Standardization policy:

> The ALWR program recognized the importance of standard designs and the historic problems associated with customized designs. Accordingly, the program developed design requirements intended to form the technical foundation which will lead the way to one or more standardized detailed designs. Key plant features were specified in sufficient detail in the URD to permit meaningful standardization.

This policy in the URD and the URD itself were created in close alignment with the NRC. The URD specifically does not endorse any regulation, but it was intended to support NRC 10 CFR 52 (NRC, 2007) and development of the Design Certification for a standardized plant. As many are aware, use of these concepts for the design and licensing of novel nuclear technologies, particularly those that do not involve light water designs, will be challenging due to the nascent maturity of many global regulatory regimes. However, this does not preclude OEMs from embracing this concept in their designs. Owner-operators (or state-level policy makers) considering fleet-level deployments of a novel technology should evaluate this criterion with an eye toward plant standardization.

The second area of consideration is SSC standardization. This is a simpler concept and is slightly related to the use of proven technology, encouraging standard, commonly available components. The nuclear industry is rife with examples of failure in this aspect, ranging from the use of custom-designed fasteners where off-the-shelf components could have been used to specially designed major system components that can have extensive lead times for replacement. Due to specific operating conditions experienced in nuclear plants (pressure, temperature, chemistry environments) and local quality assurance (QA) and regulatory requirements, it might not be possible to use off-the-shelf standard components in many instances. However, it might be possible to assemble a set of standard subcomponents or to use the same dimensional design. For example, a specific valve might need to be made with a specialized material and fabricated using a specialty QA approved process, but the overall dimensions might be the same as a standard model. When evaluating this level of standardization, it will not be practical, or perhaps even possible, for the owner-operator to inspect the design of individual components. And, for low-maturity designs, many components will not yet have been defined. Instead, the review team should inspect the OEM's internal guidance, policies, and procedures provided to its design staff.

Simplification, proven technology, and standardization are overarching concepts that should, in effect, be addressed in all areas of a nuclear plant's design, operations, and maintenance. Innovation should be used where needed and demonstrated to provide benefit. The review team can encounter these concepts as they review other criteria in this section and should use that input to inform their assessment of this criterion.

3.4.2 Design Processes and Tools

The processes used to design a nuclear plant might not seem to be related to technology or design selection, but they are important as described in the following three scenarios:

- *Unfinished Design* – For a plant that is not yet completely designed, evaluation of the design process used by the OEM and other major suppliers provides insight into the ability of the designers to meet technical and regulatory requirements and achieve the goals of a robust and nuclear plant.
- *Unbuilt Design* – Even a plant that has been fully designed and licensed, but unbuilt, will likely require additional design work. For example, in the United States, receipt of a DC, and CP or COL, allows for construction to start while major portions of the plant are in the design phase. The ability of the OEM and suppliers to continue developing a robust design under the stressful time constraints of a construction schedule is important to understand. Also, it is likely that design changes will happen during construction, and the design team's ability to respond quickly and appropriately is important.
- *Previously Built Design* – Building a new plant based on one that has already been fully designed and successfully built at another location will still likely require additional design work based on needed customizations for local conditions.

> Two areas that are almost surely true are: 1) design changes to accommodate ground and seismic conditions, which could require changes to the foundation and other structures, component support, and piping restraints; and 2) design changes to adjust for the overall siting to accommodate tertiary systems, such as cooling water supply and placement of cooling towers; other water supplies, such as fresh water and for fire protection; and placement of incoming and outgoing power lines or steam piping. Much of this work will likely be performed by an AE, but integration with the OEM is still required to ensure that the impact to the plant's safety basis is not compromised.
>
> Also note that the construction of a plant in a locale with different regulatory requirements can effectively turn a fully designed plant back into an unfinished one.

Some designers of today's ARs, particularly SMRs, are expecting to incorporate design features that minimize these aspects, for example the use of seismic isolation to minimize the need for design changes to accommodate local seismic conditions.

Most importantly, even in a case where the plant is expected to need minimal additional design work, the owner-operator should still expect that the designers used a proper design approach that ensures a well-designed plant that is robust and meets the design philosophy and safety goals defined in the preceding sections. Some other key points from the URD are:

- The design process should be managed as a single integrated process, even if several organizations, such as the OEM, AE, and constructor, are involved.
- The designer should prepare design basis documents for each plant system and indicate how safety margin above the licensing design basis will be achieved.
- Interdisciplinary reviews should be conducted throughout the design to confirm that the concepts covered in Sections 3.4.1 and 3.4.2 are met.

The owner-operator should evaluate the following attributes, taken from the URD, on the overall design plan of the OEM and other suppliers:

- *Iterative Design Approach* – The plant's initial design concept should be developed and matured by an ongoing process of iteration between the initial design concepts, initial hazard and risk analysis, and initial design basis accident mitigation strategies. The design team should routinely make iterative changes to the design concept, the hazard and risk analysis, and the beyond-design-basis strategies to achieve optimum reliable operation, accident robustness, usable mitigation capability, and plant economic viability.
- *Configuration Management and Information Management System* – The plant designer should have a well-developed and comprehensive configuration management program to ensure that plant SSCs and computer software conform to approved design requirements. The configuration management program will be applicable throughout all phases of the plant life, including the design phase, and will provide for turnover of the program to the owner-operator for use during startup and operation. This configuration management process should be backed up by a proper information management system, which is necessary for meeting the requirements of configuration management and making effective use of computer-aided

design and construction tools. The configuration management program should not only include physical layout, but also processes and capabilities for managing requirements, design margin, I&C software and setpoints, procedures and documents, and inspection and test management.

Compatibility of the tools used by the OEM, AE, and constructor with those used by the owner-operator are paramount. Care should be taken to ensure that the design and all information in the preceding paragraph can and will be turned over in a format readily usable by the owner-operator (or potentially interfaced with by the owner-operator during the development project). This could require the owner-operator to procure new systems to ensure compatibility.

For perspective, see the following EPRI reports on configuration management:

- *Elements of Pre-Operational and Operational Configuration Management for a New Nuclear Facility* (EPRI, 2011)
- *Impact of EPRI Pre-Operational and Operational Configuration Management Report (1022684) on the Nuclear Industry* (EPRI, 2013c)
- *Data-Centric Configuration Management for Efficiency and Cost Reduction: An Economic Basis for Implementation* (EPRI, 2014b)

Also, note that information turnover must be accounted for early in the design and construction plan for effective turnover, as discussed in EPRI's *New Nuclear Power Plant Information Turnover Guide (Revision 1)* (EPRI, 2016).

- *Design and Design Processes* – The designer and other suppliers should have in place proper processes and procedures to ensure that they are adequately defining, and designing to, proper design bases. This includes the structural design criteria applicable to all buildings and SSCs and should address both passive structural elements and active equipment functions. A unified system of classification with respect to function and structural integrity should be established, with all relevant codes and standards identified and acceptance criteria established. The processes should help show that design loads and load combinations, as well as the required measures to mitigate the effects of in-plant hazards, will be identified and addressed. This includes the design for all site-related criteria, including natural phenomena and environmental conditions; and all relevant design functions, such as mechanical and electrical, not just structural.
- *Design for On-line Condition Monitoring* – In the lifetime of commercial nuclear power, condition-based maintenance is a relatively new concept that has been shown to be cost-effective and safe. However, operating experience with the existing fleet has shown that maximum efficiencies cannot be gained using manual processes often employed due to a lack of on-line sensors and monitoring. Even some of the most advanced plants recently deployed, despite being highly wired with thousands of sensors, were not done so in a manner to allow for on-line condition monitoring. The designers of any plant should demonstrate that they understand the concepts and value of on-line condition monitoring and have taken steps in the design process to evaluate the best SSCs for monitoring based on the failure impact to the plant and evaluation of the current state of technology for sensors and data processing. With the advent of artificial intelligence and other digital technologies, a move to predictive

monitoring is also a potential. There are too many references to list in this report, but EPRI has done extensive research and developed many reports on condition-based maintenance and on-line monitoring, with a good starting point being *Guidelines for Transitioning from Time-Based Maintenance to Condition-Based Maintenance* (EPRI, 2013b).

- *Design for Testing and Commissioning* – New reactor designs that take advantage of reduced SSCs and passive safety systems may end up with systems that are more difficult to isolate and test during startup testing and commissioning. The OEM should account for this in their design.
- *Project Control Functions* – Any study of large facility design and construction will demonstrate the need for proper and robust project management and control. The OEM and other suppliers must demonstrate that adequate capability is in place, based not only on current needs, but also on the ability to grow as the project does.
- *Tools* – A review of the software design tools used by the OEM and key suppliers should be completed. Key factors to review are interoperability between the tools themselves, interoperability between suppliers and the owner-operator, their ability to support configuration management and information turnover as previously noted, and last, what results (deliverables) the owner-operator will receive. Care should be taken if proprietary tools are used by the OEM or other suppliers of which the owner-operator will not have access after plant turnover.

When evaluating the attributes of this criterion, it is not intended that the owner-operator evaluate the actual design—that is addressed elsewhere—but rather that the designer and key suppliers have demonstrated a design philosophy that is compatible with the owner-operator's mission and business objectives and that they demonstrate that they have the processes and procedures in place.

3.4.3 Safety, Reliability, Availability, and Sustainability

These four concepts are interrelated. Safety, often referred to as *nuclear safety*, is a measure of the plant's ruggedness to avoid or mitigate accidents resulting in the release of nuclear material. *Reliability* is a measure of a plant's dependability to be available for its mission. *Availability* is a measure of how often the plant can perform its mission. *Sustainability* is a measure of the plant's ability to be both reliable and available over its lifetime. Typical considerations from a technical standpoint include:

- An overall design of SSCs that demonstrates a robust design margin and minimum failure rates, preferably demonstrated by a probabilistic risk assessment (PRA, see below)
- A design that supports operating the plant safely and efficiently, including resilience against transients to support operators having sufficient reaction time, effective plant layout for ease of manual operations, and a robust I&C system that makes use of proper human factors engineering

- Ability to perform on-line maintenance and refueling without the need to reduce power or fully shut down the plant, including multiple trains of systems important to safety, and production to provide for on-line maintenance or unexpected failures
- A design that supports efficient maintenance, online or off, including room for maintenance staff to work, the ability to replace large components, and simplification and standardization to help ensure materials and equipment supply over the life of the plant

A crucial point from the ORG is that different markets and missions have their own metrics for reliability and availability. Although a highly dependable, available, and sustainable plant is preferable, the owner-operator should consider total construction and O&M costs and resist paying a premium for more than they need if this can be done without compromising nuclear safety.

These overarching topics are assessed through four criteria:

- Safety
- SSCs
- Human Factors, I&C, and Cybersecurity
- O&M

The review team should take care to ensure that criteria are not evaluated more than once. For example, safety functions are implemented by specific SSCs, I&C systems can have a significant impact on safety, and the design of SSCs can have an impact on operations and maintenance. The review and evaluation are not expected to delve into the deepest details of any design; therefore, the evaluation is considered at these higher levels even though there is some overlap. This is because of their importance and the likelihood of there being data and information available.

3.4.3.1 Safety

The need for nuclear safety is a given, and all technologies and designs currently under serious consideration offer the promise of levels of safety that exceed that exhibited by the existing global nuclear fleet. When it comes to new technologies, the key term here is *promise*. True nuclear safety can be demonstrated only in the ultimate design. When evaluating this criterion, the following subtopics, all of which can be found in the EPRI URD (EPRI, 2014) and EPRI ORG (EPRI, 2019b) should be addressed:

- *Design Margin* – At its core, the concept of design margin is that the plant should be designed to be a forgiving, rugged plant that will have a long lifetime (potentially beyond its original design life). Enhanced design margin should also allow for potential future modifications—upgrades and flexibility to operate in new regimes that might be presented in the future (such as changes in electrical grid operations due to future increases in intermittent sources). From the URD, design margin provides for:
    - The capability for the plant to accommodate transients without initiation of engineered safety systems

  - Considerable time for the operator to assess and deal with upset conditions with minimum potential for damage
  - Enhancing system and component reliability and minimizing the potential of exceeding limits

  Increased design margin might come at a higher price, and the owner-operator should understand how increased design margin might affect the cost of the plant and their financial bottom line. Although the URD specifically notes the expectation that the plant be able to exceed its design lifetime, the owner-operator should compare that with their mission and business objectives. It should also be noted that there is some consideration in this space for designing plants with more limited design margins, resulting in shorter design lifetimes or a need to replace SSCs on a more frequent basis, but with lower upfront cost. This is an untested concept for now, but one that the owner-operator should be aware of.

- *Accident Resistance* – As noted in the URD, the plant should be designed with features and attributes that minimize the frequency, severity, and propagation of initiating events, which could challenge the safety of the plant and reduce dependence on plant safety systems. Accident resistance is related to design margin and simplification (both are noted in the preceding). However, in addition, accident resistance includes the ability to withstand seismic events, temperature excursions, and material degradation; the inclusion of diagnostic and monitoring systems for advanced warning that allow for operator-initiated safe shutdown; and other factors.
- *Core Damage Prevention (or equivalent)* – the EPRI URD contains extensive requirements for core damage prevention in its related policy and specifies a maximum core damage frequency for any new advanced light water plant, including special considerations for lwSMRs. When it comes to ARs, the concepts of core damage become a bit murkier. Core damage frequency, a commonly used metric for assessing core damage prevention, might have less meaning in different AR designs. For example, liquid fuel designs already contain melted fuel, and TRISO fuel is damage-resistant. Therefore, the equivalent assessment of this subcriterion might need to be based on other scenarios that could result in severe damage to the primary system, resulting in an off-site release of fissile material due to postulated severe events.

  Two reports from the U.K.'s National Nuclear Laboratory, *Review of Metrics Relevant to Reactor Systems* (NNL, 2012b) and its *Addendum* (NNL, 2012), specify several characteristics that can be evaluated with respect to core damage prevention and related safety parameters. These include reactivity control, decay heat removal, low uncertainties on dominant phenomena, fuel thermal response, source term, energy release mechanisms, system response times, and effective holdup. Active versus passive safety features might also need to be considered.

- *Accident Mitigation* – The design of the nuclear plant should assume that an accident will happen. A comprehensive understanding of the consequences of various accident scenarios and the potential release of nuclear material is essential for engineers and lead designers of safety-related and mitigation-related plant SSCs. As noted in the URD:

  > The Fukushima accident strongly reinforced the basic lesson, "things happen that you do not expect." And, that the consequences of those "happenings" can be very severe. It is essential to the success of the new plant that the design team intentionally and effectively balances safety, reliability, costs, and operability.

  The URD contains several requirements for accident mitigation for advanced light water designs. Additional information on potential actions for light water plants can be found in EPRI's *Severe Accident Management Guidance Technical Basis Report*, Volume 1 (EPRI, 2012) and Volume 2 (EPRI, 1993).

  However, there is little guidance on postulated accident and potential mitigations for non-light water designs. The owner-operator will likely need to rely on the OEM to develop these considerations, which could be complicated by a regulator's lack of familiarity and experience with understating and evaluating them. When evaluating this criterion for non-light water designs, the owner-operator will need to ask probing questions about the design to ensure that appropriate scenarios have been evaluated and the potential mitigations are satisfactory. This might require significant effort on the part of the owner-operator, possibly requiring expertise that they do not have in-house.

- *Accident Scenarios and Consequences* – The review team should understand the major accident scenarios identified by the OEM and their potential consequences. Although accident scenarios for large light water designs are well known and evaluated, new concepts might postulate different initiating events and sequences. New technologies and designs can provide for safety improvements, and other design considerations (such as below-grade construction and less fuel inventory) could reduce consequences; however, this must be verified and considered in the criterion evaluation. A PRA (see next bullet) can help the plant understand these safety issues.

- *Probabilistic Risk Assessment* – The URD safety policy makes significant use of PRA in evaluating core damage prevention and accident mitigation (particularly for off-site dose). The use of PRA is a well-established concept in the nuclear industry for the existing fleet (and is used in other industries, such as aviation). However, it is not embraced by all regulators globally.

  Traditionally, PRA has been applied to public safety considerations (that is, defining the risk of releasing radioactive material to the environment). However, the ORG also includes the goal to use PRA for investment protection in addition to safety. Defining the economic and operational risk associated with failure of critical equipment is also important and can give the owner-operator more confidence in the plant's robustness.

  It is well considered that the use of PRA in plant design is an enabling feature that can both ensure that plants are safe and reduce construction and O&M costs. However, an important requirement of PRA is having a known operating history and an understanding of degradation mechanisms for SSCs. Use of PRA is therefore complicated in novel designs, including light water designs, if new components or materials are used or well-known materials and components are operated under new conditions.

In the United States, the NEI has addressed these issues with NEI-18-04, *Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development, R1* (NEI, 2019). The report provides a detailed, risk-informed approach to help demonstrate a safe design. As noted in the report, the review team should verify that the designers have included:

> … incorporation of safety analysis methods appropriate to early stages of design, such as FMEA, HAZOPs, and other PHAs, provide industry-standardized and established practices to ensure that early stage evaluations are systematic, reproducible, and as complete as the current stage of design permits.

When evaluating this subcriterion, the owner-operator should consider the underlying basis used by the OEM when they present the results of any PRA.

- *Hands-Free Safety* – This is an aspirational goal noted in the ORG based on using passive safety features so that the period in which the reactor can remain safe after an event without operator action or off-site electric power is unlimited (or exceptionally long, such as 30 days). This concept may be espoused by OEMs for their plant design, but successful qualification, demonstration, and regulator acceptance might be difficult.
- *Investment Protection* – Although not specifically considered part of "nuclear safety," both the URD and ORG examine the concept of investment protection, development of which would follow many of the same techniques and principles. The ORG specifically notes in its Investment Protection policy that the design should ensure that the plant is protected from extensive, costly, and potentially irrecoverable damage. The design should include features that ensure that forced shutdowns not due to major equipment problems are recoverable without a prolonged shutdown period, and the OEM should provide guidance on how to recover from such issues.

3.4.3.2 Structures, Systems, and Components

The purpose of this criterion is to evaluate the actual design of SSCs. It is not intended that the owner-operator take on the role of design reviewer. Instead, the intention is for the owner-operator to investigate the design at a level of detail necessary to be comfortable that the design will be adequate to their mission and business objectives, and to unearth potential pitfalls that might prevent the plant from achieving a robust design and efficient O&M.

Because all designs will eventually go through a licensing process and are expected to demonstrate that they meet regulations and other minimum requirements, the goal of this evaluation by the owner-operator is to ensure that the design of the SSCs will meet their goals and business objectives over the life of the plant. Examples of questions that the owner-operator should ask are:

- Do the SSCs demonstrate enough margin for the expected lifetime and under currently planned and potential future operating regimes, including margin for potential uprate?
- Are the plant's SSCs and control systems designed so that the plant's maneuverability and flexibility capability will meet the organization's goals for today and any future changes?
- Do the tradeoffs in the design of SSCs appropriately balance upfront costs, O&M costs, and reliability?

The EPRI URD (EPRI, 2014) contains an extensive list of SSC and related design criteria that can be evaluated against the plant design, particularly for ALWRs. The EPRI ORG (EPRI, 2019b) takes a different approach with less specification of requirements but rather identification of key attributes and goals that a new AR design should, as a minimum, specify for the owner-operator to review. The SSCs that one would evaluate for light water plants in a typical electrical-generating mission are well established and covered in Tier 2 of the URD. Owner-operators might want to systematically address those systems, as follows:

- Power generation systems
- Reactor coolant system and reactor non-safety auxiliary systems
- Reactor systems
- Engineered safety systems
- Building design and arrangement
- Fueling and refueling systems
- Plant cooling water systems
- Site support systems
- Electric power systems
- Radioactive waste processing systems
- Main turbine-generator systems
- Materials

However, AR designs and plants expected to perform different missions might not have the same systems. The ORG specifically addresses some requirements for the following reactor types in its Tier III requirements:

- *Gas Reactors* –HTGRs, gas-cooled fast reactors, very-high-temperature gas-cooled reactors
- *Liquid Metal Reactors* – Sodium-cooled fast reactors, lead-cooled fast reactors
- *Molten Salt Reactors* – MSRs, fluoride salt-cooled high-temperature reactors
- *Water* – Supercritical water-cooled reactors

Additionally, the IAEA's *Nuclear Reactor Technology Assessment for Near Term Deployment* report (IAEA, 2013b) provides an alternative categorization that might be useful for less traditional designs:

- Nuclear island
- Conventional island
- Electrical systems and components
- Balance-of-plant
- Cooling systems
- Civil works and structures
- Plant simulator
- Mechanical
- Architectural finish

When assessing this subcriterion, the owner-operator should also evaluate how the designer is addressing the design and reliability of SSCs. As noted in the Tier 2 URD requirements, the plant designer should develop a design reliability assurance program (D-RAP) which, at minimum, would be based on the design or, at best, be used to inform the design. The URD specifically notes that "the D-RAP shall also provide basic information for consideration by a future owner/operator for plant reliability assurance activities" (EPRI, 2014).

3.4.3.3 Human Factors, I&C, and Cybersecurity

This criterion could technically be included with those defined in Section 3.4.3.2; in fact, many external references previously noted include them in that manner. However, for this report, it is broken out separately due to the impact that digital technology is expected to have on modern designs. Existing modern ALWRs have already significantly embraced digital controls, digital control rooms, and more automation than has been used previously, and upcoming ARs are expected to double down on that aspect in their designs. As is already seen in other industrial areas (including aviation and transportation), the use and role of these systems are changing rapidly and will greatly impact the design and operation of any modern industrial facility.

Much of the underlying technology already exists and is in use today. But there are nuances and complexities that must be addressed for their use in nuclear energy.

This criterion covers four specific areas. Each area approaches the whole criterion from a different engineering approach, but the four are ultimately linked and must work well together. The four areas are as follows:

- *Automation and Man-Machine Interface System* (M-MIS) – The general requirements for a M-MIS, sometimes referred to as the *human-machine interface*, are well described in the EPRI URD (EPRI, 2014). The URD notes that:

  > The M-MIS encompass all instrumentation and control systems provided as part of a [nuclear] plant which perform the requisite monitoring, control, and protection functions associated with all modes of plant normal operation (i.e., startup, shutdown, standby, power operation, and refueling) as well as off-normal, emergency, and accident conditions.

  The M-MIS considers several functions, including equipment for data gathering, data communications, data processing, information display, and process control systems. The URD goes into detail in several areas for the M-MIS, including:

  - Instrumentation, including sensors and local instruments, for all safety and nonsafety systems throughout the plant.
  - Automatic and manual controls for all safety and non-safety systems.
  - Protection functions, including safety and non-safety systems.

  Both the URD and the EPRI ORG (EPRI, 2019b) specifically call out policy statements on this subject, with the ORG noting in its *Human Factors and Automation Policy* that the

  > Human-machine interfaces…should be simple and intuitive, be consistent across all system displays, and consider remote or multi-unit operation where permitted by regulations. Any interaction between human and machine creates opportunities for human error.

  It is expected that more modern designs will incorporate more automation than what has been seen to date. Although this level of automation is now common in other industries, the state of the art for new nuclear designs will likely eclipse what has been seen in nuclear so far. This will involve using new types of equipment and software systems in ways novel to nuclear. It will be incumbent on the designers to fully test and vet these systems, and obtaining approval may stress some regulatory regimes.

  An aspirational goal noted in the ORG is for fully remote or autonomous operation by personnel located off-site or for operation to be self-controlling within certain constraints. Automated operation opens the opportunity for many new mission and siting options for nuclear, but it also increases the need for system resiliency and validating safety requirements, and it could induce complications for maintenance.

  When evaluating this subcriterion, the review team will want to ensure that the systems are as simple as possible, consistent throughout the plant, and extensible for future operational changes. Concepts that may push the boundaries for licensing or untested automation should be carefully considered to ensure that they meet the owner-operator’s mission and business objectives and clearly add value (for example, see “Control Rooms” in Section 3.3.1.6). Finally, automation should balance the reduction in human errors with reliability, staffing considerations, and costs.

Human Factors Engineering – The EPRI URD contains a separate Human Factors Policy that expects all aspects of plant design for which there is an interface with plant personnel to incorporate human factors considerations. A key part of this policy is that HFE activities must be included at the beginning of the design and iterated along with the design throughout. The designer should develop clear, written human factors guidance per state-of-the-art expectations and provide that guidance to its design team and its suppliers as requirements.

The EPRI report *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification* (EPRI, 2015b) provides extensive and detailed baseline guidance on human factors design. The EPRI report *Human Factors Analysis Methodology for Digital Systems: A Risk-Informed Approach to Human Factors Engineering* (EPRI, 2021e) takes a modern approach to human factors analysis, balancing the interactions between nuclear safety, economic operation and environmental risks, and the accommodation of human abilities and limitations in the design.

When evaluating this subcriterion, the review team should ensure that that OEM and suppliers are working toward well-developed, fully documented internal guidance that is based on tested and vetted design principles and conforms to societal norms (for example, reading direction, significance of colors).

- *I&C* – The URD and ORG contain extensive requirements for I&C systems. The existing fleet of nuclear reactors was built out using predominantly analog I&C systems, particularly the earlier designs and especially in the United States. Digital systems were included more widely later in the fleet's deployment, gaining more ground outside the United States due to differing regulatory requirements. Today, in the United States and globally, many existing plants have already performed digital upgrades or are planning to do so, increasing the use of digital systems in their plant. The latest ALWR designs that have been licensed and deployed are now extensively digital plants.

  The use of digital systems for I&C is expected to increase as ARs are deployed. However, as noted in the ORG, analog or digital nonprogrammable control systems, especially for safety or post-accident monitoring systems, can (and sometimes should) be considered.

  A significant issue with digital systems for I&C is the concept of diversity and the potential for common-mode failures. There is much discussion in the regulator community about what exactly denotes common mode failures for digital systems and their software, and any digital I&C system will need to balance its approach for cost control, system complexity, reliability, and licensing requirements.

  The EPRI report *Digital Engineering Guide: Decision Making Using Systems Engineering* (EPRI, 2021d) provides a detailed methodology for developing digital systems based on the concepts identified in ISO/IEC/IEEE 15288-2015, *Systems and Software Engineering – System Life Cycle Processes* (ISO/IEC/IEEE, 2015) and ISO/IEC/IEEE 15289-2017, *Systems and Software Engineering – Content of Life-Cycle Information Items* (ISO/IEC/IEEE, 2017). This guidance takes a modern, risk-informed approach to digital engineering that is consistent with the guidance used in other non-nuclear but safety-related industries, such as transportation and aviation. This guidance is currently being used extensively by the U.S. nuclear fleet as they modernize their designs to incorporate more digital systems, and it is recommended that those developing innovative designs follow these principles.

When evaluating this subcriterion, the review team should ensure that the OEM and suppliers are working with clear, modern, standards-based guidance that incorporates risk in their overall design. Design teams should demonstrate that they are taking an iterative systems engineering approach to the design. The review team should also evaluate the licensability of any novel concepts taken on by the OEM and suppliers.

- *Cybersecurity* – Cybersecurity has always been a concern for nuclear. However, the advent of modern digital systems, combined with an increased threat from individual and state actors, significantly increases the need to ensure that any nuclear plant is as secure as possible.

  One of the defining issues in nearly all the digital technology space is that cybersecurity tends to be an afterthought. This is exhibited daily when threat actors take advantage of the design of the internet, which did not specifically consider cybersecurity at the start; internet digital communications protocols are now a patchwork of standards, with cybersecurity controls being added as new threats emerge. For this reason, the URD notes that cybersecurity must be considered throughout all stages of the design process. Further, the ORG states (emphasis added):

  > The concern for malicious acts targeting information systems has become a critical issue for nearly all commercial endeavors and in all public infrastructure. Nuclear power plants represent large capital investments and are sometimes key nodes in infrastructure networks. Maintaining cyber security is essential to the continued security of any large asset and most existing installations have been forced to apply retroactive solutions to facilities that either pre-date most digital technologies or were built when cyber security threats were much less prolific. ***Cyber security should be inherent in the design to ensure that advanced reactor facilities are hardened against the cyber threats of today and tomorrow.***

  Many cybersecurity programs, and much of the guidance available today, takes a deterministic and prescriptive approach to cybersecurity. This approach can be useful for addressing known threat vectors but can be cost-inefficient and often does not allow for resiliency against future threats. Therefore, a more risk-informed approach can support sufficient levels of protection, ensuring plant safety while appropriately minimizing upfront and O&M costs and providing a system that is resilient and flexible against future threats. EPRI's *Cyber Security Technical Assessment Methodology: Risk Informed Exploit Sequence Identification and Mitigation, Revision 1* (EPRI, 2018) provides a basis for a cybersecurity engineering framework that meets these needs. It aligns with EPRI's *Digital Engineering Guide* previously referenced. When implemented together, the two reports provide an iterative process that will ensure that cybersecurity is not considered as an afterthought. This systems engineering approach covers all aspects of the plant's design, and when done appropriately, can inform areas beyond digital engineering and I&C. For example, the layout of the plant could change to add secure rooms, or equipment could be redesigned to minimize its control requirements and thus its digital attack surface.

  When evaluating this subcriterion, the review team should verify that the OEM and suppliers use modern systems engineering-based and risk-informed approaches that incorporate cybersecurity throughout the design and design process. The cybersecurity systems and programs should also be evaluated against local regulations for licensing purposes (see Section 3.4.3.4).

3.4.3.4 Operations and Maintenance

As noted in the Tier 2 Operability and Maintainability requirements of the EPRI URD (EPRI, 2014), there is a "strong relationship between operability and maintainability and overall plant availability and equipment reliability." For this reason, they are treated together as a single criterion in the assessment process. The OEM and suppliers must demonstrate that they have included operability and maintainability features that support the plant's safety, reliability, availability, and sustainability goals.

The URD promotes Operability and Maintainability as top-tier design requirements and sums them up by noting that the following must be included in the design of the nuclear plant:

- The plant must have built-in features that allows for "forgiving operations." This includes features that give operators (human or machine) the time to maneuver the plant, design margin for transient tolerance, and an operations environment in the control room or plant that does not overly tax the operators.
- The plant must be designed for maintenance. This includes not only ready access to equipment for maintenance activities, but consideration of the need to change out equipment if needed (such as consideration of lifting and rigging needs as well as potential obstructions).
- As noted in the EPRI ORG (EPRI, 2019b), health and safety hazards to all personnel, including radiological exposure, must be considered in the design. For example, components and systems requiring frequent maintenance should be in low-dose areas of the plant, and industrial safety should be given equal consideration as radiation protection.

It is incumbent on the designer to not lose sight of the long-term service needs for O&M while concentrating on reducing construction costs and increasing plant efficiency and performance. The designer must find a balance, and that balance must be in alignment with the mission and business objectives of the owner-operator.

- *Operability* – Both the URD and ORD specify many requirements for operability considerations, and the review team should consult these reports for details. In general, the requirements center on ease of operation, simplification, use of modern digital technology and effective HFE, and a forgiving design margin.
- *Maintainability* – The subcriterion of maintainability covers three related and linked attributes—inspection, testing, and maintenance (ITM). The URD's Plant Maintainability and Equipment Reliability Policy notes that plants should be designed from the outset to ensure that they are readily maintainable for their lifetime.

Accessibility to components is a key need for ITM that must be considered in the design. As noted in the EPRI URD:

> Current operating plant designs are large scale facilities that are generally accessible for the conduct of ITM activities. However, due to the nature of evolving requirements based on gained operating experience, even current plants have often found the necessity to seek regulatory relief or have found the need to defer maintenance in order to comply with expanded ITM criteria

Therefore, it is especially important for smaller plants to ensure that ITM is fully considered in the design. Where space is at a premium, automation can make operational tasks easier in confined spaces, sensors and online monitoring can potentially take the place of manual inspection tasks, and automation combined with sensors and online monitoring can be combined to allow for automated testing.

- *Remote or Autonomous Operations and Maintenance* – O&M activities that can be performed remotely or autonomously can increase safety and provide cost efficiencies. Fully remote or autonomous operation of the plant is covered briefly in Section 3.4.3.3. In this subcriterion, the goal is to evaluate more specialized activities, such as online refueling, used fuel and high-level waste management, and automated or robotic maintenance, particularly for reactor designs where such activities could expose personnel to significant hazards such as radiation, radioactive contamination, or chemical or respiratory hazards.
- *Large Component Replacement* – The owner-operator should understand the expected lifetime of large components and the expected methods for potential replacement. For example, is the plant designed for easy removal and replacement, or will SSCs need to be altered or removed to accommodate? The costs for replacing large components, including the purchasing, labor, and lost production for potential extended outages, should be included in the cost calculation in Section 3.5. The review team is cautioned to account only for planned replacement and costs but might account for risk in the suitability scoring (see Section 2.6).

  Note that some proposed advanced reactor designs include an assumption that reactor vessel components, or other large SSCs, will need replacement periodically over the plant's lifetime. This is an important metric that the owner-operator must include in their evaluation for meeting their intended operating life and inclusion in cost calculations.

The significance of this criterion cannot be understated. Although criteria such as Safety, SSCs, and HFE and I&C (see Sections 3.4.3.1–3.4.3.3) are important, they are likely to be considered fully adequate by the time any plant is fully designed and licensed. The owner-operator might have preferences, but any licensed plant should be deployable due to extensive and well-documented requirements and regulatory review. On the other hand, there are fewer regulatory requirements in this area, and nearly none requiring O&M to be efficient and cost-effective if safety is maintained. The owner-operator will have responsibility for operating and maintaining the asset for decades, and unplanned downtime and O&M costs can easily affect the ROI.

A detailed evaluation of this criterion requires an in-depth understanding of the full nuclear plant design, not only from the OEM, but major suppliers as well. For a design previously built, sufficient information will be easily available, perhaps including a tour of an existing facility and interviewing O&M staff. For an unbuilt design, particularly one that is unlicensed, the evaluation should consider the information that is available and the alignment of the overall design philosophy (see Section 3.4.1) and design processes (see Section 3.4.2).

When evaluating this criterion, specific consideration should be taken to ensure that the OEM and other suppliers have evaluated historical operational experience, not only from nuclear but also other industries. They should also have a philosophy of incorporating attributes that provide value and designing out those that do not.

3.4.4 Flexibility and Resiliency

The *Flexibility and Resiliency* criterion includes the traditional consideration of flexibility, maneuvering to support load-following, grid frequency control, and other considerations that are covered in EPRI's *Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability* (EPRI, 2017). Based on this, the EPRI ORG (EPRI, 2019b) notes in its *Flexibility Policy*, in part, that:

> Designs should be adaptably deployed and operated under challenging, changing, or uncertain external conditions and constraints …As a result of this, other components of operational flexibility include the ability of a reactor to use various types of nuclear fuel, being able to integrate with technologies such as topping cycles and energy storage, or the ability to operate in "island mode." …A plant that is flexible can justify or adapt deployment and operation under challenging or uncertain external conditions and constraints, operating when it may otherwise need to shut down, increasing revenues and reducing financial risks.

The ORG further notes in its aspirational goals off-grid operation and black-start capabilities, and the Tier 1 Category for *Reliability and Availability* includes provisions to help ensure that the plant can withstand anticipated equipment failures and "achieve required availability metrics without undue assumptions for off-site support services (e.g., short term storage of fuel)."

EPRI's report *Expanding the Concept of Flexibility for Advanced Reactors* names three flexibility subcriteria, each with several attributes as identified in Table 3-1.

Table 3-1
Flexibility subcriteria and attributes

Subcriteria	Attributes	Description
Operational	Maneuverability	Ability to change power level and outputs in terms of extent and rates to match changing operational requirements
	Compatibility with Hybrid Systems	Ability to operate in concert with other energy-related technologies, such as intermittent sources and energy storage
	Diversified Fuel Use	Ability to operate using a variety of fuel designs, materials, and compositions
	Island Mode Operation	Ability to operate in isolation from other electricity distribution networks, either on a routine or exceptional basis
Deployment	Scalability	The ability to be sized to match energy demand, including current requirements or future growth (such as potentially uprating or adding modules)
	Siting	The extent to which a reactor can be licensed, constructed, and operated where desired
	Constructability	The relative ease with which the reactor system can be built on schedule and within budget

Table 3-1 (continued)
Flexibility subcriteria and attributes

Subcriteria	Attributes	Description
Product	Electricity	The ability to efficiently convert thermal power to electricity
	Process Heat	The ability to produce the desired quality and quantity of heat needed for production
	Radioisotopes	The ability to produce and allow extraction of desirable radioisotopes

The owner-operator will need to carefully consider their mission and business objectives to decide what attributes are important to them. Be careful not to include too many attributes; include only those needed because it is unlikely that any one design could supply them all. Adequate designs could inadvertently be screened out because they cannot meet a specific attribute that was not really required. It is also possible that any design that purports to meet too many attributes could be financially inefficient.

The review team should examine the specific SSCs that would be specifically associated with achieving the goals of the noted attributes. For example, and as noted by the IAEA (IAEA, 2013b) for maneuverability, that examination could involve review of the turbine generator and its control system, an assessment of load rejection capability, an understating of operational margin when at lower power, increased waste generation, and impact on fuel reliability. For diversified fuel use, that might include a review of the primary system flow rates, temperatures, water chemistry, impact from transients, and number of cycles allowed per day.

As with other criteria in this overall section, the ability to review and understand the early and preliminary designs will be more difficult due to lack of information. However, the review team should work diligently to address this criterion, especially if more novel flexibility attributes are required for project success. The IAEA notes a word of caution for these types of flexibility reviews in their Maneuverability element (emphasis added):

> The experience base of the technology holder for this element needs to be established through reviews of technology holder information, historical experience, and discussions with other operators of the equipment (or similar equipment) whenever possible. ***Evaluating the technical features and the key features of load following without data from experience will be difficult***.

The evaluation for a nuclear plant performing the traditional role of firm baseload power is relatively straightforward, especially for already designed, licensed, or deployed plants. However, the idea of nuclear plants taking on other and more diverse missions is relatively new, with little history or established guidance. Even today, existing plants are being asked to operate in ways unplanned by their designers. Even modern ALWRs, which were technically designed more than a decade ago, might not have all the capabilities desired by the owner-operator.

Note: The review team should be sure to consider any other O&M costs incurred operating flexibly when calculating their LCOE or LPC in Section 3.5.2. Typical costs include additional chemical and consumable costs, as well as additional materials and labor costs for increased O&M. EPRI's report *Flexible Power Operations–Guideline for Assessing Costs* (EPRI, 2019c) provides a good set of examples for LWRs and can provide insight when considering non-light water designs.

3.4.5 Fuel, Fuel Cycle, and Waste Management

Regardless of locale, regulations will necessitate that used fuel and radioactive waste be responsibly managed, stored, and, as available, appropriately disposed. Although much of this criterion is focused on the fuel cycle specifically, consideration of other wastes cannot be discounted. Other high- and low-level wastes have traditionally been somewhat easier to manage and dispose, but new designs with novel fuels, fuel designs, and chemistries and materials introduce situations that will need to be addressed.

- *Closed Fuel Cycle* – The EPRI ORG (EPRI, 2019b) notes an aspirational goal of having a plant with a fully closed fuel cycle or using specialized reactors capable of using used fuel from another reactor. A closed fuel cycle is more environmentally and energy-efficient, but external political and economic issues relevant to the locale may be bigger drivers in its success. When evaluating a closed fuel cycle, the owner-operator should evaluate any internal process equipment that would be involved, as well as the entire fuel cycle reprocessing and supply chain outside the plant if external reprocessing is used.
- *On-Line Refueling* – The ORG also notes on-line refueling as an aspirational goal. Some reactor and associated fuel designs are more amicable to on-line refueling than others. Typically, LWRs have not included on-line refueling, but heavy water CANDU reactors have. Reactors using pebble beds or liquid fuel are also obvious candidates for on-line refueling. When evaluating this attribute, the review team should carefully consider the systems used for on-line refueling, their ease of use, maintenance requirements, and potential failures and consequences. Cited here purely as an example, in 2002, EPRI performed a review of the maintainability of the Pebble Bed Modular Reactor Demonstration Plant (EPRI, 2002) and found that for the fuel-handing system:

  > A fuel ball, stuck or lodged in the transport system, will be an enormous problem for the plant. Having a plan for removing a stuck ball, no matter how low the probability of occurrence, and adjusting the system and equipment design where necessary to allow this, is important. Of equal importance is identifying those attributes of the system, equipment, and installation that the plant depends on to ensure that a ball never gets stuck. These attributes should be rigorously monitored during fabrication and installation to ensure that they are obtained.

- *No Refueling* – Some OEMs are sponsoring designs, particularly for microreactors, that are fueled once, potentially at the factory, and then decommissioned, typically after 10 years or 20 years of operation. There can be merit in this paradigm where simplicity is maximized and complexity is reduced, offering significant opportunity for reduced construction and O&M costs. The key attributes for this evaluation are the financial criterion, considered in Section 3.5, and the design of related SSCs for safety, reliability, operability, and maintenance, which are considered in this overall section.

- *Waste and Used Fuel Management* – The ORG includes a policy on Waste and Used Fuel Management, noting that "production and management of wastes should be considered during design and be consistent with anticipated (local) regulatory requirements." Therefore, the following should be considered in the design, particularly for O&M:
  - *Fuel Handling* – the ability to easily manage all aspects of the plant's fuel internal fuel cycle, including receipt and storage of new fuel, new fuel loading, and used fuel unloading operations.
  - *Fuel Pool Storage (or Equivalent)* – an evaluation of how used fuel will be stored immediately after unloading, either briefly for some type of "fuel shuffling" or longer-term but temporarily while the fuel cools before movement to another storage location. The capacity of the fuel pool (or equivalent) to support the life of the plant (including contingency) should be evaluated.
  - *On-Site Dry Storage (or Equivalent)* – an evaluation of how fuel will be stored long-term on site. On-site storage could be needed for an extended time, and this should be accounted for (for example, currently in the United States, there are no other long-term storage options available). The capacity of the dry storage pad (or equivalent) to support the life of the plant (including contingency) should be evaluated.
  - *Low-Level Waste* – 3-52ndersta the issues pertinent to the handling of low-level waste for the existing nuclear fleet of water-based reactors are well known, deployment of new technologies and designs may bring additional or novel considerations, including differing volumes, chemical and radionuclide makeup, waste forms, handling, packaging, and disposal requirements.

  The EPRI URD (EPRI, 2014) contains requirements for the design of liquid, solid, and gaseous radioactive waste management systems particularly relevant to LWRs.

  Non-light water reactors can bring on added complexity requiring new SSCs and potentially more automation due to increased radiation, chemical, and gaseous hazards. Novel designs should, as a minimum and according to ORG policy, demonstrate that they can do the following, all while demonstrating nuclear and worker safety under normal and postulated event conditions:

  - Manage waste and used fuel in a way that minimizes the effect on normal operations.
  - Minimize inventory of difficult-to-manage waste streams.
  - Provide radioactive waste forms compatible with and suitable for offsite transportation and disposal without extensive onsite processing

As previously noted, the owner-operator should not assume any availability for off-site used fuel storage. Although some locales might have different capabilities available, owner-operators are reminded that nuclear plants typically have long lifetimes that can span changes in governing laws, regulatory policy, and citizen sentiment. As noted in the ORG:

> History has shown that the assumption of used nuclear fuel removal from commercial nuclear plants has led to unforeseen complications of plant operations and refueling due to accumulation of inventories and the need to implement alternative on-site storage solutions.

When evaluating the design for this criterion, the owner-operator should evaluate fuel (new and used) and waste storage capacity, equipment capability including automation, plant layout, and SSCs associated with waste and fuel handling. An expectation for the mass of used nuclear fuel[7] created and needing management and storage over the plant's lifetime should be provided by the OEM and the plant design compared against that value. Extra considerations should be placed on operability and maintainability of equipment, including potential worker radiation and contamination exposure for each.

3.4.6 Proliferation Resistance and Physical Protection

The purpose of this criterion is to evaluate the plant's design for *Proliferation Resistance and Physical Protection*. There is no specific definition of *proliferation resistance*, but a plant design can be thought of as being proliferation-resistant if its use and operation would not significantly increase the potential proliferation of nuclear weapons. The plant's use and operation must consider the entire fuel life cycle and the ease with which fissile material can be separated from the fuel and the physical safeguards and security measures used to protect the plant. Although *proliferation* refers to the production of nuclear weapons, the plant must also be protected from other threats and sabotage for the protection of the public and investment protection. The criterion evaluation in Section 3.1.3.2 is intended to be a high-level review, primarily looking at the intrinsic safety and security of the fuel and fuel cycle. For this criterion, more detail will be reviewed.

- *Nuclear Security* – As defined by the IAEA (IAEA, 2020c), and noted by the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA) Office of International Nuclear Security (INS) (DOE/NNSA/ANL, 2021), nuclear security is the "prevention of, detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities." The EPRI URD (EPRI, 2014) has a specific sabotage protection policy that specifies that the design should consider protection along with safety, operability, and costs throughout the design process, and the design should include features (layout, hardening, and backup systems) that specifically address physical protection in the design.

  The EPRI ORG (EPRI, 2019b) includes a policy for threat protection that specifies that the design of the plant should:

  > Protect against internal and external physical and cyber threats that could credibly challenge the integrity of fission product barriers, provide unauthorized access to the fuel, or affect the availability of the plant to fulfill its mission.

  The ORG expects that the plant will be protected and safe, but it also expects that AR designers will take advantage of potential features of their underlying designs to minimize lifetime costs and reduce the need for large numbers of security staff. The IAEA provides recommendations on nuclear security and plant design in *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities: Recommendations* (IAEA, 2011) and associated *Implementing Guide* (IAEA, 2018b): Section 3.28 of the *Recommendations* notes that:

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[7] Used fuel mass is normally represented as metric tons of heavy metal (MTHM), which refers to the mass of all elements with an atomic number greater than 89 in the fuel.

> For a new nuclear facility, the site selection and design should take physical protection into account as early as possible and also address the interface between physical protection, safety and nuclear material accountancy and control to avoid any conflicts and to ensure that all three elements support each other.

This concept is defined in the *Implementing Guide* as "Security by Design," which includes incorporating the required level of security in a cost-efficient manner that is compatible with operations, maintenance, safety, and safeguards.

- *Nuclear Safeguards* – When evaluating this criterion, the owner-operator will also want to review with the OEM their process of achieving "Safeguards by Design." The IAEA report *International Safeguards in the Design of Nuclear Reactors* (IAEA, 2014) describes various security and safeguards functions that can be incorporated into the plant design and operating procedures. The review team will want to verify and understand the design of SSCs and related operating procedures and how they affect safeguards requirements.

  The IAEA notes three high-level objectives for safeguards applicable to a state or nuclear facility, but the objective of most concern to the owner-operator procuring a facility is the potential for the diversion of nuclear material by internal or external actors. There are many process and procedural steps necessary for safeguards monitoring, but there are facility design factors as well. Examples include:

  - Measurement points for flow and inventories of nuclear material
  - Locations for surveillance, containment, monitoring, and verification measures
  - Monitoring reactor power
  - Ensuring that the facility is designed with features relevant to safeguards

The IAEA notes several activities that can take place during various stages of the design and construction phase. A key step for the potential owner-operator is the review of the detailed facility design and confirmation that security and safeguards equipment can meet requirements, which should occur in the final design phase of the plant. Potential owner-operators are encouraged to review the IAEA considerations for SMRs and ARs. For these types of reactors, the designs and fuel and moderator makeup can significantly increase or complicate safeguard management and verification, but they might also ease security requirements.

With respect to security and safeguards, the owner-operator should ensure that the plant design is aligned with local regulatory policy as well as international requirements. The design team should be working with the local regulator, the IAEA, and other pertinent stockholders. In the United States, this would include the NRC (through 10 CFR 73) (NRC, 1993), which has responsibility for regulations, and the National Nuclear Security Administration (NNSA) (DOE/NNSA, 2022). Those outside of the United States looking to invest in U.S. technology should specifically ensure that the OEM is working with the NNSA to best understand international requirements.

Note: Because of the nature of security and safeguards information, it can be difficult to obtain the needed information from the OEM and designers until specific security requirements and processes are in place, which might be after a design choice is necessary. The owner-operator will need to work with the best information they have and then continue ongoing due diligence with the OEM and design partners.

3.4.7 Licensing

Regulatory and licensing process states are covered in Section 3.3.2 from a maturity and remaining effort standpoint. That criterion is about the current state of the licensing process and the remaining effort required, if any, to obtain proper and needed licenses (such as DC, CP, OL, or COL in the United States). Although there is likely to be some overlap and the information collected for that earlier criterion will be useful, the evaluation under this criterion focuses on the technical and prescriptive aspects of licensing. Unlike the previous criterion in Section 3.3.2, when evaluating this criterion, the review team should assess the plant's licensing pathway compared only to the currently known (or imminent) aspects of the regulatory status in their locale. Three attributes are considered under this criterion:

- *Licensing Status* – This is a straightforward evaluation of the current licensing status. Have licenses been obtained, and if so, which ones? If not yet, what exactly has been done to date? For example, have applications been submitted, or are topical reports under review?
- *Ability to License* – This is an evaluation of the expected ability to obtain proper and required licenses **based on the plant's design** (or expected design). For plants already licensed in one locale, it would include the ability to extend into other regulatory regimes if that is a goal. What must be done technically from a regulatory effort to license the existing design, or what technical modifications might be needed to obtain licenses? For plants not yet licensed, this would include an evaluation of the technical aspects of the design, particularly novel SSCs and functions, and the ability to license based on those design aspects in the target locale.
- *Licensing Philosophy* – The intent of this attribute is to evaluate any novel licensing approaches intended to be taken by the OEM. In most cases, standard ALWR designs will likely exhibit few if any novel licensing approaches. However, ARs, particularly smaller ARs, are more likely to take approaches that are novel for the local regulatory authority. If successful, these approaches could reduce licensing, construction, and O&M costs, but they could also extend licensing time or even result in an inability to license, depending on how the OEM's philosophy aligns with the regulator's.

As noted in the preceding, the evaluation of this criterion should be limited to the technical aspects of the design with comparison to the current (or imminent) regulatory requirements. Risks based on maturity and remaining effort are covered in Section 3.3.2. Care should be taken to not double-count that risk.

3.4.8 Constructability

A review of the literature on new nuclear plant development will reveal a constant refrain on the need for the plant design to exhibit *constructability*. The EPRI URD (EPRI, 2014), the EPRI ORG (EPRI, 2019b), and the IAEA *Nuclear Reactor Technology Assessment for Near Term Deployment* (IAEA, 2013b) all note constructability as a policy or key element for technology assessment.

The ORG notes that a failure to meet construction timelines, labor costs, productivity, and material costs can all move a new plant development project from a potential success to a financial burden. It further notes that although there is promise in modular construction techniques, if done improperly, they can increase the risk to a new reactor's construction. The ORG's *Construction Policy* notes that the OEM should:

> Focus on manufacturability, transportability, work efficiency, and construction duration. Similar to maintenance, practical issues relating to the construction should be considered in the early stages of design. Applicable experience and lessons learned from both recent nuclear and non-nuclear construction projects (major infrastructure and process plants) should be applied. A design that is difficult to construct increases risks of cost escalation and schedule delays. The plant owner-operator is concerned with meeting targets of cost, quality, schedule, and risk mitigation. Predictability in construction enhances the owner-operator's confidence in meeting these targets and is nearly as important as lowering costs.

Part 2 of the 2020 OECD Nuclear Energy Agency (OECD-NEA) report *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders* (NEA, 2020) has a helpful review of nuclear construction cost reduction drivers. As noted in this report, it is important for the owner-operator to understand the impacts of design maturity and effective project management for FOAK designs. History has shown that appropriate design maturity and effective project management can reduce the financial risk to a FOAK new plant project by as much as 20%.

The impact of these two components cannot be overstated. Some recent new plant construction projects have not gone well from a schedule standpoint. The NEI notes in the executive summary of their 2020 report NEI 20-08, *Strategic Project Management Lessons Learned & Best Practices for New Nuclear Power Construction* (NEI, 2020), that appropriate design maturity and effective project management are key lessons learned from recent construction projects.

The EPRI URD specifies target schedules for plant construction. From owner commitment to construct to commercial operation, the URD targets 72 months for an evolutionary LWR, 60 months for a passive LWR, and 54 months for a lwSMR. If measuring from "first structural concrete," the times are targeted at 18 months less. Some AR OEMs are proposing schedules shorter than that based on innovative design concepts and construction techniques. But the URD specifically notes that its target schedules are based on "…90% engineering completion before the start of construction to reduce capital and construction costs and the length of construction schedules and increase investor confidence." It also assumes that the design will focus on simplicity and modularization to facilitate construction and that the OEM will develop an integrated construction plan with owner-operator acceptance.

The URD, ORG, and IAEA documents all go into detail on requirements and attributes related to construction that should be assessed by the review team. For the purposes of this criterion, it is recommended that the owner-operator review the following areas:

- *Constructability* – This simply means that the plant design will promote construction in a manner that is as easy and timely as possible, at a minimum cost. Achieving an elevated level of constructability will require the balance of design features, construction techniques, and costs. There are several potential issues to consider, but the review team should be asking questions like the ones below:
  - What is the planned schedule? What is the record of the OEM and its partners?
  - Are advanced construction techniques being used to shorten the construction schedule? If so, are they novel with little history, or is there known experience?
  - Has the cost of materials been so much of a driver in the design that it is potentially reducing the size of the plant to the point of affecting construction schedule?
  - Can it be shown that an iterative design approach was taken, incorporating feedback from AEs and constructors into the design?
- *Advanced Construction Technology* – Modular construction is often considered an advanced construction technique that is necessary for future economically attractive plant construction projects. However, modular construction can be considered in two separate ways. First is the concept that new plants will be built by assembling factory-built SSCs (modules), nominally delivered preinspected and tested and by truck or rail. The second concept is similar but based on the fabrication of much larger modules on site, nominally containing several SSCs fabricated in factories and on-site, then lifted with heavy-lift cranes and set into place. The former is what is often envisioned by developers of SMRs, whereas the latter is more indicative of the techniques likely to be used for ALWRs.

  However, modular construction is not the only advanced construction technology. The URD notes other techniques, such as open top installation, automated welding, composite steel and concrete structures, preassembled reinforcing steel curtains for wall panel and columns, and use of single, continuous concrete pours (often with self-consolidating concrete). Other potential techniques include component fabrication using advanced techniques such as powder metallurgy or additive manufacturing, electron beam welding, 3-D printed concrete, automated rebar placement, all-weather and around-the-clock construction, and use of modern building management information systems, including the use of 3-D and 4-D models.

  The review team will want to understand what techniques the OEM and construction partners are proposing and evaluate the potential risks and rewards of the different techniques.
- *Construction and Design Coordination* – As mentioned under “Constructability,” coordination of design and construction activities is necessary. The URD notes several requirements in Tier 1:
  - Constructor personnel will take part in the design process.
  - The plant design goals should include simplifying and easing construction.
  - SSCs should be standardized (see Section 3.4.1) to increase productivity.

  - Reasonable construction tolerances shall be specified. (Note that this is an important lesson learned from recent projects. Tolerances that are overly constrained can result in significant unnecessary rework.)
  - The design team should be able to show that they have incorporated lessons learned into their design, not just from nuclear development, but other related industries.

  For a completed but not-yet-built design, the review team will want to understand how much coordination was done between the design and construction teams. For less mature designs, the review team will want to understand how much coordination is taking place currently and see specific activities in the development schedule that point to when other activities will happen.

- *Integrated Construction Planning* – As previously indicated, NEI 20-08 notes that an integrated project schedule is a key requirement. The URD goes on to note that:

  > A detailed living construction plan shall be jointly developed prior to start of construction by the Plant Designer, Constructor, and Startup Test organizations, utilizing input from principal suppliers and subcontractors.

  To evaluate this attribute, the review team will want to review any schedules available and ensure that all stakeholders had input into the schedules. The owner-operator will also want to evaluate their own confidence that the stakeholder will keep the schedule up to date as the project progresses and, most importantly, that the owner-operator will have visibility into the detailed schedule for the duration of the project. The owner-operator will want to ensure that all aspects of the construction effort are considered in the schedule and that there is alignment on what portions constitute critical path.

- *Construction Labor Requirements* – Construction labor is a significant part of the OCC (see Section 3.5) and should be evaluated based on total staff needed and overall cost. However, modular construction and other advanced manufacturing and construction techniques might require a significant portion of the construction staff to have specialized skills. These personnel might be more difficult and costly to hire or train, adding cost and schedule risk. The owner-operator should have an understanding from the OEM (or AE or EPC) on the need for specialty construction skills and staff.

When evaluating the attributes under this criterion, the review team must consider the state of the design and the OEM and constructing team’s experience. For designs that have already been built by the teaming partners, historical data will be available. The owner-operator is reminded that although there is still uncertainty, there is evidence that building a similar design more than once can significantly reduce construction risk (see Section 2 of the OECD-NEA report). For designs that have not been built, the owner-operator must obtain evidence from the OEM and construction team that the construction attributes under this criterion have been incorporated into their design and planning. As noted in the IAEA report, “Caution should be used to ensure that any benefits related to constructability are not double counted, given the tight coupling to capital costs.”

3.5 Cost and Commercial Related Factors

Cost-related factors include an evaluation of internal development and project management costs, costs supporting an OEM or suppliers through development and licensing (if applicable), site selection and licensing, construction and operating licensing, EPC costs, O&M costs, fuel costs, and decommissioning costs.

Cost-related information should be developed in a manner that provides for comparison to the budget developed for the mission and business objectives, covering the cost of explorations, engagement with potential suppliers, facility licensing, construction, and operations (see Section 2.2).

It is important to note that these cost estimates are more than just a measure of the two most common new nuclear plant costing calculations (OCC and LCOE). The owner-operator must ensure that risk—in particular, schedule risk—is included. OCC and LCOE work well when comparing two things of equal risk, but they fail when the risks diverge. This is especially pertinent when working with novel designs because much of the early upfront work could be outside those costs due to lower maturity and will therefore require more effort in a techno-economic assessment (TEA) approach versus just a cost estimating exercise. There are several TEA methods available (see the following), but all of them address key concepts:

- *Understanding and evaluating the economic status* – Will this project be profitable in terms that work for our organization?
- *Understanding maturity and remaining effort* – What R&D and related activities are required to bring this technology to market?
- *Understanding uncertainty and risk* – What variables and parameters carry the most uncertainty, and how does that affect our organization's risk calculations?

For examples of TEA approaches that have been taken for new nuclear power applications, see:

- *Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction* (EPRI, 2019)
- *Techno-economic Assessment Methodology and Results* (Quinn, 2019)
- *Techno-Economic Evaluation of Cross-Cutting Technologies for Cost Reduction in Nuclear Power Plants* (Champlin, 2018)
- *SMR Techno-Economic Assessment: Project 3: SMRs Emerging Technology* (NNL, 2016)

The EPRI ORG (EPRI, 2019b) notes in its Economics Policy that any newly developed reactor design:

> Effectively compete with other (nuclear and non-nuclear) technologies to fulfill the specified mission(s) based on evaluation of costs using clearly justified assumptions, consistent with best cost estimating practices for capital, operating, maintenance, and fuel … Regardless of any other areas in which the reactor may excel (safety, performance, environmental protection), if the reactor is not competitive in its chosen market, no owner will pursue it. It is possible for future regulations, resource availability, and market demand to significantly impact the economic performance of the reactor. Thus, a forward-thinking approach should be used to determine the economic strategy of the reactor.

Part 1 of the 2020 OECD-NEA report, *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders* (NEA, 2020), has a particularly good introduction and overview of nuclear power costs.

Because the financial health of the overall project is paramount, the OEM should be able to supply the owner-operator with the information needed to perform a proper evaluation (but not likely until Step 6, when comprehensive engagements, perhaps enabled by nondisclosure agreements, are in place). As noted in the ORG, key information that should be available is:

- *Lifetime costs* – Care should be taken to not necessarily assume the full lifetime of the plant in financial returns due to the uncertainty of long time frames.
- *Tradeoffs made by the OEM in design* – An example is high capital cost in exchange for reduced O&M costs, or vice versa.
- *Assumptions made by the OEM* – These should be very carefully defined by the OEM and fully assessed for validity and risk by the owner-operator.
- *Plant availability, reliability, and capacity* – These attributes are as specified by the OEM, but more importantly how they are being assessed by the owner-operator because they hold significant risk.
- *Socioeconomic factors, including major societal and political changes* – For example, changes in climate-change or environmental policy can drastically change the economics calculus.

The evaluation of costs and commercial considerations at each phase will be similar across the following four criteria because the information and data needed at each stage will become available at roughly the same time for each criterion:

Candidate Technologies – Because little detail is available, the cost and commercial criteria are not normally evaluated in Step 3 for screening candidate technologies. Instead, the owner-operator should have selected an initial slate of potential technologies in Step 2 based on their own mission and business objectives, thus excluding technologies that would clearly not meet their goals due to time frames or overall risk being considered too high.

Candidate Designs – As with Step 3, there is still likely limited information available in Step 5. Therefore, cost and commercial criteria are typically not evaluated in this step. However, at this point, ranges of costs might become available, although with much uncertainty. Although an exclusionary screening of potential designs is not performed, this is a suitable time for the owner-operator to reassess their budget information in their mission and business objectives. There is likely not enough information to include or exclude one design over another, but an appraisal of the owner-operator's assumptions can potentially be made.

Proposed and Alternative Designs – In Step 6, more detailed information should start to become available, but it might not be fully available at the very start of the step. At some point in the process, the best method to obtain the needed financial information will be through formal proposals from OEMs. It is certainly a best practice to obtain bids from more than one vendor, and performance of a first-pass suitability screening in Step 6 will result in a ranked list of top designs from which formalized bids can be obtained from the top two or three. The first pass of

Step 6 would likely not include evaluation of this cost and commercial criteria except on an exclusionary basis and only where enough data are available to be clear that a design will not meet minimum expectations.

Once the first pass is complete and OEMs are selected for formalized bids requests, bid specifications are created by the project team. EPRI's *New Plant Deployment Program Model* (NPDPM) (EPRI, 2008) contains a reference work breakdown structure (WBS) for compiling bids and making an assessment (see Table 3-2).

Table 3-2
WBS for bid specification from EPRI's NPDPM

WBS	Process Step
4.1	Prepare Bid Specification Outline
4.2	Prepare Bid Spec Scope Section
4.3	Prepare Bid Spec Section on Requirements for Vendor-Provided Data and Documents
4.4	Prepare Bid Spec Section on Fuel Design and Performance
4.5	Prepare Bid Spec Comm. Terms Section
4.6	Develop Bid Spec Requirements for Construction
4.7	Develop Bid Spec Input on Labor Costs
4.8	Develop Bid Spec Input on Materials Escalation
4.9	Develop Bid Spec Incentives and Penalties
4.10	Prepare Consolidated Bid Spec
4.11	Review Draft Bid Spec
4.12	Issue Bid Spec to Vendors
4.13	Vendor Meeting to Review Bid Spec
4.14	Answer Vendor Questions
4.15	Vendors Prepare Bids
4.16	Receipt of Bids
4.17	Bid Evaluation
4.18	Questions to Vendors
4.19	Vendors Respond to Questions
4.20	Review Question Responses
4.21	Recommendation to Management
4.22	Applicant Management Review
4.23	Reactor Technology Selection Announcement

Note that although the NPDPM was tailored for certified plant designs, the steps of the bid specification process will be similar for any design. An allowance for uncertainty will be necessary.

The resulting bids can then be used to perform continued assessment in one of two forms. Step 6 can be reperformed for suitability using the detailed information obtained from the bid specification process. Alternatively, the cost and commercial criteria can be evaluated by issue comparison analysis. Probably, the result will be a mixture of the two scenarios, with detailed economic analysis based on financial utility functions and issue comparison analysis used to evaluate more nebulous commercial consideration.

For less mature technologies and designs, information will be incomplete, vague, or have a risk of changing later. The review team will simply need to make their best estimates with the information available and make an accounting for risk.

The next sections detail key criteria that should be evaluated.

3.5.1 Overnight Capital Cost (or Overnight Construction Cost)

As noted by the WNA (WNA, 2021b), the OCC is the capital cost of the plant excluding the cost of financing. It includes EPC costs, including large equipment supply and installation, electrical controls, the owner-operator’s costs (land and infrastructure, project management, licensing, and so on) and any contingencies and effectively assumes that the plant could be built and paid for “overnight,” thus not requiring financing.

Note that a recent study by MIT, *Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design* (Eash-Gates, et al., 2020), found that indirect expenses contributed a majority of the cost rise seen in modern new plant construction projects and owner-operators should work to ensure that estimates used are as accurate as possible.

The calculation of OCC can be useful for several purposes. First, it provides a baseline for the cost that can then be used to determine financing, and two, it allows comparison of two separate designs. The latter purpose, however, is valid only if the comparison is between two projects that have similar uncertainty and risk evaluations; otherwise, it is the equivalent of comparing apples and oranges. Risk must also be accounted for. Unless buying from an OEM that has a demonstrated record, the owner-operator cannot count on any cost or schedule information being correct.

Note: The resulting actual financing charges that will eventually be a part of overall cost and included in the long-term costs (see Section 3.5.2) do contain a measure of risk, but likely do not capture all risks that might manifest themselves for less mature designs.

Users of this report are cautioned that OCC is easy to calculate but difficult to get right.

3.5.2 Levelized Cost of Electricity or Energy and Levelized Product Cost

The LPC is the generic equivalent of the LCOE. The WNA that the LCOE for an electrical generating plant is

> …the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period, hence typically cost per megawatt hour. It takes into account the financing costs of the capital component (not just the "overnight" cost). (WNA, 2021b)

Or, more simply, the calculation can be shown as:

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime}$$

It is beyond the scope of this report to detail the calculation of the LCOE. There are different methods available depending on the desired level of accuracy (with resulting complexity), for example, methods that factor in capacity factors, equipment degradation rates, and tax rates. Examples of methodologies can be found at the U.S. National Renewable Energy Laboratory (NREL) (NREL, 2022) and the Corporate Finance Institute (CFI) (CFI, 2022).

The preceding version of the LCOE calculation is useful for pure electrical generation missions but inadequate for missions that involve different end-products. However, in the end, this simple LPC calculation is nearly the same:

$$LPC = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Product\ Produced\ Over\ Lifetime}$$

In this case, the NPV of the product could simply be the value of steam or heat generated (that is, the equivalent of the value if produced in some other way). Or, if the plant is truly part of a non-energy mission, such as for development of chemicals or petroleum products, the NPV of the product could be considered based on those end-products, which might be much more valuable than the energy input.

For calculation of the LCOE or LPC, key parameters are plant size (output), capital investment cost, initial investment per unit of capacity, fixed costs, fuel costs, O&M costs, other per-output unit costs, the expected lifetime, and discount rate. Most utility organizations have internal methods for these calculations. It is important that all fixed and variable costs be accounted for.

Much like OCC, the LCOE (or LPC) is easy to calculate but difficult to get right. Due to long plant operating lives, there is significant risk because this calculation depends on long-term values that can change over time but are not included in the calculation (for example, changes in regulations or tax policies).

Note: Although the LCOE (or LPC) includes capital costs (that is, OCC) in its calculation, the two values are normally used at separate times for distinct reasons. OCC is particularly significant in construction financing. This is especially true when costs are reimbursed through facilitation by the local public utilities commission and the LCOE/LPC is used to evaluate the long-term costs and financial return of the facility and includes the costs of financing not included in the OCC.

3.5.3 Other Costs

This is an evaluation of costs unrelated to OCC or LCOE (or LPC) and typically includes those costs aligned with the cost of exploration, engagement with potential suppliers, and potentially facility licensing. These costs are not considered to be part of the project proper, which might have a specific definition internal to the owner-operator's organization or with regulators for tax purposes or cost recovery. These costs are especially relevant if partnering with an OEM to help shepherd a design through to commercialization. Costs can be in several areas and could be innocuous or quite large. Examples include:

- Initial team exploration
- Technology assessment (in accordance with this guidance)
- Engineering reviews of an OEM's early design and licensing
- Limited financial support for smaller tasks, such as limited testing
- Significant financial support to the OEM for design and licensing
- Risk and contingency costs (use caution to ensure that these costs are not double-counted)

The point here is to simply ensure that all costs are covered in the evaluation. The monetary value for items under this catchall is likely to be relatively low compared to the total cost of a nuclear deployment. However, if not allocated in some way to a larger formal endeavor (such as approved by the public utilities commission or company board of directors), authorized budgets for the team might also be low. The important consideration is an evaluation of the costs of working with an individual OEM against the mission and business objectives. Care should be taken to not spend too much time evaluating costs that are equivalent across the board for all candidate OEMs and designs here. Rather, concentrate on the differences based on the level of effort needed to help shepherd designs through completion of the project.

3.5.4 Commercial Considerations

Before embarking on a high-cost, high-risk project, such as building a new nuclear facility, any good organization will perform a comprehensive evaluation of the commercial relationship, engagement, and terms that will be formalized as part of final contractual agreements. Each organization will have its own internal understanding of what makes for good commercial considerations. Commercial considerations should align with the owner-operator's mission and business objectives, but it is difficult to express them early in the assessment process because the data and information is dependent on the OEM and their partners (and their respective situations and mission and business objectives). This, along with much negotiation, will drive the results.

The possibilities for different commercial considerations are many, but as noted in an IAEA presentation, *Trends and Considerations in the Development, Contracting, and Financing of New Nuclear Power Plants* (IAEA, 2019), a few that should be considered as a minimum are:

- *Ownership and Financing* – Corporate, government, or mixed; privately owned or consortium; build own and operate; vendor equity; and strategic investors.
- *Contracting* – Turnkey (EPC), split package, multiple packages, collaborative models.

- *Pricing* – Lump sum, cost-reimbursable, target price, fee at risk, hybrid or phased.
- *Regulatory Process* – Depending on the locale, there might be options for the regulatory approach that could affect total costs and risks.

Recent global new plant deployments have used several different commercial models, and some models are more aligned with certain locales and their financial and regulatory policies. There are many lessons learned about the positive and negative potential within different commercial models. Recent evidence indicates that there is no single correct model, but that the key to success is a model that aligns with the actual situation (that is, shows a true understanding of the maturity of the design and capabilities of all stakeholders) and alignment of all parties in goals of the project and its incentives.

Owner-operators are reminded that they cannot contract away all risk from projects this large, especially if working with smaller organizations, where the value to the supplier might be well less than the cost of the project.

4
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A

POTENTIAL NUCLEAR ENERGY MISSIONS

A.1 Nuclear Energy Missions

Although there are a few examples of other uses, civilian nuclear has traditionally been used for electricity generation. However, growing interest in carbon reduction, in concert with capabilities inherent in advanced designs, opens more possibilities for new missions for nuclear energy. Each of these missions will significantly alter the purpose and need for the project and will affect both the definition and identification of technologies and designs considered to be viable. Table A-1 identifies the potential missions explored in this report.

Note: The EPRI ORG (EPRI, 2019b) specifically calls out the following missions: electricity generation (grid or off grid), process heat, actinide transmutation, and radioisotope production. Other derivative missions are also noted in Table A-1.

Table A-1
Potential nuclear energy missions

Primary Mission	Business Objective	Description
Electricity Generation	The most common mission for civilian nuclear plants in the world today.	
	Firm	Often referred to as *baseload power*, firm generation is typically provided by large GW-size plants. The plant might have some limited flexible attributes to respond to the grid. This is the equivalent of Grid in the ORG.
	Flexible	The use of (typically) smaller and more flexible nuclear plants that may participate in a more decentralized system providing electricity “closer” to end-users, and potentially providing “islanded” services for communities or industrial plants. This includes Off-Grid from the ORG.
Process Heat	The use of nuclear power to generate process steam (or possibly hot water or other heat transfer medium) as a heat carrier, instead of electricity. Technically, this could be done by any nuclear plant, but higher temperatures from some advanced designs open new opportunities.	
	District Heating	Providing centralized heating for communities.
	Industrial Processes	Providing process heat for use in industrial processes, such as those used in the petroleum or chemical industry.
Cogeneration	Production of both electricity and process heat, either simultaneously or individually, based on usage needs.	

Table A-1 (continued)
Potential nuclear energy missions

Primary Mission	Business Objective	Description
Product Generation	Industrial processes in which nuclear-based electricity, heat, or a combination of the two, are used to develop products.	
	Hydrogen Production	Hydrogen can be produced by electrolysis, steam electrolysis, thermochemical production, and steam reforming.
	Desalination	Brackish water can be desalinated through thermal or membrane-based technologies.
Other Missions	Isotope Production	Use of non-power microreactors for creation of commercial isotopes for medical or industrial purposes using fission-based technologies.
	Actinide Transmutation	The transmutation (or "burning") of the used fuel from other reactors. This mission refers to the reduction of nuclear waste; however, it would likely be paired with another mission (likely electricity generation) because the transmutation process will generate heat.
	Test, Research, and Demonstration Reactors	The deployment of reactors for the purposes of testing nuclear fuels, materials, and sensors, or for demonstrating integrated performance and economics of nuclear technologies.

Note that it is possible for any nuclear facility to target multiple missions at the same time. As a cogeneration example, a plant primarily intended for firm electrical generation could use excess heat for hydrogen production instead of down-powering when solar power is at its peak.

A.2 Electricity Generation

Although there are some documented exceptions, the traditional business objective for nuclear plants globally has been *Electricity Generation*. As of October 2021, 10% of the world's electricity is generated by about 440 nuclear power reactors, with 50 more under construction. The U.S. has more reactors than any other country, with about 20% of U.S. electricity coming from 93 nuclear plants. To compare, Canada gets about 15% from nuclear, Finland and Belgium average about 35%, France about 70%, the United Kingdom about 15%, and China about 5% (WNA, 2021).

According to the February 2021 EIA Annual Energy Outlook (U.S. EIA, 2021), between 2020 and 2050, the need for nuclear electricity is expected to remain flat (500–1000 GW hours, depending on various economic scenarios), but that includes the replacement of older plants being taken offline. However, total U.S. electrical generation is expected to increase by about 1500 GW hours over the same period (again, depending on the scenario and including retirements). This outlook does not consider much conversion of non-electrical energy to electrical (for example, a transition to electric cars) for several current U.S. policy-related reasons.

According to the IEA *World Energy Outlook 2021* (IEA, 2021), between 2020 and 2050, global electricity consumption will increase from 20% to between 30% and 50% (depending on various carbon reduction scenarios), and nuclear capacity will increase by about 10–30% (depending on the scenario).

A.2.1 Firm Nuclear Generation

Until recently, in the United States, nuclear generation has been almost exclusively in the form of *firm*, or baseload, electricity.

Note that according to the U.S. Energy Information Administration (U.S. EIA, 2021b), there is a slight difference between *baseload* and *firm* power. *Baseload* means the minimum amount of electric power delivered or required over a given period at a steady rate, with *baseload capacity* referring to having the assets needed to serve those loads. *Firm* means the power or power-producing capacity intended to be always available during the period covered by a guaranteed commitment to deliver, even under adverse conditions.

Although there is no specific technical reason that it must be so, firm nuclear generation has traditionally been in the form of large GW-sized, water-based (light water or heavy water) plants. This has largely been driven by economies of scale and the needs of the power system in most countries.

Because ARs have the potential to be more economically viable at smaller scales, opportunities for firm power using innovative technology designs become available, for example, by deploying a smaller reactor as the firm power source for a remote community.

From a technology selection perspective, selection of any nuclear plant with an objective of firm electricity generation would follow the process and criteria in Sections 2 and 3. If significant, traditional, firm power is the goal, traditional large light water plants might make the best choice. However, it is likely that even when firm power is a driver, oncoming changes to grid operation will necessitate additional flexibility, inviting a look at AR designs.

A.2.2 Flexible Nuclear Generation

Although there have been some regulatory reasons for this (NRC, 2019), the historical makeup of the U.S. electrical system and typical use cases have not supported this operating regime. Outside of the United States, the methods of operation have been mixed, with some countries favoring the firm generating model and others allowing for more *flexible* operation. However, the global need to operate nuclear plants more flexibly is increasing. As discussed in a 2018 IAEA (IAEA, 2018) report on non-baseload power in nuclear plants:

> For commercial, technical and regulatory reasons, most existing nuclear power plants are optimized to operate at steady full power, known as baseload operation, because it is generally considered to be the most efficient use of capital investment. However, in a few Member States, the nuclear units are operated flexibly, and in several Member States, there is an increasing need to operate nuclear units flexibly, especially in those installing a nuclear power plant for the first time. The primary reasons for this are a large nuclear generating capacity relative to the total capacity, growth in renewable energy generation, and deregulation or structural changes of the electricity supply system and the electricity

> market during the long operating lifetime of a nuclear power plant. These necessitate technical and regulatory changes, and also operational, economic and financial rearrangements, to maintain the efficiency of capital investment.

The term *flexible* can have several meanings, and a new plant owner-operator should consider which of these are applicable to their business objectives. Some plant designs might be better at providing different flexibility services than others, so technology selection can play a vital role. According to the same IAEA report, typical flexibility roles include:

- *Load following*, including planned reduction or increase in power and unplanned (instructed or requested) reduction or increase in power
- *Frequency control*, including continuous frequency control, frequency control outside a specified frequency range, and frequency control within a power range
- *Other forms of flexibility*, including load shedding, design power transients, reactive power control, house load operation, and use of energy storage systems, such as batteries (electrical) or molten salt (thermal)

In locations with high renewables penetration, some type of plant flexibility will likely be a requirement. In addition, it is expected that climate change could significantly affect the entire electrical grid (U.S. GAO, 2021), requiring plants with more flexibility and resilience.

From a technology selection perspective, selection of any nuclear plant with an objective of flexible electricity generation would follow the process and criteria in Sections 2 and 3. Although some water-based GW-sized plants have capability for limited flexibility, newer AR designs are likely to be a target technology.

A.3 Process Heat

The objective of *Process Heat* involves the use of steam for *district heating* or other *industrial processes*. Most process heat applications are expected to require high-temperature superheated steam, and some reactor concepts are better suited to providing it by design than others. Added electrical heating can be used to raise the steam temperature if needed, but at the cost of reduced efficiency from the plant. Some systems might use lower-temperature water or some other heat transfer medium, such as a molten salt.

According to the International Energy Agency, nearly 6% of all global heat production is supplied through district heating (IEA, 2019), with the majority of that from China, Russia, and the European Union. Although the United States produces only a small fraction, there are still about 2500 district heating systems in the country using about 200 BBtus/year (Steve Tredinnick, 2013).

There is also a significant opportunity to use nuclear in process heat applications. In the U.S. manufacturing sector alone, nearly 7500 TBtu/year of production are needed for process heating, with only about 5% currently coming via electricity generation, the remaining from localized steam or carbon-based fuels (U.S. DOE, 2019).

In the case of process heat supply, several scenarios could arise. These scenarios are as follows:

- Process heat is to be supplied for district heating. The set of potential technologies and designs will be driven by the output temperature and overall thermal demand. Siting will be a particular issue, limited to areas within a feasible heat transfer supply (steam, hot water, or other heat transfer fluid) distance from the designated community. ARs are expected to have small emergency planning zones (potentially limited to the site boundary), and in the United States, regulations are being considered by the NRC that would allow for deployment in areas with slightly denser populations (NRC, 2022) than allowed currently. This scenario would need to balance the transmission of heat to population centers with other health and safety concerns.
- Process heat is to be supplied to an existing industrial facility (or a large industrial park). In this case, the plant would be limited to areas within a feasible heat transfer supply (steam, hot water, or other heat transfer fluid) distance from the industrial plant. SMRs or microreactors are likely to be targets for this mission.
- Process heat is to be supplied to multiple existing industrial facilities at separate locations. Similar constraints would apply as described in the first scenario. Evaluations would also have to address business, regulatory, and socioeconomic conditions at the multiple industrial/nuclear plant locations. If process heat is supplied to multiple facilities, larger reactors might need to be considered.
- Industrial and nuclear facilities are sited as a synergistic unit. In this case, the selected technologies and designs must be carefully defined based on considerations of both business optimization for the industrial plant and nuclear plant capability. Owner-operators would also need to consider business, regulatory, and socioeconomic conditions in different jurisdictions as well as consider the alternatives under regulatory processes applicable to the new industrial plant. This scenario would be complex in terms of siting and plant capability considerations, and owner-operators might wish to consult with cognizant regulatory agencies to clarify acceptable approaches.

The selection of a technology or design is not necessarily driven by siting consideration, but the final proposed and alternative designs must be compatible with the site based on several criteria, including the footprint, water needs, seismic requirements, population density, and other health and safety criteria. Siting a nuclear plant for a process heat mission can significantly reduce the available siting options for a new plant while also imposing several design constraints (see the following), so siting must be considered. Owner-operators should review the EPRI *Siting Guide* (EPRI, 2015), which contains detailed information on siting.

From a siting perspective, development of any nuclear plant with an objective of providing process heat, for district heating or industrial use, would follow the process and criteria in Sections 2 and 3. Due to the likely requirements for high-temperature steam, newer AR designs are likely to be a target technology.

When steam or heat is the product of a nuclear plant, this means that the industrial process in consideration is at least a partial heat sink for the plant. Partial or total loss of the industrial system could greatly affect the nuclear plant, causing a turbine or reactor trip. This must be accounted for in the plant safety analysis and, from a siting perspective, must be understood when sizing the nuclear plant's cooling water systems and locations of its inlets and outlets (IAEA, 2007).

Other issues are related to proximity of the industrial process to the nuclear plant and its relationship to the plant from a safety basis. The overall siting criteria must address the connection between the two systems. Principal concerns are:

- Siting *Region of Interest* – The region of interest will be constrained by the industrial use facility and the practical distance for heat transmission.
- Accidents – The coupling of the industrial systems to the nuclear plant can affect the safety basis of the nuclear plant. An understanding of how tight that coupling is and how a failure at the industrial facility could affect the plant is necessary:
    - How might an earthquake affect the plant, perhaps decoupling the heat sink?
    - To what seismic criteria must the process plant be designed?
    - How much water does the process plant require?
    - Does the industrial facility's process present a hazard to the nuclear plant (see Section A.5)?
    - How does the connection to the industrial system affect the potential for additional radionuclide pathways to be considered?
- Plant Operations – The proximity of the industrial plant, including workers and traffic, will affect nearby population calculations and could significantly affect emergency planning procedures. Depending on the ultimate product, such as chemical, petroleum, or hydrogen, there may need to be additional considerations regarding nearby hazardous land use. Locating the industrial system outside the EPZ would likely be prudent if technically feasible. Traffic to and from the facility, especially if hazardous materials are being shipped, must be accounted for. The socioeconomic criteria might need to be considered for both the nuclear and industrial facility, for example, understanding population influx if construction for both takes place simultaneously.
- Land Use and Ecological – A determination must be made as to whether the industrial facility is technically considered part of the nuclear project or rather some adjunct "businesses" where many of the siting criteria may differ because they fall under different regulatory regimes. The industrial plant's impact on the various ecological issues will need to be accounted for at some level but might depend on how tied the industrial plant is to the nuclear plant.

- Transmission – Transmission of the steam or heat will need to take place through steam or water piping, requiring a corridor to be considered and evaluated. Incoming offsite power will still be needed.
- Engineering and Costs – There will be unique considerations that must be accounted for to understand the engineering effort needed and calculate costs. For example, depending on the proximity of the industrial system to the nuclear plant, roads, rail lines, and barge access might need to increase to support construction of both facilities.

A.4 Cogeneration

Cogeneration refers to using the nuclear plant for production of both electricity and process heat, either simultaneously or separately depending on usage need (for example, generating steam heat during the afternoons when solar generation is high, then switching to electricity at night). From the perspective of electricity generation, a cogeneration plant would be considered a flexible plant. For siting, key drivers for site selection will be controlled by the technical limitations of the steam transmission system, constraining the ROI. Note that in the case of cogeneration, an electrical transmission corridor will also be needed. For technology selection considerations, key drivers will include the plant's capability to operate flexibly, potentially on short notice, and its ability to provide the needed process heat.

A.5 Product Generation

Nuclear generated electricity or process heat can be used for any number of industrial processes and product generation, with petroleum refining, chemicals, forest products, food and beverage, and iron and steel using most of this energy in the United States (U.S. DOE, 2012). However, two products are under special consideration for use with nuclear power: *Hydrogen Production* and *Desalination*.

The use of hydrogen as an energy carrier and fuel is considered desirable because of its low-carbon footprint. If carbon reduction targets are to be met:

> … a future energy economy will need to replace oil and reduce greenhouse gas emissions (GHGs) for climate protection. The worldwide interest in hydrogen as a clean fuel has led to comprehensive research, development, and demonstration activities whose main objective is the transition from a fossil based to a 'CO_2 lean' energy structure. (IAEA, 2013)

Hydrogen production methods include low-temperature electrolysis (electricity only), high-temperature steam electrolysis (steam and electricity), thermochemical production (heat), and steam reforming (heat and steam). It is beyond the scope of this report to expound in detail on these methods, but it is important to understand that some methods are generally carbon-free, whereas others are not; some use electricity only, heat or steam only, or a mixture of both; and that hydrogen production processes are rather inefficient. Although some small-scale localized production facilities serving an industrial complex, for example, could potentially make use of smaller reactors, a full-scale effort sized to meet carbon reduction goals requires gigawatts of capacity, preferably running at high temperatures for electrical efficiency or high-temperature steam production.

Clean water is a need for all global citizens. This has always been the case, but the importance is magnified as global economic development expands and the impacts of climate change (such as drought and freshwater contamination) are felt.

According to the IAEA (IAEA, 2015):

> Water scarcity is a global issue, affecting many countries every year. Apart from water conservation, pollution control and water reclamation, solutions for new sources of fresh water, including desalination, are also being considered to meet the water shortages. The rising concern over fossil fuel cost and its uncertain availability as well as other associated environmental concerns has prompted a search for alternative energy sources for the future desalination needs, including nuclear energy. Nuclear seawater desalination is becoming more favourable than conventional systems due to environmental concerns over the increasing concentration of GHG in the atmosphere, particularly carbon dioxide.

There are currently more than 18,000 desalination plants (U.S. GS, 2021) installed in 183 countries (IDA, 2021), not only in the United States (particularly southern California), but also globally (middle east Gulf countries and the Caribbean Islands, for example). However, a 2015 UNESCO study (UNESCO, 2015) noted an ever-increasing need for fresh water globally with desalination, including desalination driven by nuclear, likely being a technological necessity to achieve global heath, economic, sustainability, and social goals.

Desalination processes are nominally separated into two groups of processes—thermal-based and membrane-based. The most common thermal processes include multistage flash, multieffect distillation, and vapor compression, and the leading membrane processes are reverse osmosis (RO) and electrodialysis. Combined, multieffect distillation and RO appear to be one of the best methods for high-volume desalination (IAEA, 2007), thus incorporating both heat and electricity.

Siting and technology selection considerations for both hydrogen and desalination would be like those for cogeneration and process heat applications. Clearly, any localized hydrogen production would need to be considered as a nearby hazardous land use, and with desalination, brine discharge must be considered in relation to the plant’s cooling water supply and ecological conditions.

A.6 Other Missions

The following missions are not the focus of this report; however, they are presented here for completeness.

A.6.1 Isotope Production

For the purposes of this report, isotope production includes the bulk production of isotopes for use in medical and industrial processes, typically molybdenum-99 (Mo-99) and derivative products, produced in a non-power reactor, of which in the United States, the construction and operation fall under 10 CFR Part 50 (NRC, 1998). Prospective owner-operators are pointed to NRC NUREG-1537, *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors* (NRC, 1996b), to understand the technical criteria for an isotope production facility.

An organization's business objectives will be a key consideration in the selection of a technology and design for an isotope production facility. Although many types of larger commercial reactors can generate isotopes, dedicated isotope production facilities are generally analogous to microreactors.

A.6.2 Actinide Transmutation

Most new reactors are expected to be designed to perform electricity generation or process heat missions and will primarily serve competitive commercial markets where the end-product has economic value. However, some reactors address public needs, such as actinide burning for non-proliferation and waste management, where the service or product provides a public or societal good supported or driven by national policy.

Because reactors designed for actinide transmutation generate significant amounts of heat, it is expected that they will also support either an electricity or process heat mission as well. Whereas LWRs and HWRs (such as CANDU) can perform limited actinide transmutation, modern plants are expected to be advanced fast reactors. See *Molten Salt Reactors (MSRs): Coupling Spent Fuel Processing and Actinide Burning* (ORNL, 2003) for an example.

Although these reactors can usually be licensed through a commercial regulator, because of the non-proliferation concerns, it may be that they are licensed by another government entity in some locales. Regardless of the regulator and licensing, technology and design selection will still be based on the mission and business objectives. However, note that the process of actinide transmutation might warrant additional considerations for safety, performance, operations, and waste management that must be accounted for in the design and siting.

A.6.3 Test, Research, and Demonstration Reactors

In the United States, test, research, and demonstration reactors can be either authorized by the DOE or licensed by the NRC. Each organization has specific roles and responsibilities as well as unique definitions, rules, and requirements that must be followed (U.S. DOE, 2015) (NRC, 2021). Test and research reactors typically range from about 1 MWt to 300 MWt in size and include university or other federally operated reactors. Demonstration reactors are expected to range in size from 1.5 MWe to 500 MWe (INL, 2022). DOE licensing is not discussed further; however, both test and demonstration reactors licensed under the NRC would be considered Class 104 reactors, licensed to 10 CFR 50 (NRC, 1998). As with isotope production, developers are pointed to NRC NUREG-1537 (NRC, 1996b).

As of publication, Kairos Power, LLC, had applied to the NRC for a construction permit for their Hermes advanced test reactor, a low-power (35-MWt) test reactor intended to support development of their fluoride salt-cooled, high-temperature reactor technology (Kairos Power, 2021).

B
FUNCTIONAL ROLES IN THE TECHNOLOGY ASSESSMENT PROCESS

The process of completing a technology selection study as outlined in this report involves a multidisciplinary project team with well-defined management and technical roles, along with executive sponsorship for both authorization of resources and corporate decision-making. Project staffing (that is, the assignment of specific individuals to project roles) will vary by organization for two reasons. First, the responsibilities for the technology selection process execution, business decision-making, long-term planning, and commercial issues lie in various places within different owner-operator organizations. Second, owner-operators may elect to provide some project functions through subcontracts to specialty technical consultants.

However, even though owner-operators will fill the technology selection roles differently, there is a set of basic functional roles that must be executed. These roles and a brief description of the functions applicable to each are covered in the following sections. In addition to the responsibilities listed, persons filling these roles might also participate in criterion scoring, weighting workshops, or other activities to identify the relative importance of the assessment criteria.

Note: Project roles described in the following focus specifically on selection of a proposed design and the consideration of alternatives. They do not address the broader spectrum of roles and responsibilities that would be required for full deployment of a new nuclear power plant.

B.1 Executive Manager (Owner-Operator)

Authorize the technology selection project and budget; commit corporate funds; and make corporate decisions (or function as liaison to a corporate decision authority) on technology selection. Ratify interim decisions during technology selection analysis, as required by company operating protocols (for example, contractor selection, results of technology screening, down-select decisions, and conduct of technology and design studies). Obtain commitment for technical support resources as required from internal organizations.

B.2 Operational Manager (Owner-Operator)

Oversee functional execution of the technology selection project, coordinate inputs from internal organizations, manage subcontractor(s), and execute other duties/decisions as delegated by the executive manager.

B.3 Project Manager (Owner-Operator or Contractor)

Execute the technology selection project, as outlined in a technology assessment plan developed in accordance with this report. Coordinate technical inputs and prepare recommendations for selection and screening decisions (down-selects, technology and design studies, designation of a proposed design and alternatives).

Note: If this individual is an owner-operator employee, this function could be performed by the same individual who acts as the operational manager.

B.4 Product Use and Transmission Planning Liaison

Provide overall guidance on the relationship between the plant and its end-uses. For an electricity generating plant, this would include geographic locations and system management considerations (such as load centers, available transmission capacity, and voltage support needs). Function as a subject matter expert (SME) for transmission-related criteria, if required. For other product missions, this person would manage similar relationships, for example, between the technology selection team and an industrial facility that intends to use resultant process heat.

B.5 Communications Liaison

Provide operational guidance to project staff on internal communications and external public relations/public interface policy. Need and effort are based on how public an organization wants their selection process to be. Function as an SME for public acceptance aspects of site evaluations and technology selection, if required.

B.6 Commercial Contracting Liaison

When final designs are output from Step 6 of the process, commercial considerations are likely to weigh heavily in the decision process. Additionally, if working with multiple OEMs to receive proposals, a commercial lead is needed to manage the processes.

B.7 Technical Discipline SMEs

Collect and analyze data relevant to technology and design suitability; develop criterion ratings; recommend and conduct additional studies and characterize uncertainties. For the criteria listed in this report, expertise in the following technical disciplines could be required, depending on the complexity of the issues associated with characterizing a design’s suitability:

- Design basis (including risk and safety)
- Major plant systems (fuel, reactor, steam, turbine generator, balance-of-plant, and so on)
- Engineering (all major disciplines)
- Siting (including demographics, socioeconomics)
- Construction (technologies, management, and costing)

B.8 Existing Plant Operating Staff

Provide information and technical data to support technology selection evaluations. Provide liaison with the technology selection operations manager on evaluation of the potential impacts of selecting various technologies or designs. Input from existing operating staff can provide good insight, but care should be taken when evaluating innovative technologies that, by design, do not operate in ways that are traditional or familiar.

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