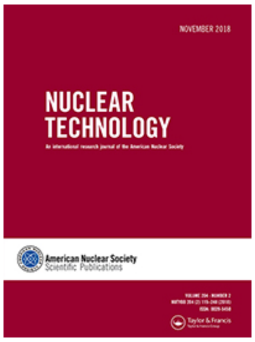

Nuclear Technology

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Taylor & Francis Group

ISSN: 0029-5450 (Print) 1943-7471 (Online) Journal homepage: https://www.tandfonline.com/loi/unct20

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To cite this article: Sherrell R. Greene (2018) The Key Attributes, Functional Requirements, and Design Features of Resilient Nuclear Power Plants (rNPPs), Nuclear Technology, 204:2, 131-146, DOI: 10.1080/00295450.2018.1480213

To link to this article: https://doi.org/10.1080/00295450.2018.1480213

NUCLEAR TECHNOLOGY · VOLUME 204 · 131–146 · NOVEMBER 2018

DOI: https://doi.org/10.1080/00295450.2018.1480213

The Key Attributes, Functional Requirements, and Design Features of Resilient Nuclear Power Plants (rNPPs)

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Received March 16, 2018
Accepted for Publication May 21, 2018

Abstract — *This paper builds on previous work that characterized the nature of the nuclear power plant (NPP)–electric Grid system, the concept of Grid resilience, and the potential of current U.S. NPPs to enhance the U.S. Grid, integrated Critical Infrastructure, and societal resilience. The concept of a resilient nuclear power plant (rNPP) is defined. Two rNPP Key Attributes and Six rNPP Functional Requirements are presented. A preliminary discussion of some rNPP design features that could enable an NPP to achieve the Six rNPP Functional Requirements is presented, along with a preliminary discussion of some rNPP regulatory, siting, and economic considerations. Taken as a package, the Six rNPP Functional Requirements define an NPP performance envelope that extends the societal value proposition of nuclear energy well beyond that of traditional baseload electricity generation. The paper lays the foundation for exploration of high-value rNPP applications and for future rNPP conceptual design studies.*

Keywords — *Grid resilience, Critical Infrastructure resilience, resilient nuclear power plant (rNPP).*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Previous analyses of the response of current U.S. Generation II and Generation II+ nuclear power plants (NPPs) to major Grid anomalies[1–3] concluded that current U.S. NPPs do not deliver the Grid resilience benefits nuclear power can and should provide. In those analyses, the author introduced the concept of a "resilient nuclear power plant," or "rNPP"—a NPP intentionally designed, sited, interfaced, and operated in a manner to enhance the resilience of the U.S. national electricity supply system, or "Grid"—along with Six rNPP Functional Requirements. This paper moves beyond the previous analyses to provide a more detailed description of the Six rNPP Functional Requirements and a preliminary assessment of rNPP design features that would enhance a plant's ability to achieve the Six rNPP Functional Requirements. Both the previous analyses and those discussed in this paper are products of the multiphase research effort depicted in Fig. 1. This paper discusses the results of Tasks 4 and 5 in Fig. 1.

Section II briefly reviews the definition of Grid resilience adopted by the author and employed as the context for the analyses discussed here. Section III defines the concept of an rNPP in terms of its purpose, and the two rNPP Key Attributes. Section IV provides an in-depth discussion of the Six rNPP Functional Requirements—the performance attributes that distinguish rNPPs from current U.S. NPPs. Having defined the concept of an rNPP, its two Key Attributes, and the Six rNPP Functional Requirements, Sec. V provides a preliminary characterization of some of the design features future rNPP designers might consider as avenues to achieving the Six rNPP Functional Requirements. Section VI briefly

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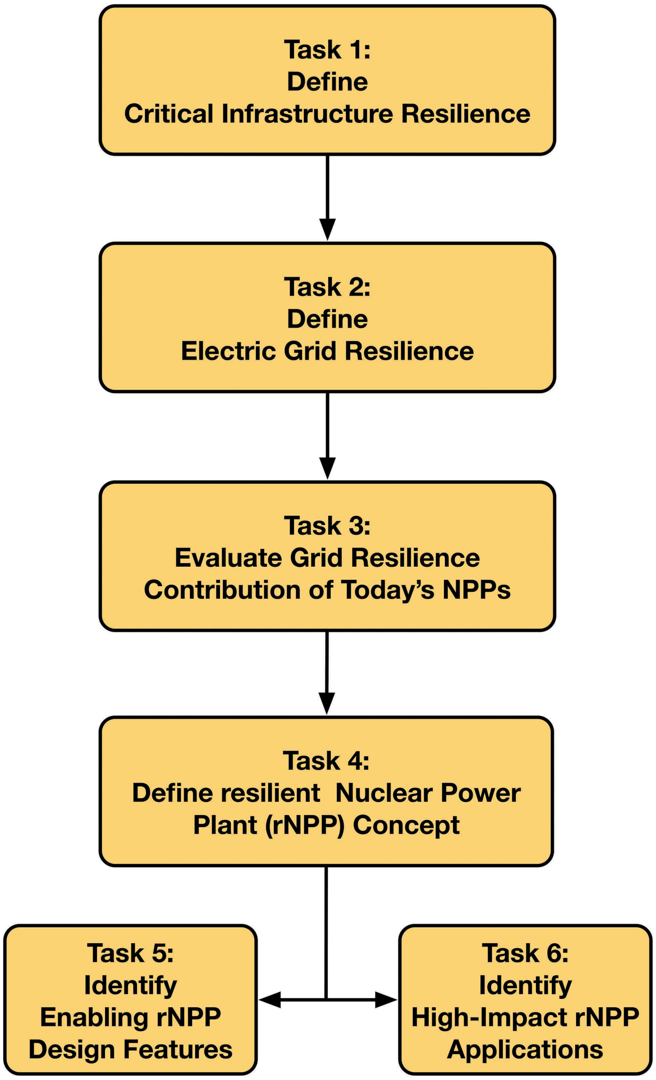


Fig. 1. Grid resilience and rNPP conceptualization process.

discusses three additional issues related to rNPP development and deployment: potential regulatory barriers, rNPP siting considerations, and rNPP cost and economic considerations. The main points of the paper are summarized in Sec. VII.

II. GRID RESILIENCE—A WORKING DEFINITION

The Grid is the integrated network of electricity generation, transmission, and distribution assets required to produce and deliver electricity to the end user. The Grid is arguably the most critical of all U.S. physical infrastructures because it is the infrastructure upon which virtually every other civil infrastructure depends for the energy required to execute their functions. Thus, Grid resilience is a matter of great importance from the energy security, economic prosperity, homeland security, and national security perspectives.[4]

Despite its ubiquitous usage, the term "resilience," as applied to the Grid, is one that is not easily defined.[4] System resilience has been generically defined[5] as "*the ability of a system to withstand a change or a disruptive event by reducing the initial negative impacts (absorptive capability), by adapting itself to them (adaptive capability), and by recovering from them (restorative capability).*"

The practical challenges of applying this definition to the Grid and to the analysis, operation, and planning of Grid architectures have been previously discussed.[3] The author has offered the following working definition of Grid resilience: "*Electric Grid resilience is the system's ability to minimize interruptions of electricity flow to customers given a specific load prioritization hierarchy.*"[2,3]

III. RESILIENT NUCLEAR POWER PLANTS DEFINED

Given the challenges associated with quantification of Grid resilience, it is useful to consider qualitative approaches to understanding and enhancing Grid resilience—approaches that focus on individual elements (generation, transmission, and distribution) of the Grid, and the characteristics of generic resilience systems. With this in mind, a resilient Nuclear Power Plant (rNPP) has been defined as follows[2,3]: "*A resilient nuclear power plant (rNPP) is one whose performance attributes and functionalities enable and enhance electric Grid resilience—the system's ability to minimize interruptions of electricity flow to customers given a specific load prioritization hierarchy.*"

When combined with the generic definition of system resilience cited in Sec. II, it is clear rNPPs [and resilient power plants (rPPs) in general] must possess Two rNPP Key Attributes:

1. *rNPP Key Attribute 1*: rNPPs enhance the Grid's ability to absorb and adapt to a broad spectrum of Grid anomalies and upsets.
2. *rNPP Key Attribute 2*: rNPPs enhance the Grid's ability to recover from upsets and to restore electric service in a manner consistent with the system operator's load prioritization hierarchy.

Resilient nuclear power plants would be NPPs that are intentionally designed, sited, interfaced, and operated in a manner to enhance electric Grid resilience.

IV. THE SIX FUNCTIONAL REQUIREMENTS OF rNPPs

Given the foregoing discussion, what are the key functional requirements an rNPP must meet in order to maximize its Grid resilience benefit, i.e., maximize the Grid's ability to absorb and adapt to major disruptions and accelerate Grid recovery and restoration in the wake of major Grid disruptions? The Six Functional Requirements of rNPPs are summarized in Table I and discussed below. It should be noted that an NPP does not have to possess all six of the rNPP Functional Requirements listed in Table I in order to provide Grid resilience benefits. It is not an all-or-nothing proposition. But, the degree to which an NPP does provide Grid resilience benefits is directly related to the number of (and which specific) rNPP Functional Requirements it exhibits, as well as the attributes of the Grid into which it is interfaced. The six rNPP Functional Requirements are currently articulated in qualitative terms consistent with the immaturity of the rNPP concept. Quantification of the qualitative descriptors employed here (e.g., "robust," "flexible," and "immunity") will be a focus of future work.

IV.A. rNPP Functional Requirement 1—Robust Real/Reactive Load-Following and Flexible Operation Capability

The ability to meet widely varying and dynamic load (real and reactive power) demands (e.g., from 100% power down to housekeeping loads) is a critical rNPP functionality.

Modern U.S. NPPs were designed with some load-following and flexible operation capability. However, they have traditionally operated in baseload mode. The nuclear steam supply system (NSSS) of a typical Generation II Westinghouse pressurized water reactor (PWR) was designed to provide the following operational capabilities:

1. 15% to 100% of rated power consistent with the cyclic nature of the utility system load demand
2. 10% of rated power and ramp changes of 5% of rated power per minute
3. a daily load cycle of 12 h at 100% power, decrease to 50% power over 3 h, 6 h at 50% power, and return to 100% power over 3 h (Ref. 6).

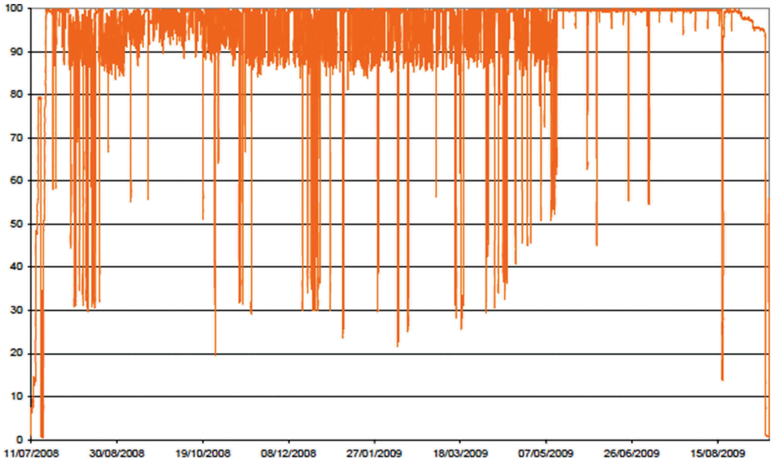
Load rejection capabilities of up to 100% load were available as a design option for many U.S. plants at the time they were ordered. However, the absence of a compelling need at the time, and the increased capital costs of providing such functionality, dissuaded most plant purchasers from availing themselves of the option. The reality was that the provision of load-following and flexible operating capability for both nuclear and nonnuclear generating units was primarily a financial question given the technical approaches required to achieve it, as well as the potential plant and component lifetime degradation issues associated with it.

While only a few U.S. NPPs operate in a load-following mode (due to their electricity market conditions), many European NPPs maneuver between 100% and 30% power over short periods of time.[7] NPPs in Europe

TABLE I

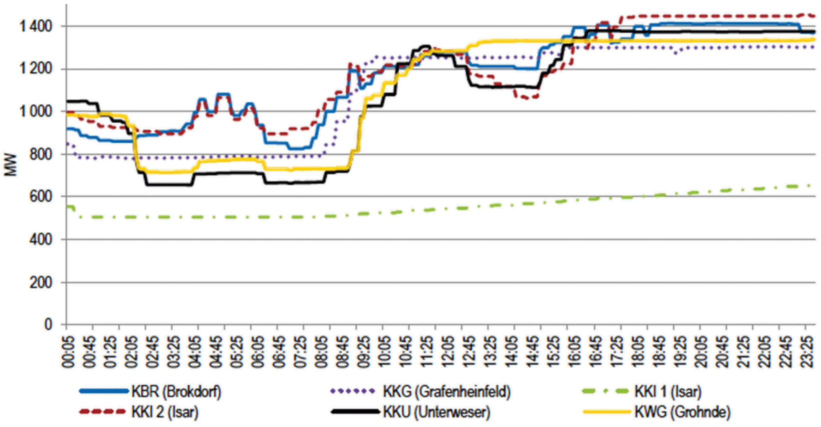
Six rNPP Functional Requirements

rNPP Functional Requirement	Relevant Resilience Characteristics
1. Robust real/reactive load-following and flexible operation capability	Absorptive Adaptive Restorative
2. Extremely low vulnerability to damage from external events (including Grid anomalies)	Absorptive Adaptive
3. Ability to avoid plant shutdown (reactor scram) in response to Grid anomalies	Absorptive Adaptive
4. Ability to operate in Island Mode (i.e., without connection to offsite transmission load and electric power supply)	Adaptive Restorative
5. Unlimited independent safe shutdown cooling capability (i.e., requiring no offsite power or resupply of diesel fuel from offsite)	Adaptive Restorative
6. Independent self-cranking black start capability (i.e., the ability to start with no offsite power supply from the Grid)	Restorative



Courtesy of Électricité de France (EDF)

Fig. 2. Typical Électricité de France NPP power maneuvering operations (percent of rated power versus time).[7]



Courtesy of E.ON Kernkraft

Fig. 3. Typical German NPP power maneuvering operations.[7]

(where the share of nuclear power generation in some countries' electric Grids is higher than in the United States) do operate in more dynamic power maneuvering regimes than do their U.S. counterparts. As is evident from Fig. 2, NPPs in France frequently maneuver between 100% and ~30% power over short periods of time. German plants (Fig. 3) routinely maneuver between 100% and ~50% power over several-hour periods. In both cases, this operational flexibility is necessitated by regional Grid and electricity market demands.

The Electric Power Research Institute, in its 2014 study of the options for transitioning NPPs to "flexible operation,"[8] identified four key operational characteristics of "flexible nuclear power plants":

1. *rate*: the rate at which a plant can change power levels over time
2. *depth*: the extent (percent of full power) of a power reduction a plant can make while still having the capability to return to the initial power level
3. *duration*: the length of time a plant can maintain a given power level
4. *frequency*: the frequency of significant changes to a plant's power levels.

While these four parameters may be a sufficiently complete set of flexible operational characteristics for "normal" flexible operations, these four operational parameters (or rather the values established for their required ranges) are almost certainly not sufficient to characterize rNPP load-following operations during plant black start and Grid recovery operations. For instance, during the early stages of Grid recovery operations, the potential exists for real and reactive load swings at the terminals of the NPP's generator that exceed those deemed acceptable during normal plant operations. This is particularly the case if the rNPP were being employed to crank another generating plant—an operation current U.S. NPPs are not allowed to conduct. Thus, there is a need to distinguish between the real and reactive power maneuvering capability for normal conditions and those an NPP would encounter during early Grid recovery operations.

IV.B. rNPP Functional Requirement 2—Immunity (Extremely Low Vulnerability) to Damage from External Events

The rNPP must be capable of withstanding credible external (natural or man-made) events that disrupt the electric Grid, without incurring significant damage itself, and the rNPP must be capable of operating as required in the wake of such events to aid in Grid recovery and restoration. There must be no credible "common mode" Grid-rNPP failure mechanisms.

A fundamental functional requirement of an rNPP is that it must be available when the Grid needs it most. The rNPP cannot be vulnerable to being damaged or rendered inoperable by the same external events that could damage the Grid and trigger the need for the rNPP to power Grid recovery and restoration efforts. This calls for rNPPs to be designed, sited, interfaced, and operated in such a way that they are effectively immune to credible natural hazards and malevolent human threats to the Grid and their induced Grid anomalies—including external events of a type and/or magnitude outside the design basis of current U.S. NPPs:

1. seismic events (earthquakes and tsunamis)
2. terrestrial weather events (including flooding)
3. electromagnetic disturbances (both geomagnetic disturbances induced by space weather and electromagnetic pulse attacks)
4. cyber attacks.

This functional requirement might seem to be self-evident. However, from the practical engineering standpoint, this functional requirement could well be the one that is most difficult to achieve and/or to confirm that it has been achieved. The definition of "credible" should be informed by lessons from decades of probabilistic safety and probabilistic risk assessment (PSA/PRA) and by realistic evaluation of the changing (or changed understanding of) external risk and threat environments. For instance, evolving knowledge from ongoing solar heliophysics studies indicates that the probability of a coronal mass ejection and associated geomagnetic disturbance (GMD) of the magnitude of the 1859 Carrington Event is actually greater than that of some external events commonly considered in the design basis of existing commercial NPPs (Ref. 1). The Carrington Event set telegraph equipment afire across northern North America and Europe.

IV.C. rNPP Functional Requirement 3—Ability to Avoid Plant Shutdown in Response to Grid Anomalies

Avoidance of reactor trips and plant shutdowns triggered by external events is a key functional capability of future rNPPs.

This functional requirement is closely related to rNPP Functional Requirements 1 and 2. NPPs prefer to serve "high-quality" (stable real/reactive power) electric loads and to be served by "high-quality" (tightly controlled voltage and frequency) offsite power supplies. Rapid and/or significant variations in either the electric load served by the plant or the offsite power supply quality to the plant can result in reactor trips and plant shutdowns in current NPPs. Indeed, the typical U.S. NPP's response to major Grid anomalies is to "shut down and wait" until the Grid is energized and real/reactive power flows (loads) are stabilized.[3] Only then are efforts made to restart the NPP.

The shut down and wait response has potentially negative consequences both for Grid resilience and for NPP safety. If the plant shutdown is an artifact of load variations, isolating the plant from the Grid may actually exacerbate the problem at the Grid level by removing generating capacity precisely at the time it is needed to stabilize and restore the Grid. This concern over the potential for an NPP shutdown to worsen an already difficult situation is one reason system operators are reluctant to place NPPs back in service until late in the Grid restoration process. This concern is heightened in systems where nuclear generating capacity makes up a significant fraction of overall system generating capacity. In addition, shutting down the NPP in response to Grid anomalies transitions the plant to shutdown cooling at a time when no one can know how long the Grid will be compromised and how long shutdown cooling must be maintained without the aid of offsite power. Finally, the need to maneuver through a series of Limiting Conditions for Operation[1,3] (LCOs) would almost certainly undermine the ability to rapidly restart NPPs that have tripped due to Grid anomalies, thus further undermining their ability to serve as Grid recovery assets.

IV.D. rNPP Functional Requirement 4—Ability to Operate in Island Mode

The ability to operate for extended periods in an "Island Mode" is a key functional capability of future rNPPs.

Island Mode operation is an operating mode in which the NPP is isolated from the Grid (both load and offsite power supply) and operating at a power level sufficient to meet all of its housekeeping loads. It is essentially in a "hot spinning reserve" state, ready to reconnect to the Grid. An rNPP could theoretically enter Island Mode by either of two paths (1) automatic or manual transition to Island Mode directly from its normal power generation mode or (2) by restarting into Island Mode following plant shutdown:

1. *Transition to Island Mode from normal power operations*: In the absence of advance warning of the need to transition to Island Mode operations from normal power operations, the rNPP must be capable of detecting anomalies in the load it is serving and its offsite power supply, and distinguishing between those it can tolerate (with its enhanced load-following capability) and those it cannot tolerate. This detection and discrimination would have to occur extremely quickly if the transition is to be performed automatically. Conversely, manual transition to Island Mode operations would likely require that the system operators and rNPP operators have advance warning of the need to transition to Island Mode. In either case, the first step in the process is to isolate the rNPP from the Grid (load and offsite power supply) coincident with a power cutback.

2. *Transition to Island Mode from shutdown configuration*: The rNPP's reactor must be capable of restarting (cranking) in order to achieve Island Mode operation if the reactor trips in response to the Grid anomaly. Offsite power would be available to crank the plant if the transition to Island Mode is executed in advance of an anticipated Grid anomaly. However, it is likely offsite power would not be available to crank the plant if the transition is occurring in direct response to a real-time Grid anomaly. The ability to restart the plant and achieve Island Mode operations in such cases would depend on whether the plant had its own self-cranking capability (rNPP Functional Requirement 6).

Conventional large NPPs comprised of GWe–class reactors would probably have difficulty achieving and sustaining Island Mode operation since such operations require the reactor to idle at power levels only a few to several percent of its rated power level. On the other hand, large NPPs comprised of multiple "small" (e.g., <300-MWe) reactors and MWe–class reactors would probably have less difficulty providing this functionality because their NPP housekeeping loads could be met by a single reactor module operating within its normal power generation levels, feeding power to the other modules. It is also technically possible (though unlikely from the economic perspective) that MWe–class reactors could be colocated with the rNPP to operate in Island Mode as dedicated rNPP cranking and shutdown cooling power sources.

IV.E. rNPP Functional Requirement 5—Unlimited Independent Shutdown Cooling Capability

The ability to meet all shutdown cooling requirements indefinitely without reliance on offsite power or other assistance is an essential functional capability of rNPPs.

Unlike other forms of electric generating plants, NPPs cannot be completely turned off. Subsequent to shutdown, nuclear reactors continue to produce decay heat and therefore continue to require some form of cooling to maintain adequate heat removal. For example, nuclear fuel still produces ~1% of its original operating power 2 h after shutdown. The decay power level drops to ~0.4% 3 days after shutdown, ~0.3% 7 days after shutdown, and ~0.04% to 0.05% 6 months after shutdown. The time-dependent shutdown decay power produced depends on factors such as the original operating power level, time at power, reactor fuel composition, fuel burnup, etc.

Figure 4 depicts a typical decay power curve for a nominal 1-GWe (~3000-MWt) NPP. The core of a 1-GWe commercial nuclear reactor still produces ~2 to 3 MWt of power 3 months after the reactor has shut down. Thus, in the absence of forced cooling, a reactor of this size, depressurized to 1 atm pressure, would boil off (and would need a supply of) 3200 to 5000 kg/h or ~830 to 1320 gal/h of water to remove this much energy. This decay heat is produced whether the fuel is in the reactor or in the plant's spent fuel pool and must be removed (in current reactors) by pumping cooling water through the core of the reactor and/or spent fuel pool. This function is provided in current plants by electrically-driven, direct diesel-driven, or steam-driven pumps—the latter only functional as long as the reactor system is pressurized. The power for the electrically-driven cooling systems is supplied from the Grid under normal circumstances. NPPs typically rely on onsite diesel-driven generator systems to supply backup power in the event offsite alternating current (AC) power is not available. All diesel-driven approaches depend on the continued availability of diesel fuel.

Nuclear power plants have made great strides in their ability to deal with a wide range of external events

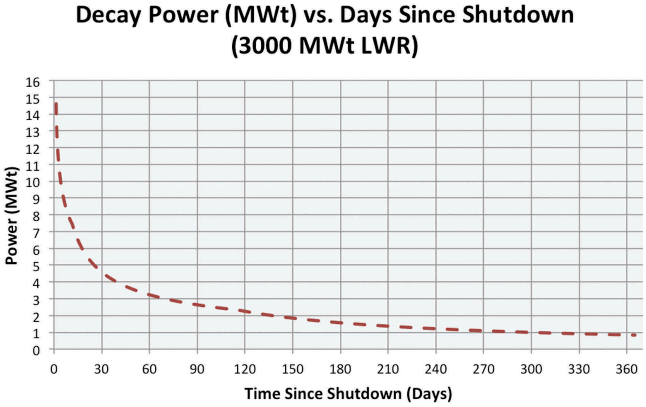


Fig. 4. Approximate shutdown cooling requirements for a 1-GWe/3000-MWt NPP.

and maintain safe shutdown cooling for long periods of time. Still, the industry's current FLEX procedures ultimately depend upon the provision of offsite support (diesel fuel, equipment, power, etc.) to maintain safe shutdown cooling for events involving extended loss of AC power.[9] As a result, NPPs are priority or "critical" loads Grid operators must meet during system restoration activities before other loads can be served. *Thus, today's NPPs actually present a burden on—rather than an asset to—Grid operators during system restoration activities*. The development of NPPs that do not pose a burden on the electric Grid in the case of a major Grid disruption would be a major step along the way to developing rNPPs. rNPP Functional Requirement 5 addresses this need.

IV.F. rNPP Functional Requirement 6—Independent Self-Cranking Black Start Capability

The ability to start without reliance on offsite power (e.g., the ability to self-crank) would be a transformational capability of future rNPPs.

Many potential threats and hazards to Grid resilience could result in a Grid that is fractured into dark (deenergized) Grid "islands."[10] The electric power industry has prepared for such circumstances through its provision of "black start resources" (generating plants) that have the ability to start/restart with no offsite power support.

The normal electric Grid recovery scenario (Fig. 5) is a classic bootstrap procedure in which small (typically <50-MWe) gas turbine and hydro black start plants crank larger plants. Once started, these larger plants crank even larger steam cycle plants in a carefully choreographed procedure designed to rebuild and synchronize blocks of stable load and electrical generation until normal Grid operation is restored.

Today's NPPs play no supportive role in the early stages of Grid recovery. NPPs are typically among the first plants to drop off the Grid and the last plants to return to service in response to major Grid disruptions. This behavior is an artifact of several plant and Grid characteristics:

1. the NPP's size and its resultant need for large blocks of stable load and transmission line capacity
2. the NPP's limited load-following capability

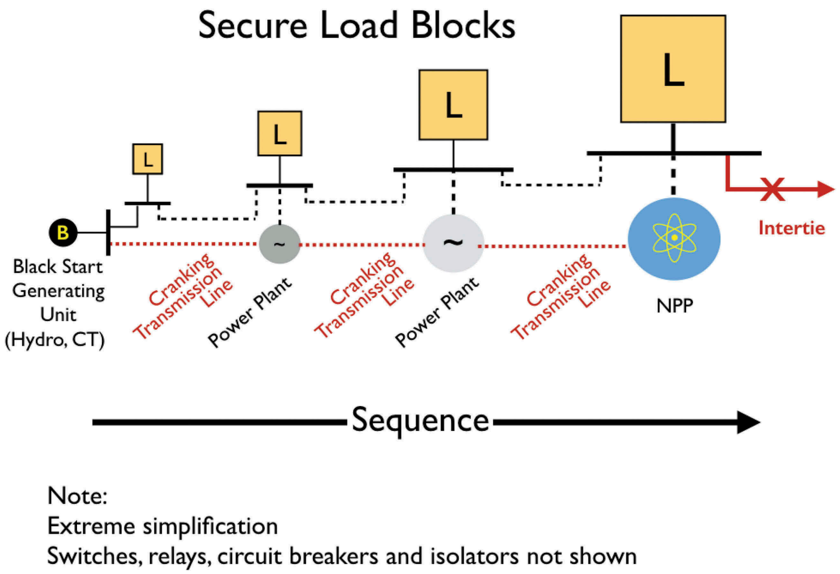


Fig. 5. Current Grid black start recovery approach.

3. the NPP's LCOs and associated time required for plant restart[3]
4. the NPP's need for high-quality offsite power
5. the large cranking power requirements (typically a few tens of megawatts electric) for GWe–class NPPs.

Resilient nuclear power plant Functional Requirement 6 would be enabled by (1) achieving very small cranking power requirements and (2) providing those cranking power requirements from secure and reliable onsite power sources that have no common-cause failure modes with offsite power sources. The smaller the cranking power requirements, the more options exist for providing that cranking power. Both traditional cranking power sources, such as onsite diesel generators and gas-/oil-fired turbines, and nontraditional renewable energy sources are viable candidates if the NPP's cranking power requirements are sufficiently small. Nontraditional cranking power sources could include colocated utility-scale battery storage systems, compressed air energy storage systems, solar photovoltaic systems, and fuel cells—and as noted, even dedicated MWe–class reactors.

V. POTENTIALLY ENABLING rNPP DESIGN FEATURES

The design of an NPP is, like that of any complex system, an exercise in multiparameter optimization (tradeoffs and compromises) in an environment rich in requirements, desires, and constraints. Each design feature must be assessed in terms of its impact on plant safety, reliability, availability, maintainability, lifetime, cost/economics, and a host of other factors. The expansion of the NPP design exercise to encompass new rNPP and electric Grid resilience goals adds another dimension to this endeavor.

The rNPP Functional Requirements defined in Sec. IV are technology-neutral. Designers of future rNPPs would logically evaluate every system architecture and technology selection decision in terms of its impact on the ability of the plant to achieve the Six rNPP Functional Requirements while still meeting the plant's traditional functional requirements.

Table II presents a preliminary list of some NPP design features that impact the NPP's ability to achieve the six rNPP functionalities. Many of these design features summarized in Table II are relevant to rNPPs that are employed strictly for electricity generation as well as rNPPs that are employed for combined heat and power generation. Plant architecture and technology decisions are obviously interdependent rNPP design issues. Each design "trade" decision would be accompanied by its own plant performance and cost implications. The intent of this section is simply to demonstrate there is a design "trade space" available to rNPP plant designers. Detailed definition and examination of each of these options is a topic for future work. The rNPP design features are discussed from the outside-in or Grid-to-fission perspective, consistent with the use-inspired philosophy that underpins the rNPP concept.

V.A. Direct-Current NPP–Grid Interfaces

The resilience value of an rNPP is not only a function of the rNPP itself. Its value as a Grid resilience asset is also a function of the manner in which the rNPP is sited and interfaced with the Grid and the world outside the plant boundary. rNPP Functionalities 1, 2, and 3 would all be enabled by designing rNPPs with the capability to buffer the NPP from and moderate the coupling of Grid anomalies (transmission load and offsite power quality) into the NPP. How might this be accomplished?

The U.S. Grid consists of three Interconnections (Eastern, Western, and the Electric Reliability Council of Texas) that are connected via direct current (DC-DC) interties and variable frequency transformer (VFT)-based interties. Among other things, this intertie technology decouples Grid frequency and voltage anomalies in one Interconnection from the other. This same principle could be employed to accomplish similar goals for an rNPP and the Grid it serves. DC-DC bridges or VFT bridges (rather than traditional AC-AC interfaces) could be employed in the plant's switchyard. This approach would buffer the rNPP from offsite transmission system and offsite power system voltage and frequency transients the plant might not otherwise be capable of tolerating. Depending on the manner in which they are implemented, the use of DC-DC and VFT rNPP-Grid interfaces could require or enable extensive redesign of many of the plant's electrical systems. While there is a natural tendency to view this as a negative factor, it could also be viewed as an opportunity to rethink and improve some aspects of the NPP's overall electrical design. Thus, it is difficult to assess the impact of this plant interface approach on overall performance and cost until (at least) preconceptual rNPP electrical system designs are developed.

V.B. Substitution/Switching of High-Capacity Load and Heat Rejection

The ability of a power plant to substitute an alternate thermal or electrical load when confronted with a loss-of-load event would reduce the severity of reactor power

TABLE II

Potentially Enabling rNPP Design Features

Potentially Enabling rNPP Design Features	Impact	Enables rNPP Functional Requirement Number[a]
1. DC-DC or VFT NPP interface with Grid	Buffers rNPP from Grid transmission load and offsite power quality anomalies	1, 2, and 3
2. High-capacity load switching and heat rejection	Substitutes alternate thermal or electrical load in case of Grid-based loss-of-load events	1 through 4
3. Multimodule (reactor) NPP architecture	Enables one operating reactor module to supply shutdown cooling and housekeeping electrical loads to other rNPP reactor modules Enables one reactor module to crank other reactor modules in rNPP	4, 5, and 6
4. Small reactor (module) size	Reduces cranking power requirements of individual reactor modules in rNPP Enables nontraditional cranking power supplies for rNPP Reduces individual reactor module shutdown heat removal and housekeeping electrical loads.	1, 3 through 6
5. Adaptive turbine-generator systems	Enhances rNPP load-following and flexible operation capability	1, 2, and 3
6. Passive shutdown cooling	Eliminates dependence of rNPP on consumable onsite resources and offsite assistance to maintain safe shutdown state	5
7. Inherent reactor system energy storage capacity	Buffers rNPP and individual rNPP reactor modules from electrical (transmission system) load transients	1 through 4
8. Optimized reactor core physics design	Enables rapid rNPP reactor module power maneuvering and restart across entire fuel cycle	1 through 4, 6
9. Robust nuclear fuels	Increases rNPP reactor module's power maneuvering capability	1 through 5
10. Plant electrical, instrumentation and control (I&C), and computer technologies that are resilient in face of GMD, EMP, and cyber attack	Enables rNPP to avoid damage and continue to function in event of GMD, EMP, or cyber attack	2

[a] 1 = Flexible operation/robust load-following capability; 2 = Immunity to damage from external events; 3 = Ability to avoid plant shutdown in response to grid anomalies; 4 = Ability to operate in Island Mode; 5 = Unlimited independent safe shutdown cooling capability; 6 = Independent self-cranking black start capability.

maneuvers required to cope with such events. This concept is, of course, the basis for the incorporation of robust turbine bypass and high-capacity main steam condenser systems in existing commercial PWRs. Current PWRs also dump steam directly to the atmosphere via special main steam relief values during reactor startup and plant trips. However, neither of these systems are designed for sustained continuous operation at high power.[8] rNPP designers could expand the use of this load switching concept to enable rNPPs to avoid reactor scram and continue to operate at relatively high power levels (whether connected to the Grid or in Island Mode) in the face of extreme load anomalies.

One approach to achieve this functionality would be to utilize high-capacity turbine bypass/condenser systems and main steam dump systems designed for high-capacity, sustained, and continuous operation. While the use of large steam bypass/condenser systems moderates the reactor power ramp rate and cutback power levels required to cope with load rejections, the use of large condensers can actually complicate the attainment of stable (low reactor power) Island Mode operation. Large condenser systems are subject to unstable condenser behavior when operated at low powers, along with the accompanying thermomechanical stresses and associated risk of accelerated equipment aging. This issue would be a design consideration both for large reactors coupled to large condensers and clusters of small reactors coupled to a common large condenser. However, multiple reactor/condenser configurations are possible:

1. several reactors coupled to a single large condenser
2. one reactor coupled to one condenser
3. hybrid configurations in which one housekeeping reactor module is coupled to its own condenser while the remaining reactor modules share common (large) condensers.

Detailed design studies would of course be required in order to understand the performance (real-time and lifetime) trade-offs of different reactor/condenser configurations. Any realized performance benefits would come with the cost implications of forgoing the economies of scale associated with large condensers.

Another option would be to incorporate some form of electric load dump for some portion of the load. This concept of course underlies the use of pumped storage hydroelectricity, electric-driven flywheel storage systems, etc. However, it is difficult to envision how such systems could be acceptably interfaced to the rNPP from both the technical and economic perspectives.

Resilient nuclear power plants that are employed for combined electricity and process heat production or as elements of hybrid energy systems could be designed with the ability to dynamically allocate electricity and process heat loads (or thermal energy storage[11]) in the event of Grid load disruptions, presuming their process heat customers could tolerate such operations. The insertion of shared multireactor thermal energy storage reservoirs between the reactors and their power conversion systems, or between an rNPP employed for process heat generation and its process heat transmission/distribution system, would both buffer the reactor system from variations in process heat demand, and serve as a process heat collection point for multireactor plant configurations. Oak Ridge National Laboratory's incorporation of a shared thermal energy reservoir for collection and storage of the thermal output in its multiunit SmAHTR plant concept is an example of the later approach.[12]

V.C. Multimodule (Reactor) NPP System Architecture

The use of multiple reactor modules to achieve the rNPP "nameplate" electrical generating capacity (rNPP Design Feature 3 in Table II) is perhaps the single most enabling design feature of an rNPP. This approach is incorporated in NPP designs currently proposed by NuScale Power.[13] Modularity potentially enables attainment of several rNPP Functional Requirements. Individual reactor modules in an rNPP could conceivably be powered up and down to enhance the plant's overall load-following capability (rNPP Functional Requirement 1). The multimodule plant design architecture would also enable one reactor module (when coupled with the necessary electrical system design features) to supply housekeeping and shutdown cooling power to other reactor modules in the rNPP, thus enabling Island Mode operations and enhancing shutdown decay heat removal functionality (rNPP Functional Requirements 4 and 5). Such a design would also enable one reactor module to supply cranking power to other reactor modules (rNPP Functional Requirement 6). Additionally, the use of multireactor modules reduces the size of the cranking power supply required to restart the entire rNPP by limiting it to that needed to crank one reactor module (also enabling attainment of rNPP Functional Requirement 6). Finally, the use of multiple (smaller) reactor modules potentially reduces the plant's accident source term for certain types of accidents. NuScale Power has already sought (and been granted) some regulatory relief from the U.S. Nuclear Regulatory Commission (NRC) based in part on this multireactor/multimodule design feature.[13–15]

V.D. Small Reactor (Module) Size

The use of small [less than ~1-GWt] reactors in each rNPP reactor module (rNPP Enabling Design Feature 4 in Table II) enables attainment of multiple rNPP Functional Requirements. Small reactor size would enable a single reactor module in a multimodule rNPP to operate at near-normal power levels while supplying housekeeping loads for the other reactor modules, potentially enabling Island

Mode operations (rNPP Functional Requirement 4). rNPP Functional Requirement 5 is enabled by reducing the shutdown decay heat removal demand of individual modules, preferably to levels achievable with inherently passive cooling approaches. The cranking power requirement for a small (~200-MWt) light water–cooled reactor concept could be as low as 1 to 3 MWe (Ref. 16). As previously discussed, such low cranking power requirements would enable the rNPP to utilize both large diesel generators and nontraditional cranking and shutdown cooling power supplies.

V.E. Adaptive Turbine-Generator Systems

Despite not being located in the plant's switchyard, the terminals of the rNPP's generator are in many respects the plant's principal interface to the Grid. The use of adaptive turbine-generator systems (rNPP Enabling Design Feature 5 in Table II) having a robust ability to tolerate Grid voltage, frequency, and reactive power anomalies would enhance a plant's ability to load-follow, avoid damage in response to Grid anomalies, avoid reactor scram (rNPP Functional Requirements 1, 2, and 3), and enable the use of the rNPP as a black start resource presuming rNPP Functional Requirement 6 is met. This approach would require a rethinking of NPP turbine-generator system design: the physical and electrical design of turbines and generators, turbine-governor control (TGC) schemes, grid automatic generation control (AGC) schemes, etc. Such systems would require enhanced reactive power maneuvering flexibility to deal with real/reactive power swings and to reduce their susceptibility to self-excitation, which is a particular risk should plants be employed as black start resources or energy resources during the early stages of Grid recovery and restoration in the wake of major Grid anomalies.

V.F. Passive Shutdown Cooling

Passive shutdown cooling (rNPP Design Feature 6 in Table II) reduces individual reactor and overall NPP shutdown cooling power requirements. This directly impacts the plant's ability to achieve rNPP Functional Requirement 5 (Unlimited independent safe shutdown cooling capability). As noted in Sec. IV, NPPs are currently considered priority loads during the early stages of Grid recovery operations. The incorporation of reliable passive shutdown cooling would reduce the urgency with which offsite power must be restored to the NPPs in Grid deenergization events. This would, in turn, enable Grid operators to focus more attention and resources on gaining situational awareness and damage assessment during the earliest stage of Grid recovery operations.

V.G. Inherent Reactor System Energy Storage Capacity

The inherent energy storage capacity (i.e., bulk heat capacity) of the reactor's primary coolant system (NSSS in traditional Rankine cycle NPPs) and the associated system thermal inertia have a significant influence on the reactor system's dynamic response to load transients. Higher bulk heat capacity and thermal inertia buffer the reactor from load variations by slowing the thermodynamic response of the primary coolant system to load changes. These features enhance the dynamic stability of a reactor system and reduce the severity of the safety challenge posed by operating transients and accidents. These features, coupled with the reactor's intrinsic reactivity feedback characteristics and the actions of the reactor power control system, have a dominant impact on the reactor's rapid power maneuvering capability. Thus, the thermal design and the neutronic/core physics design of the reactor system are tightly coupled. Many of the attractive behavioral attributes of graphite reactors, liquid-metal–cooled reactors, and liquid salt/molten salt reactors derive from their high primary cooling system heat capacity and thermal inertia.

The inherent heat capacity and thermal inertia of the reactor's primary coolant system are (for a single-phase system) functions of the specific heat and thermal conductivity of the materials of construction and the mass of the system. These factors are, in turn, dictated by several related primary coolant system design features:

1. system architecture (volume in particular)
2. choice of reactor fuel, coolant/working fluid, and structural materials
3. reactor's thermodynamic operating state (temperature/pressure/phase).

These design choices also drive pumping power requirements (and therefore cranking and housekeeping loads), system heatup and cooldown rate capabilities (plant startup behavior), and other plant operational characteristics. All of these design choices impact the plant's ability to achieve rNPP Functional Requirements 1 through 4. Of course, high system heat capacity and thermal inertia generally translate to higher system cost because these attributes are a function of the size and mass of the primary coolant and reactor system.

V.H. Optimized Reactor Core Physics Design

An rNPP should have robust flexible operation and load-following capability, Island Mode operation capability, and start/restart capability throughout its entire fuel cycle from reload to reload in order to achieve rNPP Functional Requirements 1 through 4 and 6). Provision of these functionalities near the end of a fuel reload cycle (when core excess reactivity is low) would be a design challenge. These functionalities could be enabled by reactivity control strategies involving various combinations of fission spectrum, physical dimensions, lattice pitch (in solid fuel designs), fuel enrichment, reactivity feedback coefficients, and fixed burnable and soluble neutron absorbers (neutron poisons). As previously stated, these design decisions must be made in concert with decisions that impact the reactor system's inherent energy storage capacity and thermal inertia.

V.I. Robust Nuclear Fuels

Robust nuclear fuels (from the thermomechanical and chemical perspectives) would enhance the rNPP's load-following capability during normal operation, enable rapid power ramping and transition into Island Mode operations, and facilitate prompt reactor restart in the event of plant shutdowns. Nuclear fuels with these characteristics would directly enable rNPP Functional Requirements 1 through 5. Much of the work currently underway in the federal and private sectors to develop accident-tolerant fuels for light water reactors[17,18] is directly applicable to this requirement.

V.J. Plant Electric, Instrumentation and Control (I&C), and Computer Technologies That Are Resilient in Face of GMD, EMP, and Cyber Attack

Extreme naturally occurring GMDs (such as the 1859 Carrington Event), along with electromagnetic pulse (EMP) attacks and cyber attacks, would present special challenges to all U.S. Critical Infrastructure—especially the Grid. The ability of an rNPP to survive and continue to function in the wake of such events would enable the plant to serve as the foundation for recovery and restoration of regional Grid and Critical Infrastructure functionality during circumstances the nation has never before confronted. Thus the adoption of rNPP and rNPP–Grid interface technologies that are resilient in the face of extreme GMD events, EMP attacks, and cyber attacks would greatly magnify the rNPP's value to society.

VI. REALIZATION OF rNPPs—OTHER CRITICAL CONSIDERATIONS

Work to date on the rNPP concept has focused on identification and characterization of rNPP Key Attributes; high-level rNPP Functional Requirements; and identification of relevant and enabling rNPP system architectures, components, and technologies. Other critical issues such as rNPP regulatory barriers, siting considerations, and economics are also important determinants of overall rNPP viability. Although detailed evaluations of these issues cannot proceed until (at least preconceptual) rNPP designs are available, a few initial observations are evident.

VI.A. rNPPs and the U.S. Nuclear Safety Regulatory Framework

The development and deployment of rNPPs will take place in the context of evolving nuclear safety regulatory frameworks. One immediate question that arises is, "How compatible are the rNPP Functional Requirements proposed in Sec. IV with the existing NRC regulatory framework?"

The Six rNPP Functional Requirements and the enabling rNPP design features discussed earlier present some obvious points of tension/conflict with the 64 General Design Criteria (GDCs) in 10 CFR 50, Appendix A (Ref. 19) and the manner in which these GDCs are currently implemented via various regulatory guidelines and standards. It is clear that departures from traditional design approaches for executing various rNPP safety functions will be both required and justified in some instances.

One obvious area of regulatory tension will stem from GDC-17, entitled "Electric Power Systems." GDC-17 defines the high-level functional requirements and the system architecture all U.S. NPP electrical power systems must meet. The requirements of GDC-17 are implemented via NRC Regulatory Guide 1.32 (Ref. 20), Institute of Electrical and Electronics Engineers Standard 308-2012 (Ref. 21), and NRC Regulatory Guide 1.93 (Ref. 22). Briefly summarized, GDC-17 mandates that each NPP must have both an onsite and offsite power supply to permit functioning of all structures, systems, and components required to assure that (1) acceptable fuel design limits and design conditions for the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences and (2) the core is adequately cooled and containment integrity and other vital functions are maintained in the event of postulated accidents.

Island Mode operations, shutdown cooling, and self-cranking during a "dark-Grid" condition would all require the rNPP to operate in the absence of any offsite power supply. However, an rNPP possessing independent shutdown cooling capability, Island Mode operation capability, and self-cranking capability could not operate in those modes in the United States today because such operation would violate current offsite power mandates stemming from GDC-17. Thus, achievement of rNPP Functional

Requirements 4 (Ability to operate in Island Mode), 5 (Unlimited independent safe shutdown cooling capability), and 6 (Independent self-cranking black start capability) would all be impeded by the current wording of GDC-17 and its associated implementation practices.

It is anticipated that rNPPs would not require offsite power in order to successfully execute any required safety function, so an exemption from offsite power requirements stemming from GDC-17 would be justified. Indeed, the NRC recently granted NuScale Power's request for exemption from the Class 1E electrical system requirements emanating from GDC-17 (Refs. 23, 24, and 25). That waiver is specific to NuScale Power and not a general modification of the existing GDC-17–based regulatory requirements. However, the NRC's willingness to grant NuScale's request demonstrates their willingness to depart from traditional GDC requirements when plant design and performance features justify such actions.

The operating characteristics of future rNPPs would probably also justify either exemptions from or modifications of regulatory requirements originating from other GDCs—or at least the traditional interpretation and implementation of the GDCs. In any case, it is evident the operational characteristics and functional capabilities of rNPPs should enable some simplification of the current U.S. NPP GDCs and the associated U.S. commercial nuclear power regulatory framework.

VI.B. rNPP Siting Considerations

Siting flexibility is an important consideration for rNPPs because much of their potential utility and value depends on the ability to site them at optimal locations within the Grid, in close proximity to existing transmission line corridors and/or other Critical Infrastructure. An rNPP possessing the six functional capabilities discussed in Sec. IV would differ from current NPPs in ways that should expand siting options for the plants.

Resilient nuclear power plants will not require offsite power to maintain fuel integrity and safe shutdown status (reactor and spent fuel pool cooling)—reducing or eliminating the requirement for offsite power supplies and, at least theoretically, reducing the contribution to overall core damage probability from such accidents. As noted above, by granting NuScale Power's recent request for exemption from normal Class 1E electrical power system requirements, the NRC has signaled its willingness to eliminate this requirement when such action is merited by the plant's design. Thus, all else being equal, risk-based siting practices should broaden the siting opportunities for rNPPs.

Resilient nuclear power plants that employ multiple small reactor modules might benefit from three siting advantages:

1. *Smaller emergency planning zones (EPZs)*: The accident source term for any individual reactor is reduced due to its smaller unit size. The manner in which this impacts overall accident source terms and plant safety risk profiles will be a design-specific factor related to reactor size, operational interdependence/independence of the reactor units, containment design, and a number of other detailed design considerations. Here again, NuScale Power's request to reduce the EPZ for its multi-module SMR (small modular reactor) plant is a pathfinder activity directly relevant to rNPPs (Refs. 13, 14, and 15).

2. *Reduced need for cooling water for rNPPs that employ "dry" or other nontraditional heat rejection techniques*. Geographic proximity to major estuaries and reservoirs would be a less dominate siting criterion in such cases.

3. *Decreased vulnerability to some natural hazards and man-made malevolent threats as a result of below-grade and underground siting enabled by the smaller physical size of individual rNPP reactor modules*.

VI.C. rNPP Economics

Many will assume the rNPP functionalities in Sec. IV and the design approaches identified in Sec. V will render the plants too expense to build and uneconomical to operate. This may indeed be the case. But, economics of rNPPs will be a function of both their cost (capital, operating, etc.) and the monetized value (energy, capacity, reliability, resilience) they provide. rNPPs are envisioned as elements of a future Grid in which a power plant's Grid resilience contribution is monetized and compensated in some manner.

Expansion of nuclear power's value proposition—from simply supplying baseload electricity to enhancing Grid resilience—is a significant expansion in NPP performance. History suggests that system performance and system capital costs are not independent parameters. Whether it is home appliances, automobiles, aerospace vehicles, or NPPs, higher-performance systems are often accompanied by higher system complexity and higher capital cost. Offsetting this reality is the possibility that the Six rNPP Functional Requirements and their resultant performance attributes, combined with creative rNPP design approaches, may enable rNPP designers to simplify or eliminate some current systems and components. The elimination of Class 1E electrical systems is one example. Additionally, the likely use of multiple small reactor modules should facilitate factory fabrication of some components and systems. Some cost savings could also accrue via innovative rNPP field construction techniques.

With regard to operating expenses, the Organisation for Economic Co-operation and Development (OECD) published an analysis of impacts of load-following on existing NPPs (Ref. 7), which concluded the following: "Generally speaking…the operation in the load-following mode does not lead to any large additional costs attributable to it…especially for recent power plants. However, there is some influence of the load-following on the ageing of some operational components (e.g., valves), and one can expect a slight increase of the maintenance costs."

This OECD conclusion relates primarily to rNPP Functional Requirement 1 (Robust Real/Reactive Load-Following and Flexible Operation Capability) and conceivably to rNPP Functional Requirement 4 (Ability to Operate in Island Mode) for evolutionary rNPP concepts employing incremental changes in the current commercial light water reactor technology suite. The OECD analysis is limited in that it addresses only one element of overall plant operating and maintenance costs. It is unclear how the OECD's observations might apply to future rNPPs.

Today's commercial power reactors and future rNPPs must perform in demanding real-time economic environments in which plant costs are tangible, while the benefits and value stream produced by the plants are only partially monetized. The revenue stream of current U.S. NPPs is derived from their baseload electricity generation. Recent activities within and between the U.S. Department of Energy, the Federal Energy Regulatory Commission, and the private sector[26–28] have heightened awareness of NPP capacity, reliability, and Grid resilience contributions and have catalyzed a dialog regarding the societal value of and appropriate mechanisms for monetizing these contributions. Thus, resolution of rNPP economic viability issues ultimately rests on the characteristics of the future electricity markets served by the rNPPs.

VII. SUMMARY

The nature of the NPP–electric Grid system; the concept of Grid resilience; and the potential of current U.S. NPPs to enhance U.S. Grid, integrated Critical Infrastructure, and societal resilience have been explored in previous analyses.[1–3] This paper builds upon that foundation to provide a preliminary technical definition of rNPPs—NPPs that are intentionally designed, sited, interfaced, and operated in a manner to enhance Grid resilience.

Resilient nuclear power plants would possess two essential attributes: (1) they would enable the Grid to absorb and adapt to a broad spectrum of Grid anomalies and upsets and (2) they would enhance the Grid's ability to quickly recover from upsets to restore electric service in a manner consistent with the system operator's load prioritization hierarchy. Six qualitative rNPP Functional Requirements have been defined. The integrated package of Six rNPP Functional Requirements would enable a future plant to provide value to the Grid and to society well beyond that associated with today's baseload electricity production. However, the package of Six rNPP Functional Requirements are not an all-or-nothing prospect. Future NPPs do not have to achieve all six of the Functional Requirements in order to deliver significant Grid resilience benefits. The Grid resilience value of a particular NPP would depend both upon which of the Six rNPP Functional Requirements it achieves and the characteristics of the Grid into which it is embedded.

Resilient nuclear power plants are not technically out of reach in the first half of the 21st century. Several rNPP plant, system, and component design features with the potential to enable plants to achieve the Six rNPP Functional Requirements have been identified and characterized in a preliminary manner. While issues related to rNPP regulatory barriers, siting, and economics have been addressed in a superficial manner, detailed evaluation of these issues can proceed only in concert with rNPP conceptual design activities.

Admiral Hyman Rickover famously contrasted "academic reactors" and "practical reactors" in his 1953 memorandum.[29] Advocates of new reactor concepts such as rNPPs ignore Rickover's analysis to their own peril. On the other hand, skeptics unwisely persist in employing Rickover's analysis as an antidote to innovation in the face of changing realities. The last quarter of the 20th century and the first quarter of the 21st century have hosted a number of events and developments that ended two "nuclear renaissances." Deregulation of electricity markets, fracking and inexpensive natural gas, the accident at Fukushima, the wind and solar energy revolution, and cost overruns at the latest U.S. commercial NPP construction projects are among the factors that have led many to question the future of nuclear power and its value to society. These developments suggest that the value proposition of nuclear energy must improve in the 21st century if it is to remain a major source of electricity throughout the world. rNPPs would enhance electric Grid, Critical Infrastructure, and societal resilience in a world inhabited by a plethora of natural hazards and malevolent human threats. That is a value proposition worthy of consideration.

Acknowledgments

The work described in this paper has been conducted by the author in partial fulfillment of the requirements for the PhD in Energy Science and Engineering at the University of Tennessee Knoxville (UTK). The author gratefully acknowledges the encouragement and support of Howard L. Hall, Director, Institute for Nuclear Security, and Governor's Chair Professor of Nuclear Engineering at UTK—with whom the author is working to explore the nexus of Grid resilience, nuclear power, and national and homeland security.

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References

1. S. R. GREENE, "Nuclear Power: Black Sky Liability or Black Sky Asset?" *Int. J. Nucl. Security*, **2**, *3* (2016); https://doi.org/10.7290/V78913SR.
2. S. R. GREENE, "Enhancing Electric Grid and Critical Infrastructure Resilience with Resilient Nuclear Power Plants (rNPPs)," *Trans. Am. Nucl. Soc.*, **117** (2017).
3. S. R. GREENE, "Are Current U.S. Nuclear Power Plants Grid Resilience Assets?" *Nucl. Technol.*, **202**, *1* (2018); https://doi.org/10.1080/00295450.2018.1432966.
4. "Enhancing the Resilience of the Nation's Electricity System," *National Academies Press*, Washington, District of Columbia (2017); https://doi.org/10.17226/24836.
5. G. SANSAVINI, "Engineering Resilience in Critical Infrastructures," SET-NAV Project website (Apr. 2017); http://www.set-nav.eu/content/set-nav-discussion-paper.
6. "The Westinghouse Pressurized Water Reactor Nuclear Power Plant," Westinghouse Electric Corporation Water Reactor Division (1984).
7. "Technical and Economic Aspects of Load-Following with Nuclear Power Plants," Organisation for Economic Co-operation and Development Nuclear Energy Agency (June 2011); https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf.
8. "Program on Technology Innovation: Approach to Transition Nuclear Power Plants to Flexible Power Operations," Final Report 3002002612, Electric Power Research Institute (Jan. 2014); https://www.epri.com/#/pages/product/000000003002002612/.
9. "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," NEI-12-06, Rev. 3, Nuclear Energy Institute (2016).
10. "Severe Impact Resilience: Consideration and Recommendations," Severe Impact Resilience Task Force Report, North American Electric Reliability Corporation (May 9, 2012).
11. C. FORSBERG, S. BRICK, and G. HARATYK, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Baseload Reactor Operation," *Electricity J.*, **31**, *3*, 23 (2018); https://doi.org/10.1016/j.tej.2018.03.008.
12. S. R. GREENE et al., "Pre-Conceptual Design of a Fluoride-Salt-Cooled Small Modular Advanced High-Temperature Reactor (SmAHTR)," ORNL/TM-2010/199, Oak Ridge National Laboratory (Dec. 2010); https://www.osti.gov/biblio/1008830/.
13. "NuScale Standard Plant Design Certification Application, Chapter Twenty One, Multi-Module Design Considerations, Part 2 — Tier 2," Rev. 0, NuScale Power (Dec. 2016); https://www.nrc.gov/docs/ML1701/ML17013A292.pdf (current as of Apr. 2, 2018).
14. "Methodology for Establishing the Technical Basis for Plume Exposure Emergency Planning Zones at NuScale Small Modular Reactor Plant Sites," TR-0915-17772-NP, Rev. 0, NuScale Power (Dec. 2015); https://www.nrc.gov/docs/ML1535/ML15356A842.pdf.
15. "Methodology for Establishing the Technical Basis for Plume Exposure Emergency Planning Zones at NuScale Small Modular Reactor Plant Sites," TR-0915-17772-NP, Rev. 1, NuScale Power (Mar. 2018); https://www.nrc.gov/docs/ML1807/ML18071A354.pdf.
16. S. R. GREENE, "Resilient Nuclear Power Plants (rNPPs) — Potential Building Blocks of U.S. Electric Grid and Critical Infrastructure Resilience," ATI-TR-2017-14, Advanced Technology Insights (Apr. 2, 2018).
17. K. CUMMINGS and J. GROBE, "Accident Tolerant Fuel — Developing an Efficient Approval Process," Nuclear Energy Institute (Sep. 7, 2017); https://www.nrc.gov/docs/ML1725/ML17255A004.pdf.
18. B. McCAUGHEY, "Status of DOE's Accident Tolerant Fuel Program," U.S. Department of Energy Office of Nuclear Energy (Feb. 27, 2018); https://www.nrc.gov/docs/ML1805/ML18057A187.pdf.
19. *Code of Federal Regulations*, Title 10, "Energy," Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," U.S. Nuclear Regulatory Commission; http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html.
20. "Regulatory Guideline 1.32, 'Criteria For Safety-Related Electric Power Systems for Nuclear Power Plants,'" U.S.

Nuclear Regulatory Commission (2004); http://www.nrc.gov/docs/ML0406/ML040680488.pdf.

21. "IEEE Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Stations," IEEE-308-2012, Institute of Electrical and Electronics Engineers (2012).
22. "Regulatory Guideline 1.93, "Availability of Electric Power Sources," U.S. Nuclear Regulatory Commission (2012); http://www.nrc.gov/docs/ML0905/ML090550661.pdf.
23. "NuScale Standard Plant Design Certification Application, Chapter Eight, Electric Power, Part 2 — Tier 2," Rev. 0, NuScale Power (Dec. 2016); https://www.nrc.gov/docs/ML1701/ML17013A279.pdf (current as of Apr. 27, 2018).
24. ADVISORY COMMITTEE ON REACTOR SAFEGUARDS, Memorandum to V. M. McCREE, "Safety Evaluation of the NuScale Power, LLC Topical Report TR-0815-16497-P, 'Safety Classification of Passive Nuclear Power Plant Electrical Systsems,'" Rev. 1, U.S. Nuclear Regulatory Commission (July 26, 2017); https://www.nrc.gov/docs/ML1720/ML17205A380.pdf.
25. "U.S. Nuclear Regulatory Commission Approves Key Safety Aspect to NuScale Power's Advanced Reactor Design," NuScale Power (Jan. 9, 2018); http://www.nuscalepower.com/pdf/key-safety-approved.pdf (current as of Apr. 27, 2018).
26. R. PERRY, Memorandum to N. CHATTERJEE et al., "Secretary of Energy's Direction that the Federal Energy Regulatory Commission Issue Grid Resilience Rules Pursuant to the Secretary's Authority Under Section 403 of the Department of Energy Organization Act," U.S. Department of Energy (Sep. 28, 2017); https://www.energy.gov/sites/prod/files/2017/09/f37/Secretary%20Rick%20Perry%27s%20Letter%20to%20the%20Federal%20Energy%20Regulatory%20Commission.pdf.
27. "Order Terminating Rulemaking Proceeding, Initiating New Proceeding, and Establishing Additional Procedures," RM18-1-000, Federal Energy Regulatory Commission (Jan. 8, 2018); https://elibrary.ferc.gov/idmws/common/OpenNat.asp?fileID=14792904.
28. C. SMITH, FirstEnergy Solutions, Letter J. R. PERRY, U.S. Department of Energy, "Request for Emergency Order Pursuant to Federal Power Act Section 202(c) (Mar. 29, 2018); https://statepowerproject.files.wordpress.com/2018/03/fes-202c-application.pdf (current as of Apr. 30, 2018).
29. H. G. RICKOVER, U.S. Atomic Energy Commission, Untitled Memorandum (June 5, 1953); http://ecolo.org/documents/documents_in_english/Rickover.pdf (current as of Apr. 30, 2018).