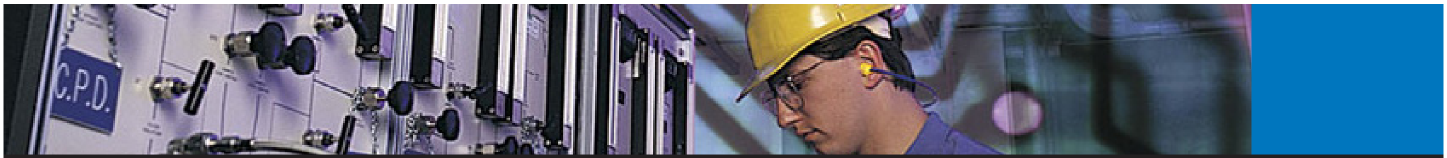
TECHNOLOGY INNOVATION: A ROADMAP TO LEVERAGE EXISTING NUCLEAR POWER PLANTS TO INCREASE ZERO-CARBON ENERGY PRODUCTION

November 2021



Foreword

Since its inception, nuclear power has provided clean, carbon-free energy to the world's electrical grids. It is estimated that the use of nuclear power has reduced carbon dioxide (CO_2) emissions by more than 60 gigatons—nearly two years' worth of global energy-related emissions [1].

The continued operation of the existing commercial nuclear fleet with expansion from new nuclear builds and existing nuclear capacity increases is critical to achieving the CO_2 emissions reductions called out by the Paris Agreement [2].

This report focuses on how the existing commercial nuclear power fleet can add additional energy to the world's electrical grids. The climate change benefits of commercial nuclear power extend to more than just adding energy to the electrical grid. Flexible nuclear power operation enables the addition of more nondispatchable renewable electrical generation from wind and solar. Nuclear power can also be used for alternative energy processes beyond electricity, such as hydrogen production and thermal heat delivery.

Discussions of those additional benefits, along with the promise of advanced reactors, are detailed in EPRI's and others' reports, with the same conclusion that commercial nuclear power is needed if the 2030 and 2050 global climate goals are to be met. Unfortunately, as evidenced by governmental policy phaseouts and lack of economic assistance in many jurisdictions, the value of commercial nuclear power is not recognized in the climate change debate. Approximately 68 premature closures of existing commercial nuclear power plants have been announced by governments or utilities between 2021 and 2035 [1]. These closures, if realized, will make it extremely difficult to achieve the desired CO_2 reductions.

The continued operation of a large part of the global commercial nuclear power fleet is primarily in the hands of the applicable governments, but adding to the value and the capacity of the existing fleet is in the hands of the nuclear power plant owners; this report is dedicated to that end. This report details the options that nuclear power plant owners have in increasing an existing nuclear power plant's output and a roadmap to research needs that will facilitate implementing those options.

Executive Summary

The existing nuclear power fleet can be leveraged to add additional carbon-free electricity to the world electric grid and support the world's 2030 and 2050 greenhouse gas reduction and net-zero carbon targets. To do this, the existing nuclear power industry must first continue to operate and, second, find ways to add additional energy to the electrical grid. This white paper focuses on the ways in which the industry can add additional energy to the electrical grid.

The existing commercial nuclear power fleet can be leveraged to provide additional energy to the electrical grid in the following three ways:

- Increase the power output (power uprate)
- Increase the capacity factor
- Increase the operating life (life extension)

These three options are evaluated with a brief synopsis of the topic, the current barriers to implementation, and the research needed to support implementation. This paper then establishes a research roadmap to formalize and lay the groundwork for future research on the identified gaps. This roadmap will be used to drive resolution of identified gaps by 2025, thereby providing time for implementation by nuclear power plants before the 2030 goal milestone.

The following are the key findings from the evaluation:

- Premature nuclear power plant closures must be stopped; this is the single biggest impact that can be made in leveraging the existing industry. Approximately 68 premature closures have been identified between now and 2035. Economic and political changes are needed to prevent further shutdowns.

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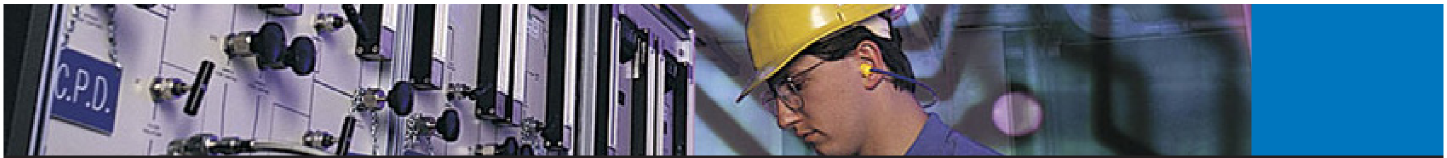
This white paper was prepared by EPRI.



- There are currently no technical barriers associated with life extension up to and beyond 80 years.
- Nuclear power plant resiliency must become a focus area to ensure that plant capacity factors continue to improve and that the plants can withstand the challenges of climate change. An operational resiliency program needs to be created for the nuclear power utilities.
- Heat sinks must become a priority for climate resiliency; research is needed in reducing heat sink temperature, mitigating droughts, and mitigating intake blockages.
- Systems, structures, and components (SSCs) coolant water flow and heat exchanger performance improvements are needed to support power uprate and improve operating margins.
- Regional climate change predictions for nuclear power plant sites need to be performed to allow for improved planning and longer horizons to mitigate challenges.
- Nuclear fuel enrichment and burnup limits need to be increased to support increases in power generation and duration between refueling outages.
- Multivariate regression modeling needs to be researched with the aim to improve plantwide sensor performance and measurement accuracy to confirm margins and potentially allow greater energy output.

A research roadmap has been created and is included with this paper to provide a path to addressing the key findings, such that utilities could implement solutions in time to support the 2030 global climate goals.

Introduction

As part of the United Nations Framework Convention on Climate Change and the United Nations Climate Change Conference, known as the "Paris Agreement," long-term goals have been established to assist nations in developing plans to address climate change. Of the 195 independent world nations, 190 of them, and all the EPRI member countries, have ratified the Paris Agreement; each of these countries has either developed its 2030 and 2050 goals or is in process of doing so [2]. For the 32 countries that have existing commercial nuclear power plants, leveraging that carbon-free energy infrastructure will be critical to meeting their individual goals.

The purpose of this white paper is to identify options, related research, and research gaps for leveraging the existing global commercial nuclear industry in providing additional carbon-free energy to support the countries' climate change goals. This paper considers only the options associated with the existing fleet of commercial nuclear reactors; new construction, small modular reactors, and advanced reactors are not a part of this paper.

To support global climate goals, the existing nuclear power industry must first continue to operate and, second, find ways to add additional energy to the electrical grid. This paper focuses on the ways in which the industry can add additional energy to the electrical grid. The issue of existing nuclear power plants' continuing operation is often economic, political, or both, and is not examined in the body of this paper. However, it would be remiss to not point out that the most significant way that the existing commercial nuclear power industry can support climate goals is to continue to operate the existing plants as long as possible.

In the past five years, owing to economic or political forces, 34 nuclear power plants have been prematurely retired; another 68 closures have been announced through 2035 [1]. The economic-related closures are primarily a United States phenomenon, with political phaseouts dominating the European and Asian actual and planned closures.

Preventing any additional premature closures is the most significant way to leverage the existing commercial nuclear power fleet in supporting global climate goals; however, this is not a technical issue and is not discussed further. In addition, because this paper focuses on options that leverage the existing fleet to provide additional energy to the grid, this paper does not discuss leveraging the existing industry for enabling other technologies or processes. For example, grid reliability would be enhanced by flexible nuclear power plant operations and nuclear power plants could supply electricity and thermal power for applications such as hydrogen production and district heating, but such options are out of scope for this paper.

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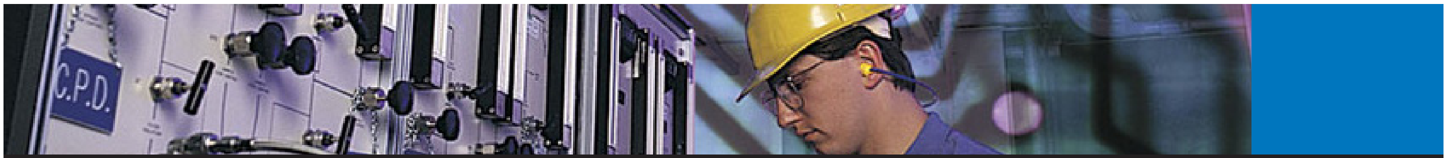


Each of these three options is evaluated in this paper with a brief synopsis of the topic, the current barriers to implementation, and the research needed to support implementation. The paper then establishes a research roadmap to formalize and lay the groundwork for future research on the identified gaps.

This paper examines the technical aspects of implementing these three options; it is realized that for any option to proceed, an acceptable business case must be made. Business case results are dependent on the specifics associated with the utility and its site-specific market; business case issues and validations are not considered in this paper.

It is expected that industry executives will be able to use this information in planning and executing options in support of adding additional energy to the electrical grid and in supporting the identified needed research.

Options to Leverage the Existing Nuclear Fleet

Power Uprates

As mentioned in the introduction, one of the most effective ways to leverage the existing commercial nuclear power fleet is to increase the allowable power output of the nuclear power plants (NPPs). This section provides a description of the technical alternatives available for an NPP to increase its allowed power level, as well as some of the critical decision points.

The process of increasing an existing NPP's maximum power output is called a *power uprate*. Power uprates can be accomplished in three ways: reducing the uncertainties of the thermal power measurement; using existing design margins; and implementing major plant modifications. These three types of uprates are known as measurement uncertainty recapture (MUR), stretch power uprate (SPU), and extended power uprates (EPU), respectively.

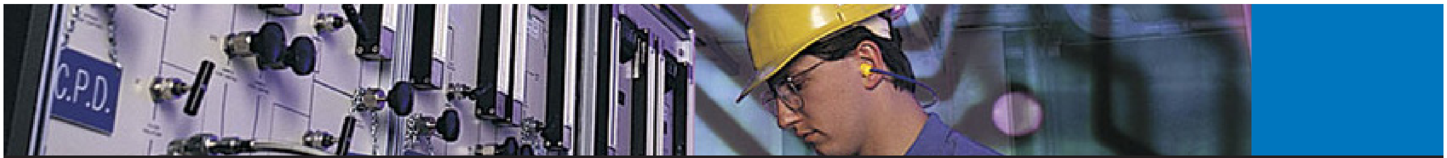
The simplest of the power uprates is the MUR; this method has resulted in power uprates as high as 1.7%. Approximately two-thirds of the U.S. NPP fleet have performed an MUR uprate [3]. There is no technical issue preventing the remaining U.S. plants or any international NPP from performing an MUR uprate. The issue is purely economic in regard to whether the NPP can receive a return on the investment. MUR uprates usually involve a modest capital expenditure for highly accurate feedwater flow measurement equipment, but data validation and reconciliation (DVR) methodology, a form of multivariate regression modeling for thermal power calculations, is becoming available and may prevent the need for any new equipment. The DVR methodology has been implemented in Europe and the methodology is currently under review by the U.S. Nuclear Regulatory Commission (NRC) [4].

The only key decision point for implementing an MUR is return on investment (ROI). An MUR uprate is a well-used and known process in the industry with very little risk, so the resulting question is whether there will be sufficient payback to make it worth the NPP's effort. Consequently, the decision comes down to each individual NPP, based on the specific conditions of price of electricity in that market and whether there are any electrical limitations in producing the extra power provided by the increased thermal power.

A SPU is distinguished from a MUR uprate in that it uses existing operational margins within the plant with little or no modifications other than setpoint changes. For example, if a plant has a redundant condensate pump, it may be able to use it to achieve a higher power by running it full time. Furthermore, new fuel designs, such as accident-tolerant fuel (ATF), may allow for increased thermal safety margins, and thus allow for a stretch uprate. A SPU will usually be less than 7%; the maximum value is dependent on the plant's operational design margins.

Similar to MURs, a business case for the SPU must be cost justifiable for the utility. The benefits are the increased power output, whereas the costs are typically based on multiple engineering evaluations on plant fuel and equipment capacity to support the additional power output. A key decision point in implementing a SPU once the business case is approved is the acceptance of the reduced margins and the associated impacts. Reduced operational margins may result in forced down powers if extreme temperatures or other external phenomena occur. This may result in reducing power when the grid needs it the most. NPPs that have previously performed a SPU may be able to perform an additional SPU with fuel design improvements and improvements in calculational methods for margin determination and best-estimate algorithms. Continued research into heat exchanger and other equipment optimization and efficiency efforts may lead to operating margin gains and increase electrical output.

EPUs are distinguished from the other types of uprates because they require significant modifications to plant systems such as the main turbine generator, feedwater and condensate pumps, and



transformers. EPUs are capital investment intensive; consequently, a strong ROI is needed. EPUs are typically greater than 7% but have reached up to a 20% increase in plant output.

The key decision points in implementing an EPU once the business case is approved is the acceptance of the financial risk of operating to the assumed ROI point. Changes in the local or state political sentiment of the plant can result in premature closure and failure to get return on the investment. Similarly, changes in external hazards, such as climate change, may result in impacts that challenge the achievement of the new full power, and, therefore, failure to obtain a full return on the investment.

Capacity Factor Increase

Capacity factor is the ratio of the actual electricity produced over a specific time period to the maximum electricity that could have been produced over that same time period. For example, periods of reduced electricity generation (outages and derates) would decrease a plant's capacity factor. Consequently, increasing a nuclear power plant's capacity factor will add additional carbon-free power to the electrical grid.

There are three ways to increase a nuclear power plant's capacity factor: improve plant resilience; reduce outage time; and increase the refueling interval for non-CANDU (Canada Deuterium Uranium) plants.

Improving plant resilience means reducing the events that lead to forced shutdowns or derates; such events include equipment failures, fuel failures, and challenging conditions such as extreme ambient temperatures or other external hazards. Globally, nuclear power plant capacity factors have been increasing steadily as a result of improved equipment reliability; the next effort will be in improving operational margins to ensure that plants are resilient to operational challenges such as external weather and other events. There is no critical decision point associated with improving plant resilience other than an acceptable business case for ROI. Nuclear utilities have been implementing reliability improvements and will continue to do so as long as there is an economic driver to do so.

Reducing outage time includes both planned and unplanned outage lengths; planned outages are required to refuel the reactor and unplanned outages result from an equipment failure or some other initiating event. Nuclear operators around the world have focused on optimizing refueling outages; in the United States alone, the average refueling outage duration has decreased by a factor of 3 since the 1990s. The average refueling outage in the United States at the end of 2020 was 32 days, but several reactors have performed refueling outages below 20 days [5, 6]. The key to the vast improvements to the average and the top performers has been in outage planning, reducing maintenance activities, and making improvements to the reactor disassembly, fuel cleaning needs, and fuel movement processes.

There is a minimum refueling outage duration that can be reached just based on the physics of cooling down, moving fuel, and heating up; the top performers in the industry are already at that minimum. Consequently, the gains in this area will be for those that have not implemented the lessons learned from the top performers. The key decision points include the applicable regulatory agency's acceptance of performing tasks on-line, as well as the investment in planning and tools to speed up the refuel process, such as reactor disassembly tools. Similar to improving resilience, nuclear utilities have been implementing outage reduction improvements and will continue to do so as long as there is an economic driver.

Increasing the refueling interval for light water reactor (LWR) plants reduces the number of outages and associated costs over the remaining life of the plant, thereby also increasing its generation and capacity factor. Most boiling water reactors (BWRs) and a small population of low power density pressurized water reactors (PWRs) are already able to operate at 24-month cycles. The energy requirements to achieve longer cycle lengths (30 or 36 months) for the 24-month plants and to enable the remaining higher power density PWR fleet to realize 24-month intervals can be achieved only by implementing the following: increasing the initial uranium-235 loading through higher-density fuel pellets; increasing the number of fuel pins (BWR only); and/or increasing the enrichment and burnup beyond the current regulatory limit. For the last option, EPRI is conducting research to inform a key issue for burnup limit extension and help enable more efficient and economic fuel management strategies leading to longer cycle lengths.

The potential for extending the refuel interval is dependent mostly on the regulatory status of increasing enrichment and discharge burnup limits. The technical issues are the responsibility of the fuel supplier. The key issues for the utility, once the business case is acceptable, is the ability of the existing instrumentation and control (I&C) equipment to perform at the extended intervals without exceeding drift limits, establishing new setpoints, and/or replacing existing equipment with newer technology that will meet the performance requirements. Another issue to be considered in this decision making is receiving regulatory approval for extension of surveillance, inspection, and testing requirements of safety-related SSCs for longer cycle lengths.

Life Extension

NPPs are granted operating licenses by their country's respective regulatory body. These regulatory bodies may grant operating license renewals or extensions after regulatory review and approval processes, extending the life of the nuclear power plants by typically another 10- or 20-year increment. To date, the longest license granted is for 80 years of operation.

Long-term operations of a NPP are supported by maintenance and aging management programs, which ensure that a plant's SSCs continue to operate and perform their intended function during the extended period of operation.

EPRI has taken the approach of forming a solid technical basis for aging management based on key aging parameters and not based simply on age (in years) of the plant. These key parameters indicate when SSCs may need additional analysis or inspections. When these key parameters reach a limit at which additional aging management actions are needed, steps can be taken to monitor components, assess and estimate remaining life, mitigate effects of aging or repair, and replace components. The key areas of focus for aging management programs are reactor vessels and internals, concrete and civil structures, and electrical components. The technical basis has been developed based on decades of accumulated and documented past research, operating experience, and inspection results in cooperation with other entities including the Nuclear Energy Institute (NEI), U.S. NRC, U.S. Department of Energy (DOE), and the International Atomic Energy Agency (IAEA). EPRI continues to support the nuclear power industry in providing new and updated research to support the technical basis for long-term operations.

The key decision point for obtaining an extended license and implementing license extensions once the business case is approved for each is the acceptance of future economic risk, largely dictated by market conditions and/or policy, and external hazards such as climate change. However, historically, the payback period of license extension can be as short as one fuel cycle. Internationally, the decision to pursue license extensions is largely supported by economics as long-term operations of existing nuclear plants represent the most cost-competitive, low-carbon solution of power generation when compared to other low-carbon generation options across all technology options [7]. In the United States, long-term operation of existing nuclear power is a mature, firm, low-cost resource for sustainable carbon-free energy [8] but is facing further economic competition in nonregulated markets without a carbon price and political uncertainty in certain markets. Changes in the local or national political sentiment of a plant can result in premature closures. Short-term economic assistance granted to economically challenged plants may not provide enough confidence for a utility to pursue large capital projects that require longer ROIs, which could deter plant improvements and modernization projects needed to support long-term operations. Similarly, changes in external hazards such as climate change may result in plant derates or impacts on environmental impact statements when applying for license renewals.

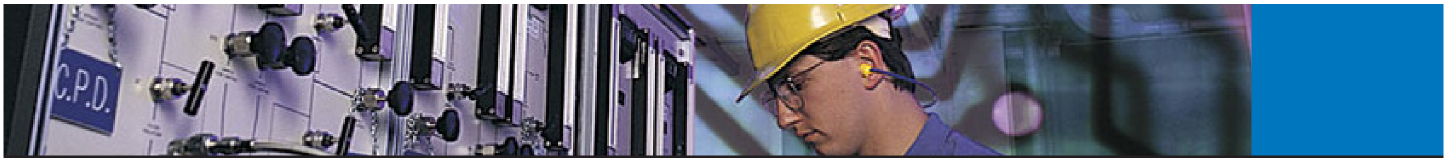
Barriers to Implementing the Options

External Barriers

Environmental, Social, and Governance

External environmental barriers affect the power uprate and life extension options. The most significant are local, regional, and national requirements associated with limiting waterway intake and discharge. These barriers are highly site specific and will have to be addressed as part of the power uprate or life extension submittal. However, given the global experience with power uprates of all kinds, it is expected that the utilities will understand the requirements and have the processes in place to address regulatory issues. Technical barriers associated with the waterway intake and release pathways also exist; they will be discussed later.

External societal barriers associated with power uprates would manifest as public opposition to potential impacts created as a result of increased power output from the plant. This could include required transmission line additions, increased water usage, and increased discharge temperatures to surrounding waterways. These issues would be handled as described earlier, through the regulatory oversight and licensing process.



External societal barriers associated with improving capacity factor should affect only the extended refuel interval option. This barrier could manifest as public opposition to the increased source term of the higher enriched fuel, both in-vessel and in the spent fuel pool. This barrier would be addressed by the licensing process and is not expected to be a major impediment to approval. Similarly, any external societal barrier associated with extending operational life would occur as opposition during the licensing process; this is not expected to be a major impediment to approval.

External barriers from governance apply to the applicable regulatory body for the nuclear power plant. In each of the options, global regulatory bodies have processes and procedures that delineate how to proceed with such activities. The power uprate, refuel interval extension, and life extension options all require regulatory approval before proceeding; the refuel interval extension would likely face the stringent reviews. Regulatory approval would be needed to increase the fuel discharge burnup and maximum enrichment percentage for extending the refuel interval, which may be contentious.

Transmission Constraints

Plants considering power uprates may be limited owing to transmission line congestion because the existing transmission infrastructure may not be able to support additional power injection. However, recent advancements have found that existing transmission line capacities could be uprated by 100% by increasing line voltage and by 250% through AC to high-voltage DC conversions. In addition, underground transmission lines or additional high-capacity overhead lines could be installed using existing transmission rights of way [9, 10]. New EPRI research may enable utilities to improve transmission line constraints to allow for power uprates where they were previously prohibited. Although transmission constraints are a technical issue, they are listed here as an external barrier because they are outside the plant's influence and jurisdiction.

Economic/Political Uncertainty

Current and future economic uncertainty is a considerable nontechnical barrier that could prohibit or limit the extent to which these options are pursued. Significant capital investment associated with extended uprates will require improved economic conditions to obtain ROI. Without future economic confidence, large options may not be pursued.

Some governmental policies have been enacted to provide zero-emission credits to economically challenged nuclear plants, temporarily financially supporting continued operations. However, short-term economic assistance granted to economically challenged plants may not provide enough confidence for a utility to pursue large capital projects that require longer ROIs, which could deter plant improvements and modernization projects needed to support long-term operations or other options such as power uprates or capacity factor increase efforts.

Similarly, current and future political uncertainty poses a barrier that could prohibit pursuing these options. Political uncertainty has already led to premature plant closures and could potentially lead to additional premature closures. In addition, future political uncertainty could deter license extension efforts, plant improvements, and modernization projects needed to support long-term operations or other options such as capacity factor increase efforts.

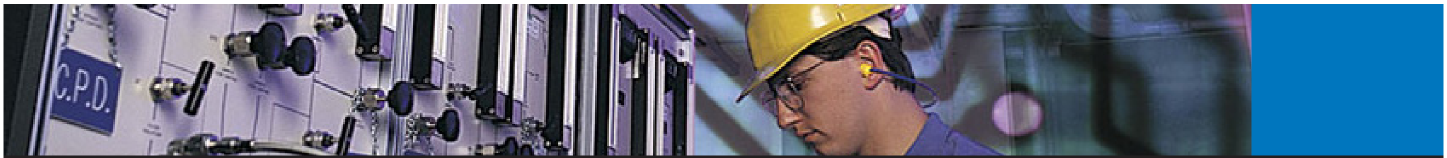
Internal Barriers

Organizational Issues

Organizational risk tolerance is an important factor when pursing the options listed earlier because there will be risk associated with any business decision. Because of the economic and political landscape around any nuclear power plant, the utility may be hesitant to take on capital-intensive projects, such as extended power uprates, or some modernization efforts for long-term operations. These large capital-intensive costs may require many years to generate a return. The profitability and ROI of power uprates, capacity factor increases, or license extensions are not guaranteed.

Similarly, organization resiliency regarding workforce stability and the approach to innovation can be an enabler to the options identified earlier, whereas the lack of resiliency would be a detriment. As technically skilled nuclear industry employees leave the workforce, nuclear plants may face challenges when pursuing or continuing to support license extension efforts, capacity factor increases, or other plantwide initiatives. Knowledge transfer from senior nuclear employees to newly hired or less experienced employees may decrease the challenges of pursuing these options.

As the economic, political, and climate landscapes change, an organization will need to innovate and adapt. Innovations in automation, artificial intelligence, and monitoring technology, for



example, have already shown benefit to other industries, and can be implemented in the nuclear industry as a part of a modernization or digital transformation effort. In addition to improving plant operations, business processes, and plant capabilities, and decreasing operating costs, these innovations could enable power uprates, capacity factor increases, or life extension options and potentially address other internal barriers. Innovation will require new and creative thinking to address current and future challenges to the nuclear power industry.

Technical Barriers

Power Uprates

The maximum licensed thermal power of a nuclear power plant is determined by the fuel heat flux during power operations and the decay heat levels under shutdown conditions. For example, in the event of a design basis loss of coolant accident (LOCA), decay heat levels must be low enough to ensure that fuel cladding temperature will not exceed 2200°F (1204°C). Consequently, to increase the allowed thermal power limit, the NPP must do one of the following:

- Use updated/more accurate codes to gain margin
- Operate with reduced margin
- Use a new fuel design that will accommodate a higher thermal margin (for example, higher heat flux while maintaining the margin to 2200°F),
- Modify the emergency core cooling SSCs to maintain margin with a higher heat flux
- Reduce the heat sink temperature or increase essential service water flows

Once it has been proven that the nuclear fuel can accommodate the higher power, the reactor vessel and reactor coolant components must be able to accommodate the higher fast neutron fluence, flows, temperatures, pressure changes, and associated stresses with removing the additional power.

Similarly, knowing and understanding the operational margins of the balance of plant equipment will provide a look into the additional barriers facing a particular plant and site. In almost all cases, the pivotal point or determining constraint in the available margin of any operational parameter depends on either materials or heat removal. Consequently, removing heat or making SSCs capable of withstanding higher temperatures will be a primary path for eliminating any power uprate barriers.

Heat sink temperature limitations are one technical barrier that can affect all three types of power uprate. The heat sink has both power generation and design basis accident response design requirements. The heat sink must receive rejected heat from the condenser under normal power operating conditions and not exceed environmental limits. The heat sink must also support operation of emergency cooling systems during design basis accidents. If the heat sink temperature cannot support design basis accident requirements or an increased turbine and auxiliaries heat load, then power uprate cannot be realized. Many NPPs are already limited by summertime heat sink temperatures; any power uprate will exacerbate this condition. To overcome this barrier, methods or technology are needed that either allow the equipment to operate at the higher temperatures, reduce the heat sink temperature, or increase cooling water flow. Other than any heat sink limitations, which include cooling water discharge temperatures, there are no technical barriers to prevent a NPP from implementing a MUR uprate; it is purely an economic issue.

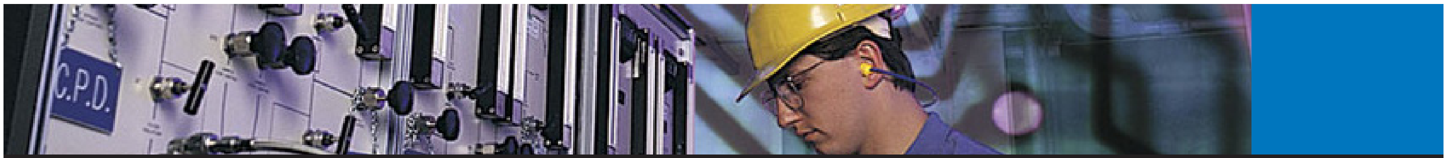
A SPU relies on using existing excess operational margins and is primarily an analytical exercise; consequently, there are no barriers to performing a SPU, other than the heat sink issue identified previously. A plant that has previously performed a SPU may be able to perform another one by using more accurate codes and taking credit for any new SSCs that have been added since the last SPU.

The more extensive EPU can face a significant number of technical barriers or limitations depending on the site, reactor design, and age of the reactor. The utility must first identify the operational margins for all equipment in the power production train. This power production train is made up of the fuel, the reactor coolant system, the steam dryers/steam generators, the turbine generator and its auxiliaries, feedwater and condensate systems, condenser and circulating water system, and the main transformers.

Capacity Factor Increase

As mentioned previously, there are three ways to increase a nuclear power plant's capacity factor: improve plant resilience; reduce outage time; and increase the refueling interval for non-CANDU plants.

Resilience is much more than just equipment reliability; it is the ability to withstand operational challenges and continue to function at power. The industry's equipment reliability process must evolve to be focused on resilience, of which equipment reliability is a



subcomponent. This refocusing of equipment reliability onto plant resilience will result in determining and tracking operational margins and creating ways to increase those margins so that the plant and its systems can withstand challenges and continue to operate.

The next technical barrier to increasing plant resilience is site knowledge of the changing external hazards associated with climate change. Nuclear plant sites need to have forecasts or predictions of how the external hazards will be changing for their specific sites. Knowing how these external hazards are predicted to change, such as frequency and severity of storms and extreme temperatures/droughts, will allow utilities to mitigate the effects before these hazards can challenge the plant.

The last barrier to plant resilience is the available solutions and technology to address the challenges—for example, ways to reduce heat sink temperature, improve heat exchanger efficiency, or allow greater operating temperatures for equipment.

There is no technical barrier to reducing outage length. As mentioned previously, many utilities have already approached the minimum amount of time for a refueling outage; late-adapter utilities need only to follow the operating experience and lessons learned from the top performers. Similarly, forced outage lengths are reduced by planning and preparation so that the unit can be returned to service in minimal time.

The most significant technical barrier associated with extending the refueling interval is the research needed to address the nuclear fuel issues identified earlier. Specifically, research is needed in the development, impacts, and business case for higher density fuel, higher enrichments, and higher discharge burnups.

A lesser technical barrier to extended refuel intervals is the identification and mitigation of SSCs that may not be able to operate for the length of the extended interval without some sort of maintenance, inspection, and testing frequency that cannot be performed on-line, and may require a license amendment request. Analysis and replacement of components that the analysis shows to be marginal can address these concerns.

Life Extension

There are currently no known technical barriers to preclude operation past 80 years of operation out to 100 years of operation, or even further. From EPRI's experience in forming the technical basis for up to 80 years of nuclear power plant operation, EPRI has a systematic approach to forming/updating the technical basis for long-term operations that includes aging management programs and practices, repair technologies, and replacements. As shown in Figure 1, aging management is a living process and EPRI is continually evaluating aging issues. Research contributing to this cycle will include continual validation of current knowledge.

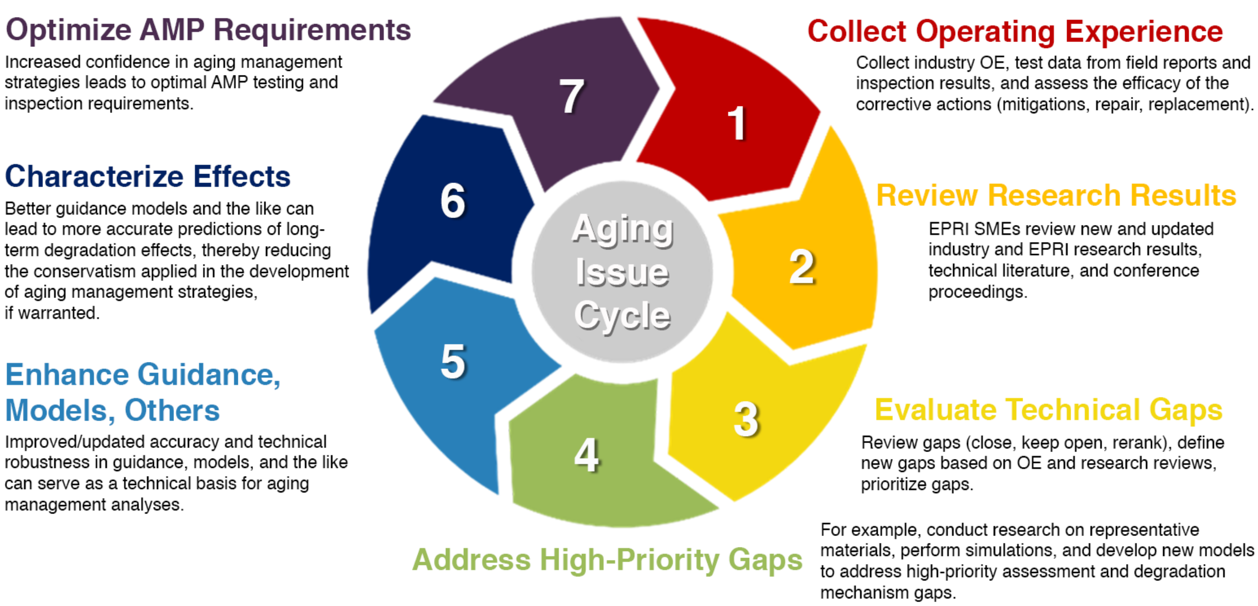
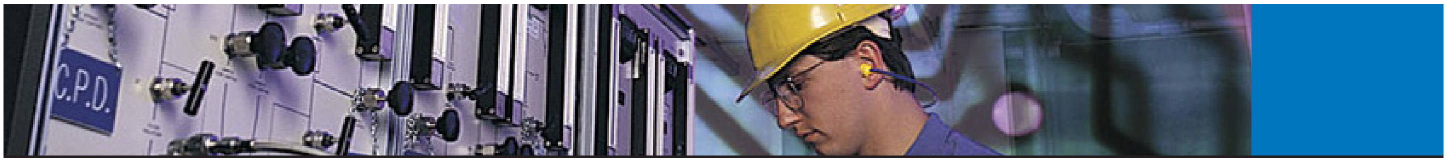


Figure 1. Aging management cycle



Although there are no technical barriers limiting operation beyond 80 years, additional research may be needed to fill knowledge gaps on aging management strategies regarding equipment obsolescence, I&C systems, buried underground piping, and intake structures. As mentioned, another area of research would be to consider the effects of climate change on plant resiliency and equipment. With increased ambient temperatures or drastic swings in ambient conditions, this may induce new stresses on plant SSCs that may need to be accounted for in aging management strategies.

Required Research to Support the Options

The barrier analysis in the previous section has identified the following needed research to resolve the issues that may be preventing a commercial nuclear power plant from implementing any one or more of the options listed previously to provide additional carbon-free energy to the global electrical grid.

Reducing Heat Sink Temperature

Reducing the heat sink temperature will not only enable power uprates but will also improve plant resiliency and, therefore, capacity factor. The large majority of commercial nuclear power plants are cooled by either saltwater (oceans, seas, gulfs), brackish water (inland seas, estuaries), or fresh water (rivers, lakes). There are potential options to reduce the intake temperature from these bodies of water, and/or to increase the amount of heat that can be rejected to these bodies of water. Research is needed that does the following:

- Identifies the different types of nuclear cooling water intake flow paths
- Evaluates solutions to reduce the intake temperature for each of those flow paths
- Provides the best options for nuclear power plants to pursue

Follow-on projects to pilot and perform case studies on the most promising options will be pursued.

Research roadmap:

- 2022–2023: Technical Report: NPP Cooling Water Temperature Reduction Options
- 2023–2024: Pilot projects implementing most promising solutions
- 2025: Technical Report: Case Studies for Reducing NPP Cooling Water Temperature

Increasing Heat Sink Resiliency to Drought and Intake Blockages

Increasing the heat sink resiliency will improve capacity factor by enabling the plant to withstand challenges and continue to operate. The two primary challenges to cooling water intakes are availability and blockages. Availability is primarily a fresh water and brackish water concern where droughts affect the available water source. Blockages, on the other hand, affect all the different water sources. Research is needed that does the following:

- Identifies options for mitigating droughts
- Provides solutions to eliminate or reduce the potential of intake blockages
- Provides the best options for nuclear power plants to pursue for both challenges

Follow-on projects to pilot and perform case studies on the most promising options will be pursued.

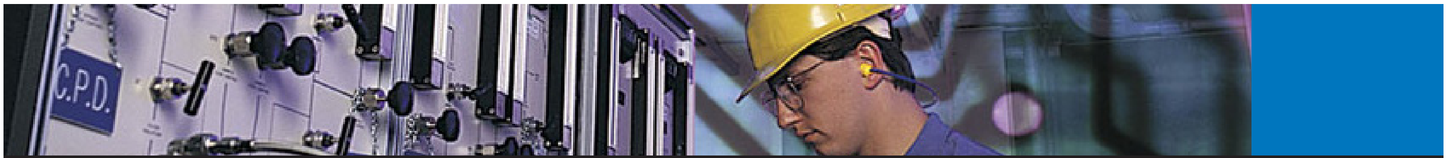
Research roadmap:

- 2022–2023: Technical Report: NPP Cooling Water Drought Mitigation Options
- 2022–2023: Technical Report: NPP Cooling Water Intake Blockage Mitigation Options
- 2023–2024: Pilot projects implementing most promising solutions
- 2025: Technical Report: Case Studies for Mitigating NPP Drought Implications
- 2025: Technical Report: Case Studies for Reducing NPP Cooling Intake Intrusions

Maintaining or Reducing Cooling Water Discharge Temperature

All NPPs will have associated country, region, or local permits that identify the allowed parameters when discharging effluents to the environment. Limiting or reducing the thermal impact of discharges will enable power uprate for any NPP that is thermally discharge limited. Several NPPs have implemented closed cooling configurations with cooling towers and other technology to address such limits. Research is needed that does the following:

- Identifies the different types of NPP discharge flow paths
- Evaluates solutions to reduce the discharge temperature for each of those flow paths
- Provides the best options for nuclear power plants to pursue



Follow-on projects to pilot and perform case studies on the most promising options will be pursued.

Research roadmap:

- 2022–2023: Technical Report: NPP Discharge Temperature Reduction Options
- 2023–2024: Pilot projects implementing most promising solutions
- 2025: Technical Report: Case Studies for Reducing Discharge Temperatures

Increasing Coolant Water Flows

NPPs will normally have three coolant loops that take water from the main cooling water source: the safety-related water system, the non–safety-related water system, and the circulating water system. Increasing the mass flow rate of the systems will provide margin to the design parameters that may be preventing a power uprate and will make the systems and associated loads more resilient to higher cooling water temperature. Research is needed that does the following:

- Identifies the implications of increasing the cooling water flow
- Identifies ways to increase the flow
- Provides the best options for nuclear power plants to pursue

Follow-on projects to pilot and perform case studies on the most promising options will be pursued.

Research roadmap:

- 2022–2023: Technical Report: NPP Safety-Related Water System Flow Increase Options
- 2022–2023: Technical Report: NPP Non–Safety-Related Water System Flow Increase Options
- 2022–2023: Technical Report: NPP Circulating Water System Flow Increase Options
- 2023–2024: Pilot Projects implementing most promising solutions for all three
- 2025: Technical Report: Case Studies for Safety-Related Water System Flow
- 2025: Technical Report: Case Studies for Non-Safety-Related Water System Flow
- 2025: Technical Report: Case Studies for Circulating Water System Flow

Improving Heat Exchanger Performance

Limitations on current heat exchanger technology performance may challenge the existing nuclear fleet's resiliency and ability to perform extended uprates. Additional operating margins within heat exchangers will be needed to both increase plants' resiliency toward future operational challenges associated with climate change, and to enable extended uprates. Research is needed that accomplishes the following:

- Identifies the various heat exchanger critical design parameters (such as materials, fluid, flow rates, tube coatings)
- Evaluates which parameters may be enhanced or modified to improve performance
- Provides the best options for nuclear plants to pursue

Sequentially, a pilot project at an EPRI member plant will be performed alongside case studies. The results of the pilots and case studies will then be published for members' consideration for implementation.

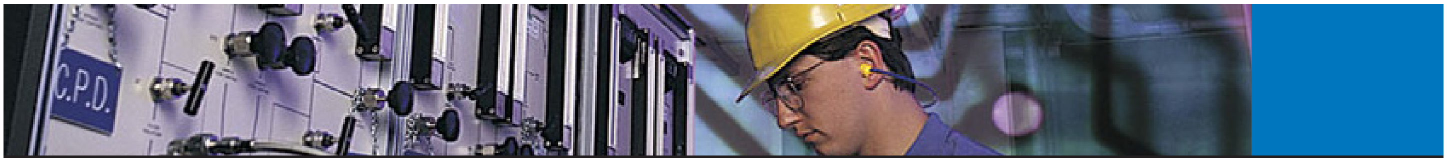
Research roadmap:

- 2022: Survey/scouting white paper
- 2023–2024: Pilot project at EPRI member plant
- 2025: Pilot results and recommendations white paper

Site/Region Climate Change Predictions

A nuclear power plant's ability to withstand operational challenges and continue to function is paramount to resiliency. To withstand future operational challenges arising from climate change, fleets will require regional and site-specific climate change impact predictions, including projected seasonal maximum and minimum temperatures and precipitation estimates. These predictions may assist a nuclear plant in performing targeted plant modifications to improve resiliency toward future climate change challenges. Research is needed to do the following:

- Document and review the potential impacts of climate change on nuclear power plants and generation reliability and identify the potential actions that could be considered for improving reliability (this report is scheduled to be published in 2021)
- Generate regional climate change impact predictions to assist nuclear owners and operators in performing plant resiliency modifications
- Offer site-specific climate change impact predictions to owners and operators for a site-specific study



Research roadmap:

- 2021: Nuclear Plant Resiliency in the Face of Climate Change (Product ID: 3002020767)
- 2022–2023: Technical Report: Guidance to Support Plants in Evaluating Operational Impacts and Vulnerabilities to Potential Climate Change Trends
- 2024+: Site-specific supplemental project offerings

Creating an Operational Resiliency Program

Existing programs, such as INPO AP-913, Equipment Reliability Program, could evolve to become an operational resiliency program. This program will combine the existing equipment reliability programs with a margin management program that identifies methods to recover operating margins. Research is needed to identify and document resiliency best practices, which will be incorporated into an EPRI operational resiliency program guide. This operational resiliency program will be piloted at an EPRI member site. The results of the study, along with lessons learned, will be incorporated into a technical report for the nuclear industry's consideration and implementation.

Research roadmap:

- 2022–2023: Operational resiliency program guide
- 2024: Pilot program at a utility
- 2025: EPRI technical report case study

Increasing Nuclear Fuel Allowed Enrichments and Burnup

Research into increased nuclear fuel enrichment is well under way. To date, no research findings have become showstoppers for implementing enriched nuclear fuel in the U.S. commercial nuclear power fleet. Research into increased nuclear fuel burnup is needed to determine whether any increased hazards are associated with large break LOCA and fuel fragmentation, relocation, and dispersal (FFRD). The results of this research will need to be reviewed and approved by the U.S. NRC and other global regulators. Upon approval, a pilot will be performed at a nuclear power plant using ATF and enriched uranium, with a goal of achieving higher discharge burnup. The results of this pilot will be documented and released as an EPRI technical report.

Research roadmap:

- 2021–2023: Deterministic or best estimate plus uncertainty for large break LOCA to address FFRD for higher burnup and an alternative licensing path using a risk-informed FFRD disposition methodology
- 2023–2024: NRC review of FFRD hazard elimination
- 2024–2027: Pilot program at a utility
- 2028: EPRI technical report

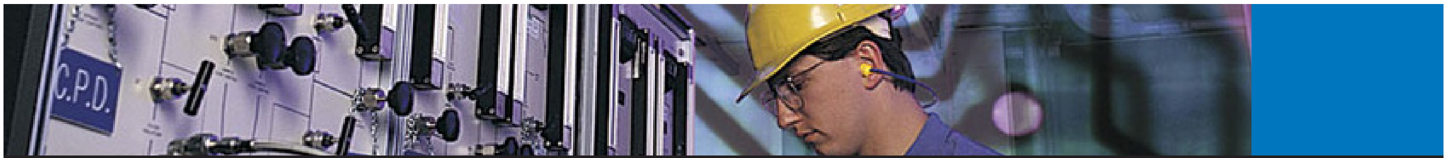
Multivariate Regression Modeling to Improve Plantwide Sensor Performance and Measurement Accuracy

Data validation reconciliation (DVR) technology, a form of multivariate regression modeling, uses plant process instrumentation data and first-principle mathematical models to validate and reconcile plant instrumentation measurements. Most notably, DVR technology has been used in Germany and Switzerland for MUR power uprates and is currently being reviewed by the U.S. NRC for application in the United States. However, multivariate regression modeling could also be used to improve plantwide sensor performance and measurement accuracy.

The use of DVR for MUR is established; no other research is needed for that application. However, research is needed in applying other multivariate regression modeling and other calculational techniques for improving sensor performance and measurement accuracy and extending calibration intervals. Multivariate regression modeling may also be used in digital twin applications, to model plant system health or improve operational margin calculations for potential stretch uprates. Research is needed to evaluate other multivariate regression modeling techniques, including applications of digital twins, to improve plantwide sensor accuracy for system health modeling and operational margin determination. This research will be piloted at an EPRI member utility for proof of concept. The results of this pilot will be published in an EPRI technical report for industry consideration and possible implementation.

Research roadmap:

- 2022: Method evaluation and modeling study
- 2023: Pilot program at a utility
- 2024: EPRI topical report
- 2026: NRC review of topical report



Summary

This white paper identifies three ways to leverage the existing commercial nuclear industry to support the 2030 and 2050 global climate goals, with the caveat that the prevention of premature nuclear power plant closures is a required first step. For the purposes of this paper, leveraging the industry is meant to imply ways to increase the amount of carbon-free energy supplied to the electrical grid by the existing commercial NPPs.

Many of the needed processes and tools are already in place to execute the options discussed in this paper; it is only a matter of the ROI being acceptable to make them happen. However, several gaps or barriers for these options were identified in this paper; the resolutions of those gaps have been placed into roadmaps, as shown in the following section. This roadmap is used to drive resolution of many of the identified gaps by 2025, thereby providing time for NPPs to implement before the 2030 goal milestone.

The heat sink capacity is a primary factor on the ability to leverage the existing fleet to add additional energy to the electrical grid. The heat sink affects both abilities to uprate and increase capacity factor. Notwithstanding the ROI, the most prevalent uprate limitations result from the heat sink temperature. Reducing the heat sink temperature would not only enable plants that are prevented from performing an initial uprate, but also may allow additional uprate by plants that have already performed a stretch or extended uprate.

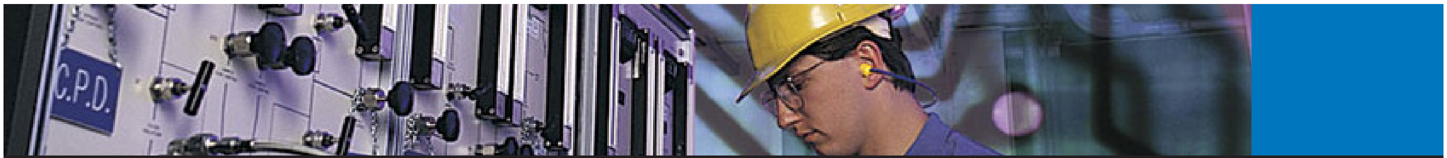
The heat sink also plays a significant role in the capacity factor increase option, as it is one of the most significant contributors to plant resiliency. Reducing heat sink temperature, mitigating drought impacts, and eliminating intake threats are the most effective ways to improve plant resiliency. A number of technologies are already available to address cooling water issues such as "shade balls" and floating reflector panels, which could shield heat sink water reservoirs from higher ambient temperatures and direct sunlight and reduce heat sink temperatures. Reduction of evaporation using the aforementioned methods may allow plants to retain more water, lowering the need for makeup water and increasing plant resiliency against future droughts. Alternatively, research into "cloud seeding," weather modification that changes the amount of precipitation and is already being used around the world, could provide the necessary makeup water to maintain heat sink water levels. Alternatives to water may have improved heat transfer properties that can be used for circulating cooling, and thus increase operating margins, decrease the need for water, and enable additional stretch and extended uprates.

Improvements in capacity factor from extending the refuel interval are dependent primarily on nuclear fuel-related issues such as increased pellet density, higher allowed discharge burnups, and higher allowed enrichments. The research needed to implement extended refuel intervals is included in the roadmap that follows.

Similar to the uprate process, life extension is a mature process that has been implemented in several countries. There are currently no known technical barriers to preclude operation past 80 years of operation out to 100 years of operation, or even further. The technical basis for aging management is a living process and EPRI is continually evaluating aging issues. As noted earlier, an economic driver or acceptable ROI must be present for any commercial nuclear power plant owner to implement any of the options identified in this report. However, that does not mean that planning for such a turn in circumstances should be stalled; rather, it is critical that the commercial nuclear power plant owner be ready for the turn in economics and be able to implement options quickly to support climate goals.

Roadmap

The needed research is shown in the Gantt chart in Figure 2. The proposed timelines for most of these research items have been selected to be complete by the end of 2025. The completed timeline of the related research is intended to allow the nuclear power industry to incorporate power uprates, capacity factor increase, and/or license extension opportunities to support the near-term 2030 greenhouse gas reduction goals for their respective countries. It is probable that new research into power uprates and capacity factor increase may emerge during the roadmap timeline, and it is highly probable that new research in the space of life extension and aging management will also emerge; as such, this roadmap is subject to change.



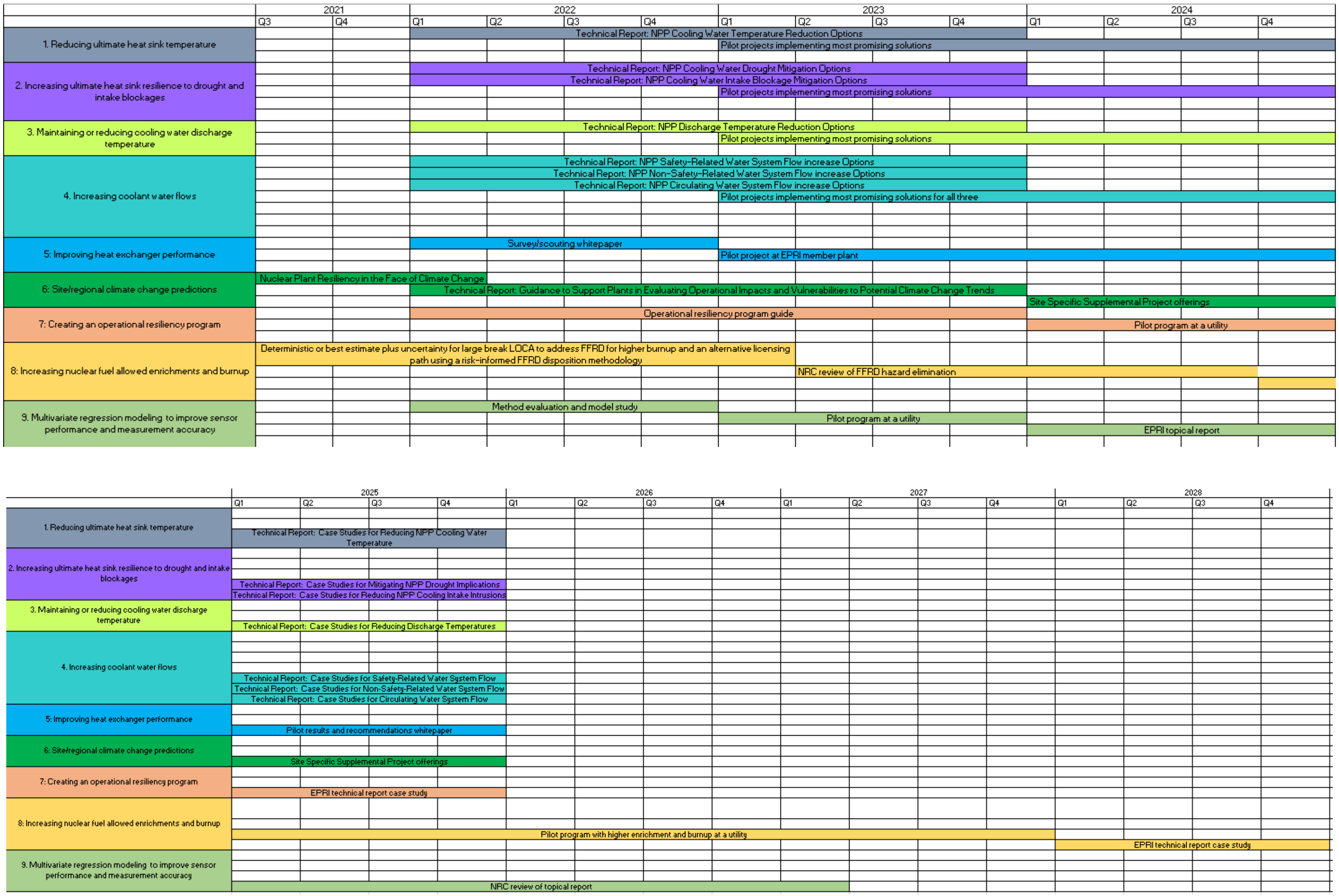


Figure 2. Roadmap of needed research

References

1. International Energy Agency. May 2019. Nuclear Power in a Clean Energy System. France. https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system.

2. United Nations Framework Convention on Climate Change. 2016. Paris Agreement—Status of Ratification. https://unfccc.int/process/the-paris-agreement/status-of-ratification.

3. U.S. Nuclear Regulatory Commission. 2021. Approved Applications for Power Uprates. https://www.nrc.gov/reactors/operating/licensing/power-uprates/status-power-apps/approved-applications.html (last modified February 5, 2021).

4. *Use of Data Validation and Reconciliation Methods for Measurement Uncertainty Recapture: Topical Report*. EPRI, Palo Alto, CA: 2020. 3002018337.

5. U.S. Energy Information Administration. 2018. U.S. Nuclear Plant Outages Increased in September after Remaining Low during Summer. https://www.eia.gov/todayinenergy/detail.php?id=37252.

6. U.S. Energy Information Administration. 2021. Capacity Outages at U.S. Nuclear Power Plants Averaged 3.1 Gigawatts this Summer. https://www.eia.gov/todayinenergy/detail.php?id=49796.

7. International Energy Agency. 2020. Projected Costs of Generating Electricity, 2020 Edition. Paris, France: OECD Publishing. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020.

8. *Program on Technology Innovation: Integrated Generation Technology Options 2017*. EPRI, Palo Alto, CA: 2018. 3002011806.

9. *Summary of Recent Increased Transmission Line Utilization Projects: 115 kV and Above*. EPRI, Palo Alto, CA: 2020. 3002020158.

10. *Increased Power Flow Guidebook—2020: Increasing Power Flow in Lines, Cables, and Substations (Platinum Book)*. EPRI, Palo Alto, CA: 2020. 3002019086.

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