U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0002115
on
Intelligent Analytics, Algorithms, and Maintenance to Optimize Operations in Advanced Nuclear Reactors

Introduction:

ARPA-E is seeking information from diverse industries about technologies that could enable advanced nuclear reactors[1] to achieve operating cost profiles that approximate those of natural gas combined cycle plants. This entails reducing operating costs per megawatt of electricity (MWe) at nuclear power plants by more than one order of magnitude.

Attaining this vision requires semi-autonomous nuclear power plant operations, a radical departure from traditional nuclear power plant operations. Because autonomy is so unconventional for the nuclear sector, attacking the problem requires operational technologies and controls strategies that have limited or no technical precedent in the nuclear community. For this reason, ARPA-E is especially interested in perspectives from outside the traditional nuclear energy space.

Today's nuclear plants are mostly conventional light water reactors (LWRs).[2] Their continued viability in the U.S. electricity mix is challenged in part by high operational and maintenance (O&M) costs compared to other electricity generation types.[3] The higher costs stem largely from the high staffing level required for nuclear power plant operation, maintenance, safety, and security. Advanced nuclear reactor systems that are anticipated to comprise the next generation of new reactor builds are likely to face costs that are similar to LWRs, should they not pursue new approaches to O&M. High O&M costs might be especially burdensome for small modular reactors (SMRs) and microreactors, which do not have the benefit of economy of scale. Much greater focus on achieving a radical reduction of O&M costs will likely prove necessary to assure the competitiveness of advanced nuclear systems.

Therefore, approaches in predictive maintenance, autonomous maintenance, fault detection and isolation algorithms, novel sensor systems, data analytics, dynamics modeling, and advanced control systems are of interest. Also of interest are advanced modeling and simulators that allow exploration of a full range of potential data streams, and can help identify/evaluate the most relevant control algorithms and sensor needs. Finally, test loops and experimental facilities that can be leveraged to investigate and validate approaches for autonomous controls, operations, and maintenance are of interest.

---

[1] Advanced reactor designs are here defined as non-light water reactors, including designs that use as heat transfer media: gas, lead (or lead-bismuth alloy), molten salt, sodium, supercritical water, or organics; and as nuclear fuel types: ceramic oxides, nitrides, metals, TRISO clad, silicon carbide clad, metal clad, or liquid eutectic.
[2] https://www.nrc.gov/reading-rm/basic-ref/glossary/light-water-reactor.html
[3] Nuclear Energy Institute. *Nuclear Costs in Context*. April 2016.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Background:

In other sectors of industry, dramatic O&M savings have been achieved through the adoption of advanced analytics (such as machine-learning-enabled predictive maintenance) and autonomous control and maintenance systems.[4] Importing these successes to the nuclear industry may enable similar dramatic reduction of O&M costs. ARPA-E is interested in understanding the current best technologies and what new developments are needed for very low-cost advanced reactor operation.

a. Industrial autonomous controls: staff optimization

The long-term economic viability of advanced reactors will be greatly enhanced through the design of intelligent control systems to provide semi-autonomous operations. Such autonomous control systems should ideally incorporate diagnosis, simulation, analysis, planning, reconfigurability, self-validation, and decision-making capabilities. Autonomous control has been researched for many years, and systems with varying levels of autonomy have been employed in applications spanning robotics, transportation, spacecraft, and manufacturing applications – but autonomous controls of any sort have not been implemented for an operating nuclear power plant. Today, nuclear power plant sensors are infrequently connected to automatic data collection systems, data that are collected are stored in disparate databases and formats, and system modeling and management are deterministic rather than incorporating probabilistic information about risks and failure potential. It is clear that further research and development is necessary to establish a suitable functional architecture and develop foundational modules to support autonomy for advanced reactors.

The development of plans and systems to semi-autonomously control future advanced nuclear power plants will rely on simulation platforms that can (1) generate data to inform operational choices and (2) serve as virtual testbeds for the control systems. Therefore, an area of potential interest is "digital twin" technology to help guide the design and testing of control systems. Digital twins are detailed software representations of an asset that typically incorporate physics models, AI/machine learning models, and visualization software.[5] Digital twins can provide information to systems that make choices and recommendations about operations and maintenance, and they are increasingly deployed in a variety of industries because of their cost-saving potential.

b. Maintenance Activities

Recognizing that unexpected hardware failures often lead to operational losses and unnecessary maintenance increases costs, fossil power plants and utilities (among other industries, including aerospace and manufacturing) have adopted predictive maintenance (PdM) techniques. PdM leverages the increasingly rich data sets generated by sensor devices as well as advanced modeling to determine the condition of infrastructure and equipment, providing early warning of maintenance needs instead of servicing on a routine, time-based schedule or responding to faults after they occur. PdM is considered an advanced subset of asset performance management (APM), which generally tracks sensor output and sends an alert when a measurement deviates from an acceptable window of operating conditions. Approaches to PdM vary widely, ranging from models that require minimal training data, such as linear

---

[4] Bloomberg New Energy Finance. "A World Where Machines Never Fail: AI and Predictive Maintenance." December 18, 2018.

[5] Bloomberg New Energy Finance Technology Radar, The digital twin edition. November 7, 2018.

regression, to the use of neural networks requiring large historical or simulated training data sets for increased precision of fault prediction.[4] The nuclear industry could benefit from the application of PdM as nuclear power plants require constant asset operation with no tolerance for failures and involve the management of assets where regular inspections are currently time-consuming and expensive.[6]

Nuclear reactor plants have some maintenance activities that expose workers to low levels of radiation. Some advanced reactor designs will have maintenance activities that may be too hazardous for humans to conduct routinely. Whether to limit radiation to workers or enable maintenance at all, advanced reactors will benefit from autonomously-conducted maintenance activities. There have been many advances in rad-hard robotics and robotic controls. However, the need for autonomous maintenance appears relatively unexplored.

c. Test loops

Test loops are thermal-hydraulic flow loops that mimic aspects of nuclear reactors at a systems level to provide physical data to support autonomous systems. A heater element is generally used in place of the nuclear heat source and is usually scaled down from a prototypical system. Test loops will need to be highly instrumented to collect the required data. Test loops can serve the dual purpose of supplying basic physical data needed and act as test-beds for control strategies, advanced dynamics modeling, parameter estimation, control system design, operations choices, and advanced maintenance activities. Automation and maintenance strategies that are successful at the test-loop level could be used to inform the design of advanced nuclear reactors not only to lower O&M costs, but to also avoid future design rework or retrofits.

d. Sensors

Sensors that provide the right data to the necessary level of accuracy and precision are crucial for the realization of optimized operations. While ARPA-E does not anticipate sensors as the primary focus of a near-term future nuclear fission program, sensors are needed to limit or eliminate the need for humans to conduct regular monitoring and maintenance and to enable early corrective action for abnormal conditions. The sensors needed for a nuclear reactor environment are especially difficult because of the high temperatures, radiation, and (often) corrosive materials involved. The conditions add an extra challenge to sensor durability and can make calibration complex. While significant research is ongoing in this area,[7] the scale and reliability of what must be measured may warrant additional development. Particular challenges exist in developing sensors that measure temperature, pressure, materials changes, stress/strain, and flowrates in the multitude of proposed advanced reactor environments while being reliable, verifiable, and redundant/independent.

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration, to inform the possible formulation of future programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

---

[6] We note that some plants are beginning to adopt such strategies, *e.g.*, https://www.uptake.com/blog/how-uptake-saved-palo-verde-millions

[7] *E.g.*, https://www.energy.gov/ne/articles/idaho-national-laboratory-awards-39-million-support-proposed-fast-spectrum-test-reactor

REQUEST FOR INFORMATION GUIDELINES:

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents should not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on April 25th, 2019**. Emails should conform to the following guidelines:

- Please insert "Responses for Intelligent Analytics, Algorithms, and Maintenance to Optimize Operations in Advanced Nuclear Reactors" in the subject line of your email, and include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 10 pages in length (12 point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

Questions:

Please provide answers and information about any of the following, noting that we do not expect any one respondent to answer all, or even many, questions. Citations are encouraged as appropriate.

a. If you are not familiar with the advanced nuclear reactor space, what information and/or tools would be key for you to engage more deeply in the development of industrial autonomy, operations, and maintenance for advanced nuclear power plants?
b. Control technology and algorithms
    i. What are the state-of-the-art systems/algorithms/strategies for semi-autonomously controlling industrial operations or other complex systems?
        1. What do they do?
        2. With what degree of precision and accuracy?
        3. What information do they need (e.g. type, resolution, distribution, frequency, confidence level)?
        4. If applicable, how do they deal with unexpected events?
    ii. What industries have you applied your systems/algorithms/strategies to? How and why did they improve performance?
    iii. What might be challenges to applying the state-of-the-art autonomous control strategies to advanced reactors?
    iv. There may exist "digital twins," which are virtual models of nuclear reactors, that could simulate real reactor operations and assist in diagnosing problems. These could potentially be leveraged or enhanced to train and test operation and maintenance systems.
        1. What are the specific nuclear systems for which digital twins currently exist?
        2. What level of validation – including validity of physical data underpinning the models – has been done?
        3. What, if any, are the restrictions or limitations on their use?

        4. Are developments still needed for such digital twins to be able to incorporate and evaluate operations control, model-based fault detection, etc.?
    v. Do control strategies need to be developed for a reactor to rapidly vary thermal output in real time?

c. Maintenance
    vi. What are the best technologies for asset performance management, including predictive maintenance, in industrial settings and what can they currently accomplish?
    vii. What systems/strategies exist for conducting maintenance autonomously in highly complex operational settings?
    viii. What gaps are there for conducting maintenance autonomously in industrial settings? What technologies are needed?
    ix. What maintenance activities in a nuclear power plant would be most beneficial to automate? Why?

d. What physical test loops/experiments could be used to validate performance of operations control algorithms and/or maintenance procedures?
    x. Describe the key parameters such as operating fluid, scale, flow rate, temperature range, etc. of the test loop.
    xi. What level and types of instrumentation do these loops employ? Is it possible to accommodate the addition of new sensors?
    xii. What operational scenarios do they test (e.g. transients such as accidents, start-up, shutdown, etc.)? How are they tested (software, controls, etc.)?
    xiii. If you believe that test loops/experiments cannot be used to validate performance of operations control algorithms and/or maintenance procedures, please comment on why. In other words, which gaps/limitations prevent test loops/experiments from being used for validation?
    xiv. Are developments still needed for the test loop(s) to be able to integrate controls for evaluation? If so, which developments are needed?
    xv. To what degree is the loop modeled in software? Is that model validated and for what scenarios or regimes?
    xvi. The various coolants proposed for advanced reactors have unique challenges and technology gaps. For which coolants would existing or proposed highly-instrumented test loops most advance the state of the field?

e. Sensors
    xvii. What, if any, are the critical gaps in instrumentation technology that prevent the acquisition of data necessary for autonomous control systems in advanced nuclear reactors?
    xviii. What advanced sensing technologies are in use by other industries that contend with high operational temperatures (*e.g.* >500 C), pressures, and corrosion that could potentially be imported to nuclear systems?
    xix. What sensing technologies might be developed (and are not already the focus of programming administered by the Department of Energy's Nuclear programs) to monitor pressure, temperature, corrosion, and other critical advanced reactor performance elements?
    xx. What developments are needed in sensor fusion, indirect sensors, observer, distributed sensors, sensor location, inference algorithms, etc. for autonomous control systems in advanced nuclear reactors?

f. Safeguards by design
    xxi. How might new control algorithms impact required application of international safeguards (a set of technical measures applied by the IAEA on nuclear material and activities, through

which it seeks to independently verify that nuclear facilities are not misused and nuclear material not diverted from peaceful uses)?[8]

xxii. How might autonomous maintenance activities impact safeguards?

xxiii. Are there opportunities to leverage tools of interest in this RFI for safeguards?

---

[8] https://www.iaea.org/publications/factsheets/iaea-safeguards-overview