Advanced Sensors and Instrumentation

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ASI Program Update

Craig Primer
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This marks the 19th newsletter sent out by the U.S. Department of Energy-Office of Nuclear Energy (DOE-NE) Advanced Sensors and Instrumentation (ASI) program and is the second of two newsletters for fiscal year (FY) 2023. This newsletter provides updates on activities related to Digital Control Systems and highlights the ASI Digital Control System Workshop sponsored by the DOE-NE held at Argonne National Laboratory over the summer.

Over the last several years, the ASI Program has sponsored research to develop a wide range of critical cross-cutting methods and technologies needed to successfully deploy U.S. advanced reactors.

These contributions are focused on three key Digital Control System areas: (1) Communications; (2) Digital Twins; and (3) Advanced Control.

Researchers are developing solutions in each area that provide the advanced reactor industry with the necessary operational and performance capabilities to achieve U.S. energy objectives. These results are aimed at increasing the competitive nature of nuclear power in the U.S. energy landscape. The targeted benefits include higher levels of work automation, more flexible operations for meeting load demand, and improved economic performance.

Several national laboratory researchers: Vivek Agarwal, Pradeep Ramahaulli, Rick Villim, Andrew Casella, and Ahmad Al Rashdan—along with input from the advanced reactor industry, assisted the ASI Program in defining key digital control objectives and capabilities, which will be necessary to support new reactor designs.

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U.S. DEPARTMENT OF ENERGY

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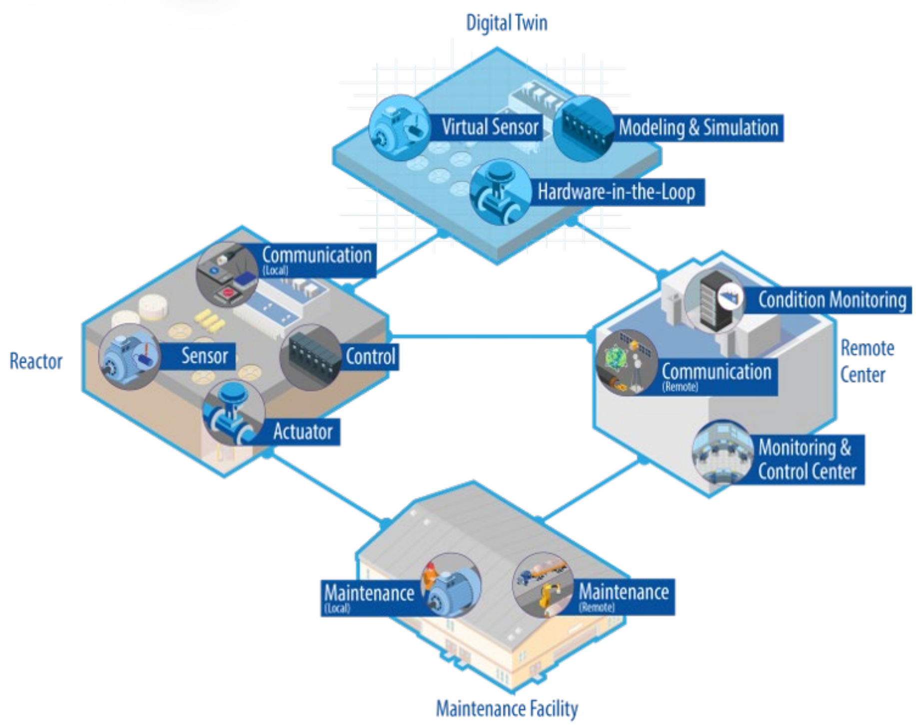


Digital Control Systems integrate Communication, Digital Twins and Advanced Control Systems.

These inputs helped develop the ASI Program's Digital Control goals and contributed to creating an integrated research strategy providing the roadmap for achieving these objectives. The goals and objectives for each area are described below.

Communication research is developing and demonstrating methods for communication to ensure that data measurements collected at scale enable monitoring, storing, processing, modeling, validation, and verification of advanced control concepts, and decision support.

These requirements include such things as:

- Develop communication models that support multi-band frequency network architecture
- Develop metrics to evaluate the resilience, reliability, latency, coverage, connectivity, and throughput of a communication network prototype under different operating conditions.

Advanced Control Systems research is developing and demonstrating real-time control of plant and experimentation process variables through advanced monitoring and control approaches required to support advanced reactor operation.

These requirements include such things as:

- Semi-autonomous operation
- Fault-tolerant control system operation
- Performance-based control algorithms that improve plant economics through increased availability and energy output
- Optimal control for dispatch and unit commitment of nuclear systems with multiple products (e.g., electricity and process heat) and/or for load following and energy storage
- Secure control and safety system designs that are cybersecurity-informed through hardware and software design.

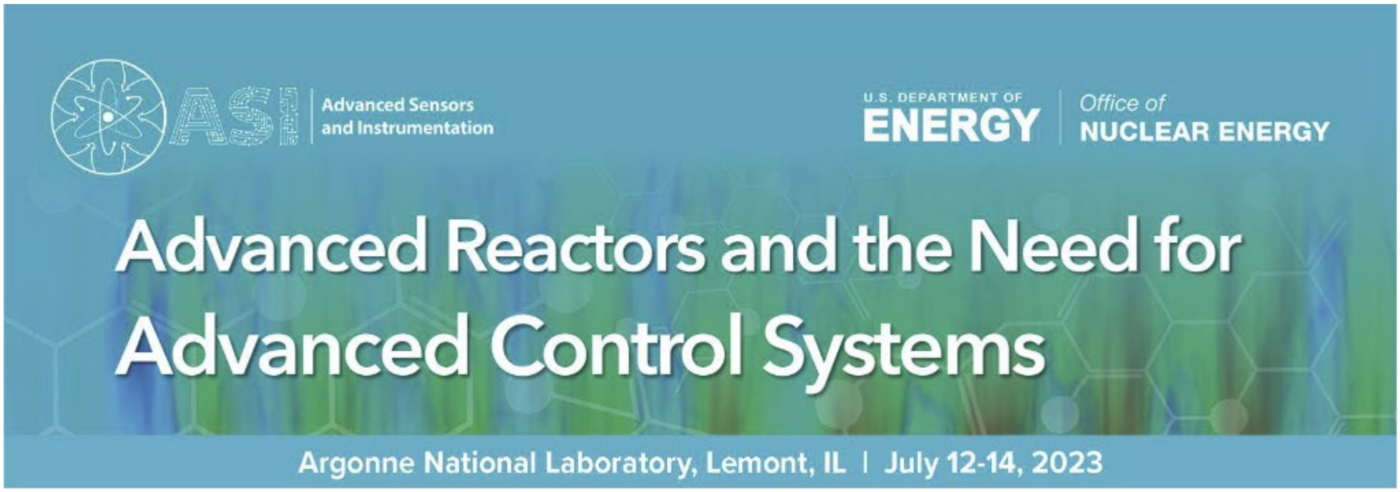
Digital Twins, research is developing and demonstrating methods that enable reliable, explainable control and decision-making that quantify the state of the nuclear system, forecast its future state, and identify options for operational actions based on the current and future states of the system.

These requirements include such things as:

- Model-based control algorithms realize greater control capability than the use of single-input, single-output feedback loops in current plants.
- Integrate risk-informed methods and uncertainty analyses to better manage responses during upset events to minimize protection system challenges.
- Develop advanced control systems and artificial intelligence that enable near-autonomous operation for microreactors.
- Artificial intelligence/machine-learning (AI/ML) control algorithms that enable operations and maintenance (O&M) cost-reduction.

This newsletter is aimed at providing an overview of the ASI research activities tied to Advanced Control systems and sharing information presented during a recent Advanced Control System workshop sponsored by DOE-NE.

DOE-NE Sponsored Advanced Control System Workshop Overview



This summer, Argonne National Laboratory hosted the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) Advanced Sensors and Instrumentation (ASI) Advanced Control Systems workshop. This workshop was sponsored by DOE-NE to gather input from stakeholders about the Advanced Control System capabilities needed to support the deployment of advanced reactors. The event provided the industry with a forum to exchange information about ongoing research for the next generation of nuclear plants. Results from this workshop will be used to identify DOE-NE ASI Program research priorities to address the identified gaps.

This three-day workshop, which was attended by over forty researchers, vendors, and industry stakeholders was broken into three topic areas:

- Advanced Controls for Advanced Reactors: Industry Needs and Requirements
- Current State of Development and Deployment of Advanced Control Methods
- Challenges and Opportunities for Advanced Control

Each session included research updates, industry panels, and break-out sessions providing time for all attendees to discuss the ideas and provide feedback on the topics presented.

Ahmad Al Rashdan
Idaho National Laboratory

The first topic area led by Ahmad Al Rashdan, covered research updates provided by Anton Moisseytsev (ANL), Taeseung Lee (ANL), Jake Farber (INL), and an overview of Digital Twin Research from NRC by Raj Iyengar.

This session then hosted industry speakers to discuss their perspectives on the needs and requirements for advanced controls. The panelists included Daniel Althouse (TerraPower), Matt Hertel (X-Energy), and Rob Meyer (NuScale).

The topic for this break-out discussion was, “What could advanced control systems be used for in advanced nuclear reactors? What are the resulting requirements for the control system?”

Dianne Ezell
Oak Ridge National Laboratory

The second topic area led by Dianne Ezell, covered research updates provided by Haoyu Wang (ANL), Tim Nguyen (ANL), Wes Williams (ORNL), Linyu Lin (INL),

and an overview by the University of Michigan on Model Predictive Controls for Microreactors.

The session led by Dianne Ezell then hosted industry speakers providing their perspectives on the need and challenges for control methods. The panelists included Roger Chin (Radiant), Bruce Greer (EPRI), Alan Smith (Oklo)

The Break Out Discussion was, “What are technology and non-technology barriers to deploying advanced controls for the envisioned advanced reactor applications?”

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Rick Vilim
Argonne National Laboratory

The third topic area led by Rick Vilim, covered research updates provided by Haoyu Wang (ANL), Akshay Dave (ANL), Dianne Ezell (ORNL), Roberto Ponciroli (ANL),

and overviews by Lefteri Tsoukalas (Purdue University) and Dan Cole (University of Pittsburgh).

The session was moderated by Rick Vilim then hosted industry speakers to provide their perspectives on the needs and challenges for advanced controls. The panelists included Corey Shore (GE), Thomas Tweedle (Westinghouse), and Zach Hachmeister (Fauske and Associates).

The Break Out Discussion was, “What are high-priority R&D activities that would aid greater efficiency and reduced O&M cost?”

Argonne National Laboratory Tours

On the final day an opportunity to tour four of Argonne laboratory facilities related to advanced controls was offered to attendees. The first tour was to the Mechanisms Engineering Test (METL) Facility.

Figure 1. METL Facility (mechanism engineering test loop).

The METL facility, established in 2018, is an intermediate-scale liquid metal experimental facility that provides purified R-grade sodium to various experimental test vessels to test components that are required to operate in a prototypical advanced reactor environment. (https://www.anl.gov/nse/mechanisms-engineering-test-loop-facility)

A tour of the Digital-Twin Health Monitoring Facility which provides a remote monitoring and diagnostic (M&D) video wall alloying demonstration of diagnosis of health of sensors and components in the METL Facility.

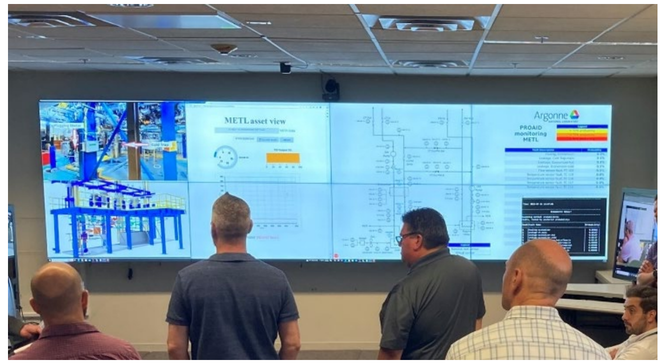

Figure 2. Digital Twin Health Monitoring Facility.

Argonne National Laboratory has developed the software package Parameter-Free Reasoning Operator for Automated Identification and Diagnosis (PRO-AID) that performs real-time monitoring and diagnostics for an engineering system using a form of automated reasoning. The code has been used to analyze the adequacy of sensor set coverage for resolving faults in a system. (https://www.anl.gov/nse/ai-ml/maintenance)

Next, a tour of the Aurora Exascale Supercomputer was provided. This facility is used to pursue science and engineering breakthroughs by combining machine learning and data science with traditional modeling and simulation.

Figure 3. Aurora Exascale Supercomputer.

The Argonne Leadership Computing Facility (ALCF), a U.S. Department of Energy (DOE) Office of Science User Facility located at Argonne National Laboratory, enables breakthroughs in science and engineering by providing supercomputing resources and expertise to the research community.
(https://www.alcf.anl.gov/aurora)

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Finally, workshop attendees were provided with a tour of the Advanced Photon Source, which is a synchrotron light source that produces high-energy, high-brightness x-ray beams. The source is optimized to put large quantities of high-energy photons into a very small area in a very short time.

Figure 4. Advanced Photon Source.

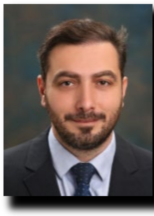
These x-rays allow scientists to pursue new knowledge about the structure and function of materials in the center of the Earth, in outer space, and all points in between. (https://www.aps.anl.gov)

Workshop Results

Results of the workshop breakout sessions were captured in notes and are presented in the following section of the newsletter. Complimenting the newsletter information, a report developed by Argonne National Laboratory is expected to be published in FY 2024.

Workshop Take-Away: The Needs and Challenges of Using Advanced Controls to Make Autonomous Nuclear Reactors a Reality

Ahmad Al Rashdan
Idaho National Laboratory



Rick Vilim
Argonne National Laboratory

Dianne Ezell
Oak Ridge National Laboratory

Introduction

Autonomous operation of advanced nuclear reactors is a key economical requirement for several types and designs of advanced nuclear reactors. Therefore, it has been receiving increasing attention as part of several U.S. Department of Energy (DOE) programs across the DOE laboratory complex. Several university and laboratory-led research and development (R&D) efforts have been investigating the potential use of classical and modern control methods and tools to demonstrate that they can be customized or enhanced to incorporate new forms of intelligence, ultimately making the case that it is possible to build semi- or fully-autonomous processes. Industry, however, has been focusing more on core reactor design problems. Control is rarely mentioned in discussions of advanced nuclear reactor design as it is assumed that when needed, the solution would be available. This is, in essence, a hypothesis that has not been validated since none of the highly autonomous nuclear reactors have been advanced to a stage where autonomous operation has been incorporated. The DOE Nuclear Energy Enabling Technology (NEET) Advanced Sensors and Instrumentation (ASI) program launched a new effort in 2022 to evaluate this hypothesis. The aim of this effort was to evaluate the current state of research, better understand the industry need, and align the program research with current gaps, reducing the risk of control becoming an unexpected hurdle to deployment of advanced reactors.

The result of the research conducted in 2022 was published in Reference [1] and made several conclusions. First, there are some unique aspects of advanced reactors that result in control requirements that must be met to enable autonomous operations. Those requirements constrain the design of a control framework. For example, using artificial intelligence/machine learning (AI/ML) to directly control a reactor might not be feasible from a regulatory viewpoint. Second, while control as a science might be mature, integrating the various forms of control and integrating control methods with other enabling technologies (like digital twins or risk modeling) is still an area of active research. This is probably the cause of the third conclusion, which is that a fully intelligent and autonomous control system for advanced nuclear reactors does not yet exist in laboratory or industrial environments. A robust nuclear system or replica that can understand and react to any form of disturbance is often discussed but has not materialized. In the view of the report authors, this system would incorporate a control loop that integrates several various enabling technologies, like the ones shown in Figure 1. The last conclusion from the effort was that the vast majority of work identified in the field of control for advanced nuclear reactors was conducted by research organizations. Very limited public information is available on what the industry is developing in this field. Therefore, there is a need to closely engage the industry and learn about industry-driven control efforts. This conclusion encouraged the DOE NEET ASI Program to organize a dedicated workshop titled "Advanced Reactors and the Need for Advanced Control Systems," in July 2023, at Argonne National Laboratory.

Workshop Scope

In July 2023, the DOE NEET ASI hosted its first control-focused workshop. The aim for the event was to convene subject matter experts and stakeholders in control methods and technologies for a comprehensive discussion on challenges and R&D needs to focus the program research. The event was organized by a committee from Argonne National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory and was hosted by Argonne National Laboratory.

The main topics addressed at the workshop were:

- Industry needs and requirements for advanced controls for advanced nuclear reactors
- Current state of development and deployment of advanced control methods
- Challenges and opportunities for advanced control

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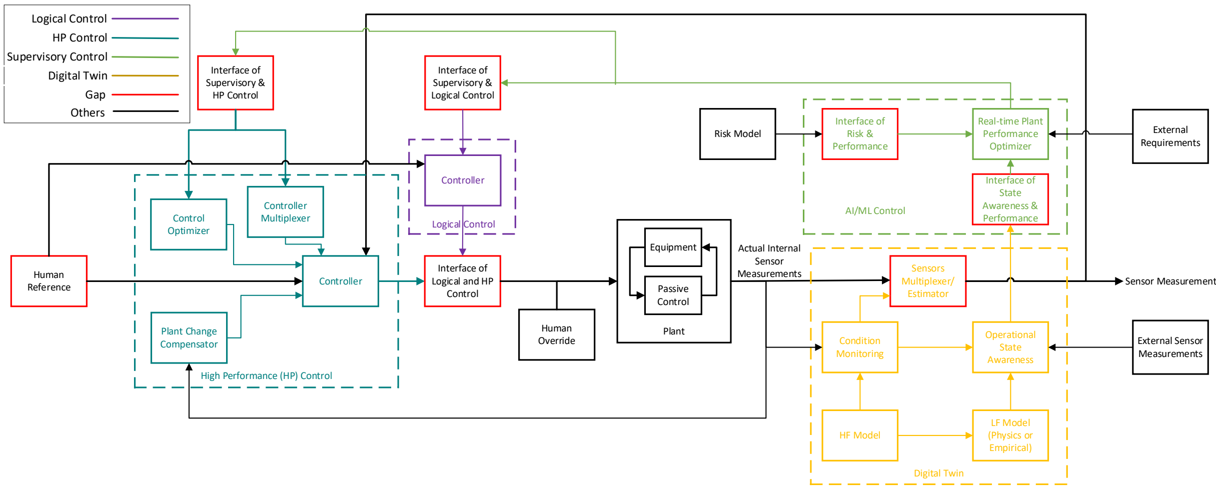

Figure 1. An approach to integrate advanced control methods and digital twins for advanced nuclear reactors. The figure demonstrates the complexity of interfacing multiple elements that are needed to achieve a fully intelligent control system.

Several researchers from the three national laboratories, the U.S. Nuclear Regulatory Commission, and universities presented their control-related work for each of the three topics. Additionally, participants from the Electric Power Research Institute (EPRI), NuScale Power, Oklo, TerraPower, X-energy, Radiant Nuclear, Westinghouse Electric Company, and Fauske and Associates took part in panels to discuss their perspective on the workshop topics—specifically, envisioned needs, use, and anticipated challenges of advanced controls. Following every topic session of presentations and panels, the participants were distributed into three groups to further discuss the topics through a set of guiding questions. The feedback was collected, summarized, and presented to all participants. A summary of the general workshop findings, as perceived by the organizing committee, is discussed herein.

The Need for Advanced Control

A key factor that was discussed when attempting to evaluate the need for advanced control in the advanced nuclear reactor industry relates to the definition of autonomous control. While the research participants identified autonomous control as the tools needed to achieve high levels of autonomy with minimal or no-human role of the controlled process, most of the industry participants defined it as a human-assisted and partially automated functions. There seemed to be a disagreement of what the human role would be in autonomous systems, which is potentially due to the different types of reactors being developed, the planned applications, the level of passive safety incorporated in the design, and regulations impact if they are to perform safety functions. Some industry participants anticipate the need for control to be limited to local control loops with a specific control function. They did not have yet a clear use case yet to what autonomous control could be used for. Others identified use cases that relate to complex or critical operational functions that could demand rapid response that might not be possible by a human, especially due to the consequence of a response delay. Some participants believed that scalable and adaptable active control methods can be standardized and used across the reactor types. Those methods would mainly differ in how they are deployed for each use case and at each reactor type. Despite the limited number of identified use cases, it seemed the vast majority of participants agreed that if needed, the control technology existed, especially when considering other industries that achieve autonomous operations (e.g., automotive or space industries).

However, the participants agreed that autonomous control in nuclear reactors has not been demonstrated and there could be challenges that they are not aware of yet. Through the detailed discussion during the breakout sessions, a list of challenges grew as discussed next.

Challenges and Current State:

Despite the nine sessions involving different teams and topics of discussion, the details of those discussions can be grouped in few themes. In each of those themes, a broader challenge was formulated and discussion of the current state in research or technology occurred. The gaps were often characterized and potential solutions, available or futuristic, were suggested. This section summarizes those findings in main themes of discussion:

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The changing environment: Though the control technologies exist, they are designed to run up to a certain operational margin (e.g., maintenance issues and sudden transients). They struggle to handle rapid changes of environment and failures. None of the non-nuclear industries that have adopted forms of autonomous operations experience the challenges an advanced nuclear reactor is expected to endure. This is mainly due to the harsh environment experienced by the sensors and equipment, and the aging characteristics of the reactor components, especially over the expected long cycles of operations without any form of human, at-site intervention. This is especially challenging if sensors and their communication modules are placed close to the reactor. There might not be a mechanism to remove or replace a failed sensor. A more challenging solution would be to deploy robots to replace it. Therefore, either the design incorporates systemic defense-in-depth including diversity or means to virtualize the sensors need to be developed. Unrecoverable failures are expected, and decisions have to be made on when and how to continue to operate or shutdown. The risk of either decision has to be considered. The controllers have to be state-informed of internal and external conditions including the degradation of control hardware and sensors. This is especially challenging in cases of anomalies avalanche, impacting multiple parts of the process at once. Coupling digital twins with controllers can enable better awareness, but this is a topic of active research. The participants have not yet demonstrated that controllers can adapt to such changing environments.

Complexity: unlike the current fleet, autonomous operations require the control loops to communicate among each other and with other plant systems. The forms of this interface are unclear and means to determine the minimum set of sensors needed to holistically meet the control objectives are needed. The validation of single controllers is not sufficient for coupled control loops. The validation effort can get exponentially more complicated as more controllers are added and coupled. Leveraging a modular approach with focus of decoupling systems to develop control functions that can be easily scaled and replicated across multiple units was discussed. It was envisioned that those modules would be supplied by dedicated vendors that pre-qualify them for use in a reliable manner.

Using a tactical approach (instead of strategic one) was also discussed for deployment of autonomous control. For example, simple controllers, like proportional–integral–derivative (PID) controllers, can be deployed for lower-level controls (i.e., simple function and localized control loops) that can be incrementally coupled to achieve more complicated functions. This approach is being investigated by ongoing research efforts.

Modeling: Models can be used in two forms for control: for controller development and optimization, and for use in a digital twin to tune or inform the controller. The main issue with the first approach (i.e., to design controllers) is the validity of the models and how that would impact the controller performance, especially since the physics of the controlled systems might not be fully understood. The operating experience does not exist to explain the various and highly coupled physics.

Discussion of digital twins identified several limitations. Digital twins are also not validated and might not be representative of the actual process they mirror. Therefore, they could introduce a risk to the controlled process if they misunderstand the process and cause a controller to act upon it. They are also slow for control use even in their low fidelity surrogate models form. Therefore, participants emphasized that digital twins are feasible in maintenance but challenging in control. Many participants indicated that digital twins are being used for maintenance; despite their need for control, only one participant indicated that they have been developing a digital twin for control. Methods to couple control with digital twins remain unclear. Using lookup tables from models was also discussed as a tool to overcome this, but a systematic approach to achieve this does not exist. Breaking digital twins into modules that can run faster was discussed as well.

Beyond-design: Because operating experience does not exist for advanced nuclear reactors, the models are usually developed to only handle known or expected scenarios. However, unknown scenarios will always exist and the ability of controllers to adapt to it is questionable. Additionally, failures are rare, and a realistic failure or transient behavior might not be experienced until the reactor is deployed. In the current fleet, the operator would intervene and move or tune the controllers to adapt to those unexpected scenarios. For autonomous operations, the models need be able to adapt after the reactor is deployed. The advanced reactor community has been focusing on using passive safety to guard against those scenarios. Without an active means of mitigation, this could result in numerous avoidable reactor shutdowns.

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The human role: One of the main obstacles for deployment of autonomous controls in advanced nuclear reactors relates to the cultural shift. Historically, the human role has been a critical aspect of the reactor's operational models, while automatic control was used for critical and safety-related functions.

A key question discussed in the workshop was when to increase autonomy, especially that it could increase potential risk of a wrong decision. Using the common metrics used in controllers: their ability to track a set point with minimal latency and in a stable and robust manner, the question would be if a human can perform this function reliably and would the human have the time and dedication to perform the function? There needs to be a systematic approach to which functions get automated and what would be assigned to the human in a supervisory role. For example, how would complexity be defined if it is used as a factor in automating the control function. Awareness of the current and historical behavior of the reactor is another factor.

The human interface with the controllers or any form of intelligence was also discussed. Whether through a digital twin or by directly informing a controller, can this interface be enabled remotely, especially given the communication latency and cybersecurity concerns? When and how would the human override the controller's decision? All those questions need to feed into an approach for the decision on what functions should be automated. There are several studies conducted for the current fleet in this regard that can be expanded to meet the advanced nuclear reactors needs.

The regulatory aspect: Because the current regulations mandate qualified solutions for safety functions, the participants agreed that for autonomous operations to be feasible, the focus would be on non-safety functions, since those are not constrained by regulations, unless they have an impact on a safety-related function. Safety functions would continue to be passively assured and supported by protection systems that usually use automated (i.e., not autonomous) forms of control. If intelligent controllers are to impact safety functions, the regulations would need to be updated to include new technologies such as the use of artificial intelligence. Many of the concepts discussed earlier are too complicated to qualify for safety systems use. They still might be needed, however, because of the changing environment challenge that could potentially impact the safety system reliability and response. The topic of using digital twins and artificial intelligence in reactors is being actively investigated by the Nuclear Regulatory Commission.

Data Infrastructure: one of the breakout session guiding points of discussion related to the infrastructure needed to deploy effective and advanced methods of control. Most of the data-structures used in the current fleet of nuclear power plants focus on operational or business needs and are measured by relevant metrics: storage capacity, archiving, and bandwidth. They follow a centralized approach to data management. Instead, control methods are most susceptible to latency, time stamping, signal synchronization, and signal reliability. For example, time delay with controls can lead to reduction in controllers' response, impacting the controlled process stability. This is especially a challenge for multi-input and multi-output controllers in which a single signal delay can compromise multiple controlled processes. A data management approach is needed with focus on control needs including communication means, protocols, and cybersecurity. The role of edge computing needs to be defined. This topic of research has been receiving interest in non-nuclear industries. For example, efficient and secure communication protocols and industrial data buses are currently used in the automotive industry.

Testing and demonstration: One of the main highlighted points made by several participants related to the lack of a platform to freely manipulate, disturb, and validate methods to develop control methods and digital twins, and a standard set of benchmark datasets and scenarios that can be used for validation. A representative hardware and software platform to perform all those functions does not exist. Using software simulators does not mirror the actual hardware and is arguably not a digital twin (as the physical twin does not exist). There is a need to validate against actual hardware and high-fidelity digital twins for control methods to be valid.

Conclusions

The need for advanced control is dependent on the type of reactor used and the level of autonomy needed. For advanced reactors that need semi-or fully-autonomous operations, the control methodology exists, but controllers have not been integrated and demonstrated for complex systems or interfaced with the needed forms of intelligence to allow the controllers to understand and adapt to environment changes. This has not been the focus of research because the industry is reliant on passive safety features and conventional safety protection systems. This approach would result in a conservative shutdown approach in which a single sensor failure could cause the reactor to shut down permanently.

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A significant human role seems to be still anticipated. This contradicts the economical mission of some forms of advanced reactors which assume a high level of autonomy. It seemed that a systematic and functional approach to define an efficient human role and means of interface with process control does not exist.

The development of valid and accurate digital twin models that are needed for intelligent control systems remain a challenge. The model uncertainty impact, during design and beyond-design scenarios, on control is not well-understood. Also, the means of signal synchronization and interfacing of those models in real-time with control has not been validated or demonstrated in real-time control applications. A control-focused data infrastructure for nuclear does not exist and could impact the performance of control especially for rapid control functions. A platform to freely perform and test the advanced control functions discussed in this article does not exist.

Several other needs were mentioned during the workshop (e.g. obsolescence management) but generated limited or very localized discussion and are not reflected in this article. A detailed report of the workshop finding is planned in Q4 of 2023.

Reference

1. Al Rashdan, A. Y., J. A. Farber, M. E. Montezzo Coelho, C. A. Primer, and V. Yadav. *Integration of Control Methods and Digital Twins for Advanced Nuclear Reactors*. INL/RPT-22-69937-Rev000. Idaho National Laboratory, Idaho Falls, ID, USA (2022).

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Workshop Session I Details - Advanced Controls for Advanced Nuclear Reactors: Industry Needs and Requirements

Ahmad Al Rashdan
Idaho National Laboratory

In the first session of the DOE-NE sponsored workshop Ahmad Al Rashdan moderated several presentations providing updates on Advanced Controls research.

Session 1 presentations included:

- Control for Micro Reactors by Anton Moisseytsev (ANL)
- Supervisory Control for Flexible Advanced Reactor Operation by Taeseung Lee (ANL)
- Digital Twins for Health Monitoring to Support Advanced Control by Raj Iyengar (NRC)
- Integration of Control Methods and Digital Twins for Advanced Nuclear Reactors by Jake Farber (INL)

Anton Moisseytsev
Argonne National Laboratory

Dr. Anton Moisseytsev is a Principal Computational Nuclear Engineer at Nuclear Engineering Division of Argonne National Laboratory.

In the presentation by Anton Moisseytsev, Control for Micro Reactors, the flexible operation of the Holos-Quad micro-reactor was demonstrated using the Plant Dynamics Code. The focus was on investigating control mechanisms for the Brayton Cycle and exploring various options for load following. This included scenarios where the grid demand changed rapidly between 100% and 0% at a rate of 10% per minute. It was found that the best option for load following involved inventory control, albeit with limitations tied to tank volume or reactor power.

A control strategy was developed, which incorporated a combination of control mechanisms, and participants were presented with options for both active and passive inventory control. The reactor and other critical components were characterized, providing valuable insights into optimizing micro-reactor operations like the Holos-Quad. A separate newsletter article has been submitted and provides more detail below. This presentation can be found on the ASI website following this Link → (Moisseevtsev)

Taeseung Lee
Argonne National Laboratory

Dr. Taeseung Lee is a Principal Nuclear Engineer at Argonne National Laboratory. Taeseung Lee provided a presentation on advanced reactors (ARs) emphasizing their role

in meeting the evolving needs of future power grids. ARs are positioned to address various demands, such as serving as a base load provider, accommodating load fluctuations, adapting to different operating modes, and responding to unexpected events.

To achieve the flexible operation required to meet these diverse demands, certain key features are essential:

Supervisory Control: The plant control system for ARs should incorporate a Supervisory Control feature. This enables dynamic adjustments in reactor operation to align with changing energy grid requirements, particularly during load fluctuations.

Dedicated Control Logic for Mode Changes: To transition between different operational modes seamlessly, ARs need dedicated control logic. This ensures that they can efficiently and safely switch between power generation, refueling, shutdown, and other modes as needed.

Prepared Procedures for Upset Events: Unforeseen events can occur, such as sudden grid disconnections. ARs should have well-prepared procedures in place to respond to these upset events swiftly and effectively, maintaining grid stability and safety.

This presentation highlighted that for ARs to successfully fulfill their role in future energy markets, the integration of supervisory control, dedicated logic for mode changes, and robust procedures for handling unexpected events is imperative. These elements ensure the adaptability and reliability of ARs as they navigate the diverse demands of the evolving power grid landscape. This presentation can be found on the ASI website following this Link → (Lee).

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Raj Iyengar
Nuclear Regulatory Commission

Dr. Iyengar leads the Reactor Engineering Branch in the Division of Engineering (DE) in the Office of Nuclear Regulatory Research.

In the update provided by Dr. Iyengar on "Digital Twins for Health Monitoring to Support Advanced Control: Enabling Technologies, Key Challenges, Regulatory Considerations, and Industry Opportunities," an overview of enabling technology was presented that included:

- Advanced Sensors and Instrumentation (ASI)
- Data and Information Management
- Data Analytics
- AI/ML
- Modeling and Simulation.

Then providing insight on the key challenges needing solutions, if the nuclear industry hopes to unlock the full potential of digital twins. Raj believes it requires a combination of technical innovation, user interface design, transparency in AI/ML, and rigorous testing and validation procedures to make digital twins reliable, informative, and effective decision-making and system optimization tools.

An overview of digital twin's use in regulatory space included activities such as:

- Information Reporting
- Operator Licensing
- Component Performance
- Event Assessment
- Safety Analysis

Finally, Raj highlighted some of the key opportunities that would likely significantly improve nuclear operations. These were:

- Data and Report Generation
- Up-to-date and Validated Simulation Model
- Real-time Condition Based Maintenance
- Virtual Environment Event Replay
- Integrated Modeling for Decision Making

The work that Raj is leading can be found on the NRC website at (nrc.gov/reactors/power/digital-twins.html) and his presentation can be found on the ASI website by following this Link → (Iyengar)

Jake Farber
Idaho National Laboratory

Dr. Jacob Farber is a research scientist in the Instrumentation, Controls, and Data Science Department at Idaho National Laboratory.

In his presentation "Integration of Control Methods and Digital Twins for Advanced Nuclear Reactors" attendees were provided an overview of current research attempting to identify:

- Control system requirements to enable more autonomous operations
- Remaining control system research gaps that need to be resolved

The research activity developed the following table to communicate a proposed set of control system requirements shown below and Farber's presentation can be found on the ASI website following this Link → (Farber).

Unique Aspect	Challenge	Control Requirement
Regulatory Requirements	AI/ML control may not meet regulatory requirements, such as deterministic and explainable behavior	Include an interface control layer between the plant and any AI/ML decision making
Operating Environment	I&C equipment will endure harsh environments for extended periods, increasing probabilities of failures	Identify and compensate for sensor, communication, and electronics failures
High Consequence	Manual investigation to reduce uncertainty and avoid shutdown may not be feasible	Incorporate risk elements to prevent unnecessary loss of power generation
Highly Coupled	Compact and simpler designs will produce strongly coupled systems, making "isolated" control less feasible	Integrate highly coupled control loops and state-awareness methods
Evolving Knowledge	Novel concepts of physics and operation will be used that may not be fully understood or validated	Incorporate robustness into the control loop design
Operating History	There will be limited operating history with which to make operational decisions	Use software models to identify and react to or track unanticipated physical phenomena Define the human role and allowable human interventions

Advanced reactors have unique aspects and challenges that resulted in the proposed set of control system requirement.

Workshop Session I Article - Simulation of Control of Micro Reactors

Anton Moisseytsev
Argonne National Laboratory

Introduction

Micro reactors are those with lower power level, usually below 50 MWe, compared to current designs of about 1,000 MWe. These reactors are being developed for remote locations that may not have a connection to an electrical grid. For these reasons, operation modes of micro reactors are expected to differ significantly from the current base-load operation of large reactors. Therefore, demonstrating the flexible operation of micro reactors, including load following, and investigating control approaches for such reactors is an important step of micro reactor development.

One example of a micro-reactor is the Holos-Quad concept proposed by HolosGen LLC to generate 22 MWth (10MWe) with a lifetime of approximately 8 effective full-power years. The design is based on an innovative high-temperature gas-cooled reactor concept using neutron-coupled Subcritical Power Modules (SPMs) that fit into one commercial 40-foot transport International Organization for Standardization (ISO) container. Each SPM seals its power conversion system, independently executing a Brayton Cycle with a recuperator heat exchanger. The Holos-Quad design was developed in collaboration between HolosGen and Argonne National Laboratory under an ARPA-E MEITNER funding program [1,2].

The purpose of the load following and control analysis described here is to demonstrate the ability of the Holos-Quad reactor for power maneuvering and reactor operation at power levels below 100% nominal. For Holos-Quad design, the load following goals are defined as ability to change electrical power output from 100% to 0% at 10%/min rate.

Analytical Tool

The analysis presented here is carried out with the Plant Dynamics Code (PDC) [3]. PDC was developed at Argonne originally for steady-state and transient analysis of supercritical carbon dioxide (sCO2) Brayton cycles. For this project, the code was modified to allow simulation of gas-cooled reactors with direct helium Brayton cycles. The PDC includes two major parts: steady-state and transient. The load following analysis presented here is done with the transient part of the PDC which solves differential equations for fluid conditions along the cycle (inlet and outlet of each pipe) for temperature, density, and flow rate, as well as at several nodes along the heat exchangers length. The transient equations also include characterization of the turbomachinery (turbine and compressors) behavior at off-design conditions.

Prior to that analysis, the PDC was used to develop, analyze, and optimize the steady-state performance of Holos-Quad helium Brayton Cycle at the design (full power) conditions [2]

For the control simulation presented in this work, the PDC includes modeling of control valves with changing valve open area. For each control valve, there is a choice of either manual or automatic control. For manual control, a user specifies a valve position versus time. The automatic control uses proportional, integral, and differential (PID) controllers with several options for a controlled parameter (e.g., fluid temperature, net generator power, etc.).

Load-Following Analysis

For the innovative concepts like Holos-Quad, there is no established solution for a load-following and plant control approach. Therefore, for this work, a methodology was taken to investigate all feasible control mechanisms that could be used to achieve load-following goals. The selection of the recommended control mechanisms—or a combination of them—will be executed in the control strategy development section discussed below. The control mechanisms identified for this work are shown in Figure 1 and include throttling valves at turbine and compressor inlets, turbine bypass loop, inventory control circuit, compressor shaft speed control, and external controls for reactor power and water flow rate in coolers.

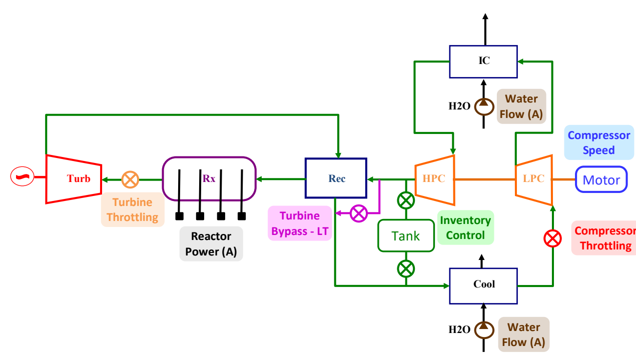

Figure 1. Holos-quad control mechanism options.

A unique Holos-Quad reactor arrangement, where the compressors and turbine are located on the opposite sides of the reactor core and do not share a common shaft, provides an opportunity of independent variation of compressor shaft speed, even when the turbine speed is fixed.

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The compressor shaft speed control could then be used to reduce helium flow rate in the cycle and lower the plant output. Unlike any other control, the compressor speed control does not require any additional equipment, as the (variable speed) compressor motor is already provided in Holos-Quad via electronic power modules to drive the compressors and for speed change from zero to full speed during plant startup.

In all the simulations presented here the reactor power is set by an automatic control to maintain the nominal 850 °C for the reactor-outlet coolant temperature. Effectively, the reactor follows the heat removal demand from the cycle by maintaining the reactor-outlet temperature constant. In the transients, the code calculates the required reactor power (from the PID control action) by instructing the reactivity control system to provide the desired heat generation in the fuel channels. Propagation of power (heat) from fuel to coolant is calculated by the code with appropriate thermal conductivities and thermal inertias (masses and heat capacities) of fuel, moderator matrix, and tubes materials (structures), and coolant. That delayed reactor response is important in some transients presented here and might be one of the limiting factors on how fast the plant output level can be changed during load following. The PID coefficients for the reactor power control were optimized for a step change in the target temperature.

Similar to the reactor power control on the high-temperature side of the cycle, the water flow rate control in cooler (Cool) and intercooler (IC) heat exchangers is used to maintain the temperatures at the low-temperature side, in particular at the compressors inlet. The controllable parameter in this case is the water pump head, which is used by the code to calculate the water flow rate in the cooler and intercooler. The controls are set to maintain the design value of 40 °C at the inlet of the LPC and HPC compressors (Figure 1).

As a first step of the analysis, load following by each individual control in Figure 1 is simulated, calculated, and analyzed. One control at a time is introduced into the PDC transient simulation with a goal of matching the grid demand. The action could be automatic or manual, depending on how each control is setup in the code.

The transient calculations showed that all the controls were able to meet the load following goals, with few limitations on the low end of the grid demand. For example, inventory control was able to reduce plant output only to 20%, before the reactor power is reduced to the decay heat level.

Figure 2 shows the comparison of control mechanisms in terms of cycle efficiency and recuperator temperatures at partial loads (other results were obtained and analyzed in this simulation but are not included here). Since cycle efficiency demonstrates how efficient the power plant operates at partial loads, this is one of the most important metrics for control comparison during load following. The results in Figure 2 clearly show the benefits of inventory control, compared to other options. With inventory control, the cycle efficiency remains above 40% all the way down to 30% load. The turbine bypass, as well as turbine and compressor throttling, are the least efficient control mechanisms, with the compressor speed showing performance somewhere in between the inventory and other control mechanisms.

Figure 2 also shows the results for temperatures at the recuperator hot side inlet. For this metric (which is also similar to the reactor inlet temperature), the inventory control shows the smallest variation, thus demonstrating another benefit of this control mechanism. All other control actions result in an increase of the recuperator temperature above the steady-state design value. The most significant increase is calculated for the compressor speed control.

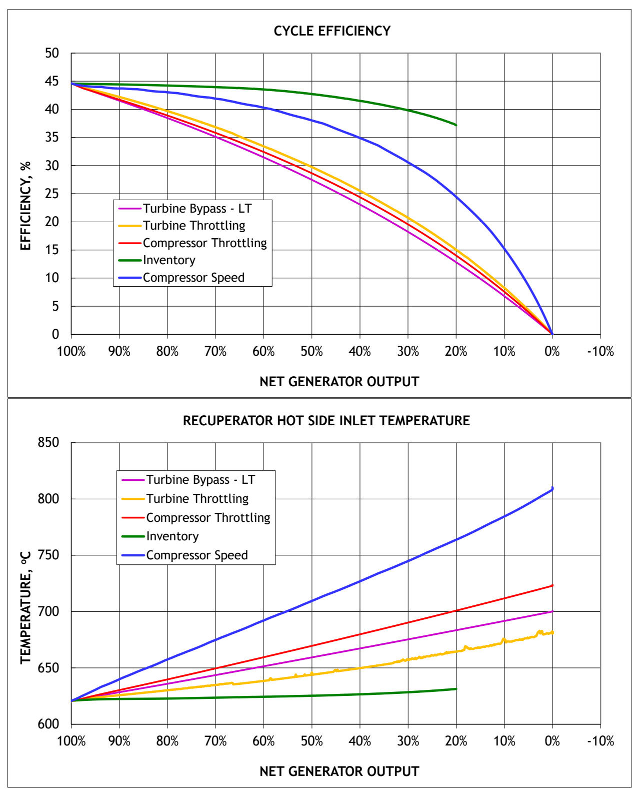

Figure 2. Comparison of control mechanisms for load following.

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The results in Figure 2 show that the inventory is a preferable control mechanism. However, it could not be used to provide load following over the entire power range. Therefore, if this control is to be used, it needs to be supplemented by other controls. Thus a control strategy, meaning a combination of control mechanisms that: a) is capable of providing control over the entire 0%-100% power range, and b) would do it while maximizing the plant efficiency at partial loads is needed.

The calculations also showed that the range of the preferred inventory control depends on the inventory control system arrangement. An active setup, with changing pumps, would eliminate the restrictions of inventory tank volume and therefore would allow using the inventory control from 100% down to 20% loads, where the limitation on the reactor power is encountered. The results in Figure 2 identified both compressor speed and compressor throttling as viable options for low loads. After comparison of performance of these controls at low loads, the compressor throttling control was selected for loads below 20%.

With a passive inventory control system, such as one shown in Figure 1, the inventory control is limited to the range of 100%-70% loads to a reasonably sized tank (1 m^3 per SPM). Below 70% and above 30% loads, the compressor speed control will be used, limited by the temperature increase in the recuperator. Below 30%, the compressor throttling control is implemented. With any control arrangement, the compressor throttling control will be used in an automatic mode as a secondary control to provide fine-tuning of grid demand matching.

The control strategies described above were demonstrated in the full down-and-up transient simulation. The entire transient simulates 30 minutes and in this time period the reactor will be brought from full power to 0% and then back to full power, with both ramps at 10%/min rate, with 5 minutes holding time after both power decrease and power increase. Figure 3 shows the results of the full range load following simulation with an active inventory control arrangement. (The results with passive inventory control option were also obtained for this transient, but are not presented here). The main result in Figure 3 is that the grid demand (e.g., W_grid in the first plot) is matched very closely by the net generator output (W_2_grid line). This is achieved by the developed control action also shown in Figure 3.

The results show that the primary goal of this analysis to demonstrate the load following capabilities of the Holos-Quad reactor at 10%/min rate has been achieved. The control mechanisms that execute these functions were identified, and a control strategy to achieve these goals has been developed for Holos-Quad. The results of transient calculations with the PDC show that the load following goals are satisfied without encountering any limitations, such as compressor stall or temperature excursions in the core.

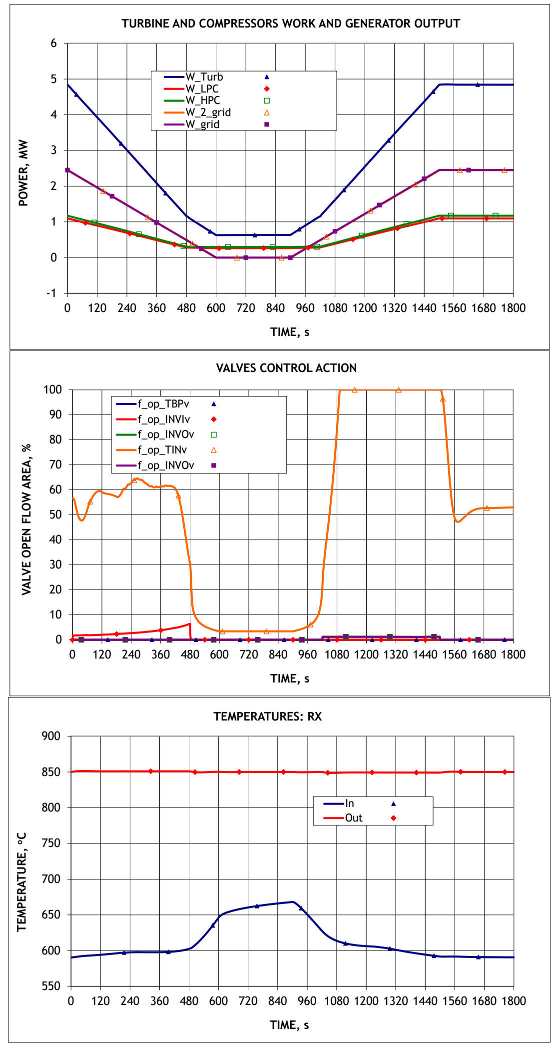

Figure 3. Full range load following results.

Acknowledgement

The work described here has been funded by ARPA-E MEITNER project under a Resource Team arrangement.

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3. Moisseytsev, A., and J. J. Sienicki, "PDC: Plant Dynamics Code for Design and Transient Analysis of Supercritical Brayton Cycles," ANL-ART-154, Argonne National Laboratory, Lemont, IL, USA, September 30 (2018).

Workshop Session 2 Details - Current State of Development and Deployment of Advanced Control Methods

Dianne Ezell
Oak Ridge National Laboratory

In the second workshop session, Dianne Ezell moderated several presentations providing updates on Advanced Controls and the current state of research.

Session 2 presentations included:

- Data-Driven Control in the Existing Fleet by Haoyu Wang (ANL)
- Digital Twins for Health Monitoring to Support Advanced Control by Tim Nguyen (ANL)
- High Fidelity Sensing & Machine Learning Inside the Control Loop by Wes Williams (ORNL)
- Model Predictive Control for Microreactors by Brendan Kochunas (University of Michigan)
- Anticipatory Control for Microreactors by Linyu Lin (INL).

Haoyu Wang

Argonne National Laboratory

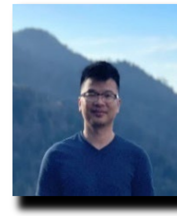
Dr. Haoyu Wang is a Principal Nuclear Engineer in the Nuclear Science & Engineering Division at Argonne National Laboratory.

Dr. Wang presentation, "Data-Driven Control in the Existing Fleet," delivered research results on developing a data-driven digital twin to optimize performance with regards to BWR moisture carryover (MCO). The effort to predict MCO was explained and details on feature and training methodology development were provided. This included:

- Engineering analysis to determine features
- Physics-informed model selection
- Hyper-parameter optimization
- Avoid overfitting.

This research successfully modeled BWR MCO. The methods that were used could be included in a feedback loop possibly providing automatic operation based on MCO prediction.

This presentation can be found on the ASI website following this Link → (Wang).



Tim Nguyen
Argonne National Laboratory

Dr. Tat Nghia (Tim) is a Nuclear Engineer in the Nuclear Science and Engineering Division at Argonne National Laboratory.

Dr. Nguyen's presentation on using "Digital Twins for Health Monitoring to Support Advanced Control" stressed the importance of diagnostics—specifically, the desire to differentiate between component and sensor faults and provide explainable diagnostics to operators. One of the additional benefits of this approach could be

This research provides examples of using physics-based diagnosis information to supplement sensor data. This approach enables detecting and differentiating between component and sensor faults, providing sufficient explanation to diagnose the condition and make the appropriate maintenance decision. This presentation can be found on the ASI website following this Link → (Nguyen).

Wes Williams
Oak Ridge National Laboratory

Dr. Wes Williams is a group leader of the Advanced Reactor Systems Group at Oak Ridge National Laboratory.

Dr. Williams provided insight into the need for integrated hardware in the loop test beds in his presentation, "High-Fidelity Sensing & Machine-Learning Inside the Control Loop." Starting with examples of Hi-Fi sensing currently in use (Tesla Autopilot), Dr. Williams then provided an update on the research underway at Oak Ridge National Laboratory leveraging Hi-Fi sensing.

Key challenges noted during his presentation included:

- A large amount of data is needed, which suggests possibly managing this through compressed sensing and offline machine-learning for fleet-level broadcasting.

This presentation can be found on the ASI website following this Link → (Williams).

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Brendan Kochunas
University of Michigan

Prof. Kochunas is an Assistant Professor in the Department of Nuclear Engineering & Radiological Sciences at the University of Michigan.

Dr. Kochunas supplied an update on Model Predictive Control (MPC) for Microreactors. This included case studies on the economic optimization of flexible power operation and system health-aware control methods.

Part of the research shared was a comparison of different control algorithms providing evidence that MPC supported the best results, but costs were the highest. (see table below).

Several challenges were presented including:

- Integrating a strategic/economic optimization with tactical control
- The need for more realistic control problems introducing more realistic complexity
- Developing consensus on how good prognostic models must be to support their use in nuclear applications.

This presentation can be found on the ASI website following this Link → (Kochunas).

Linyu Lin
Idaho National Laboratory

Dr. Linyu Lin is a research scientist in the Instrumentation, Controls & Data Science Department at Idaho National Laboratory.

Dr. Lin's presentation on "Anticipatory Control for Micro-reactors" provided examples of demonstrating anticipatory control strategy in controlling a HP-cooled micro-reactor. Research conclusions indicated that all models provide similar accuracy, while neural network (NN)-based control systems show better tracking capabilities.

Research also provided evidence that adaptive control strategy provides:

- Improved tracking and constraints handling
- Improved prediction accuracy.

A separate newsletter article has been submitted and provides more detail in the section on the next page. Also, this presentation can be found on the ASI website following this Link → (Lin).

All use a State-Space Model (LQR, H_∞, MPC)

	PID	LQR	H_∞	MPC
Accuracy	Highly depends on tuning	Depends on tuning	Depends on tuning	Depends on tuning
Easy to tune?	Difficult	Easy	Easy	Easy
Able to handle constraints?	Not general	Not general	Not general	Yes
Able to handle MIMO?	Difficult	Yes	Yes	Yes
Calculation cost	Cheap	Expensive	Expensive	The most expensive

U of M – Comparison of Different Control Algorithms for use in Microreactors

Workshop Session 2 Article: Scalable Framework of Hybrid Modeling with Anticipatory Control Strategy for Autonomous Operation of Modular and Microreactors

Vivek Agarwal
Idaho National Laboratory

Linyu Lin
Idaho National Laboratory

Joseph Oncken
Idaho National Laboratory

Introduction

Modular and microreactors, along with other advanced reactor technologies, are important contributors to the future of nuclear energy. Though designs for these reactor types are diverse, they share a common goal: to ensure that future reactor technologies have (1) low operating costs; (2) high reliability; (3) remote, autonomous, or semiautonomous operations; and (4) the flexibility to support expanded integration into electricity grids and markets at various scales (e.g., microgrids, distribution systems, and transmission systems). The advancements in modeling and simulation, sensors and instrumentation, advanced controls, communications, and artificial intelligence (AI) and their seamless integration is important to achieve this goal.

A research presented in this newsletter highlights an autonomous operation technology that uses hybrid modeling (physics-based and AI techniques) and anticipatory control techniques to achieve faster-than-real-time prediction and decision-making capabilities. The objective is to enable emerging advanced reactors, especially microreactors, to regulate their operations and proactively protect against potential anomalies, including load variations, plant component degradations, or other external events. Follows are specific outcomes achieved in this research:

An operational workflow for demonstrating and validating the autonomous load-following operations on a heat-pipe microreactor simulator in both normal and abnormal conditions using anticipatory control strategies is shown in Figure 1.

The adaptive control is achieved by using several data-driven approaches for representing the system dynamics and predicting the distributions and transients of important state variables, including temperatures and heat fluxes of heat pipe microreactors. Classical state space models and artificial neural networks, including feedforward and recurrent networks, are investigated. A comparison study is performed to identify the performance and stability of control systems based on different data-driven approaches.

A software, copyrighted to Battelle Energy Alliance, named Autonomous Controls for Reactor Technologies (ACORN) [4] is developed with graphic user interface for identifying design principles from the perspectives of human factors engineering.

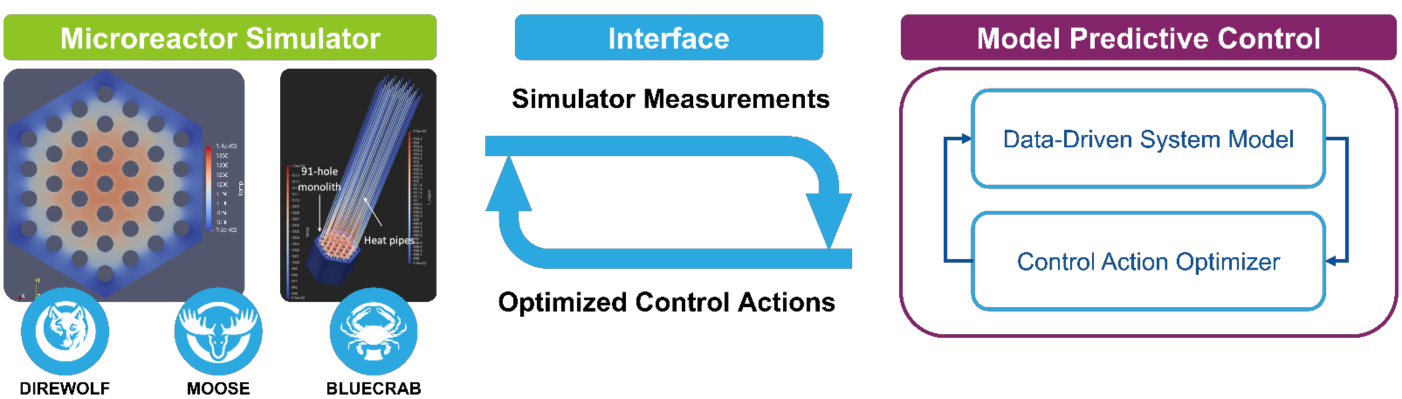

Figure 5. Workflow of demonstrating data-driven MPC to support the self-regulating of heat pipe-cooled microreactors. Major simulation tools, modelling packages and optimization tools are listed.

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Anticipatory Control

Compared to reactive or feedback control systems, anticipatory control strategies optimize reactor operations based on predictions and anticipation of future conditions for nuclear reactors, such as changes in electricity demand, system structure and component status, or safety considerations. Such strategies involve using real-time data, predictive models, and advanced automation to proactively adjust reactor parameters before actual changes in conditions occur. Based on this principle this work investigates model predictive control (MPC) to predict system transients and compute a control action sequence that optimizes the plant's future behaviors. The essence of MPC is to optimize—over the manipulatable inputs—predictions of process behaviors that are subject to equality/inequality constraints. This forecasting is performed by employing a process model (i.e., a predictor) over a finite time interval [1]. This work uses data-driven approaches to identify a surrogate process model. Moreover, due to the lack of experimental data, this work uses a high-fidelity microreactor simulator, whose results will be used to generate surrogate process models and demonstrate the autonomous load-following operations. This work uses Multiphysics Object-Oriented Simulation Environment-based (MOOSE-based) simulation tools, named Direwolf, as the plant simulator for a heat pipe-cooled (HP) microreactor. HP-cooled microreactors use HP elements to cool the core. Their system structure is greatly simplified by omitting the main pipeline, circulating pump, and auxiliary equipment. In a generic HP-cooled microreactor design, the structural materials transfer fission heat to HPs with high thermal conductivity. The heat is then transported from the cold end of the HPs to an energy conversion system. The HPs are tightly coupled, and the reactivity is sensitive to dimensional and material changes caused by the Doppler effect and stainless-steel monolith swelling. Thus, maintaining the temperatures and output heat fluxes at designated setpoints is critical for enabling stable, self-regulating HP microreactor operations, especially during load-following operations. To test the anticipatory control strategy in different reactor designs, this work also investigates the load-following operations on a generic design of gas-cooled microreactor using Bluecrab.

Results and Discussions

To directly respond to the changing demands in electricity grid, load-following operations adjust plant parameters, including reactivity, coolant flow, primary and secondary side frequency regulations, such that the efficiency and plant safety can be ensured at the same time. To demonstrate the capabilities of anticipatory control strategies, this work evaluates controller's performance in achieving and maintaining user-defined trajectories for both temperatures and heat fluxes. For temperature controls, the objective is to evaluate if controller can achieve setpoints for multiple variables. The heat flux control is to mimic load-following scenarios, where controller needs to meet external power demands.

Figure 2 compares the performance of the sparse identification of nonlinear dynamics with control-based (SINDYc-based) and long short-term memory (LSTM) based MPCs in tracking power reference trajectories with different final setpoints and ramping speeds. LSTM is one class of recurrent neural network, which deals with the vanishing gradient problem better than other types of recurrent networks. Overall, the LSTM-based MPC is more fluctuated than the SINDYc-based MPC, especially when the ramping speeds are high. However, such fluctuations better adapt the system to fast transients.

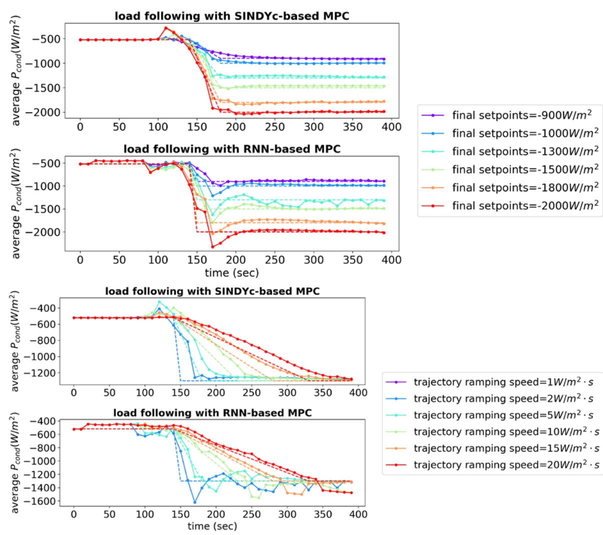

Figure 6. Comparison between the SINDYc-based and LSTM-based MPCs in regard to tracking reference trajectories with (top) different final setpoints and (bottom) ramping speeds.

Figure 3 shows the performance of MPC with three data-driven approaches in achieving two temperature reference trajectories, including feedforward neural network (FNN), recurrent neural network (RNN) with LSTM, and SINDYc. Overall, though SINDYc based MPC produces stabler and more accurate validation results, the inherent variance of artificial neural network models produces higher change speeds in their control actions, and the MPCs based on feedforward and recurrent neural networks are better able to track any drastic setpoint changes [2]. This is consistent with the observations made in the heat flux control scenario.

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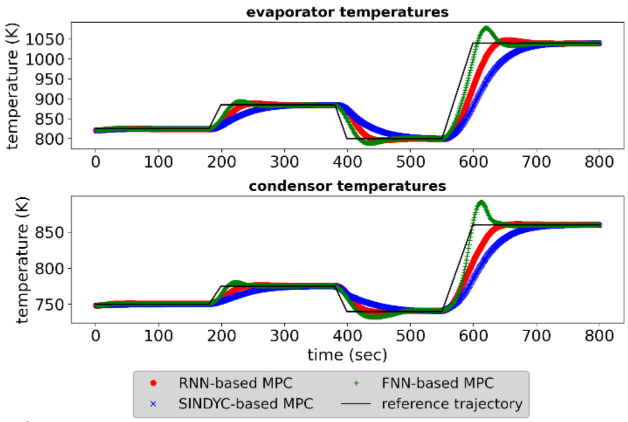

***Figure 7**. Performance of the FNN-, RNN-, and SINDYc-based MPCs in tracking the reference temperature setpoints of the central HP evaporator and condenser.*

This work also investigates the event of a system anomaly, such as a HP failure, and the control system needs to adapt to degraded states and maintain autonomous load-following. A detection module was built into the MPC to detect HP failure and—should a failure be detected—to adapt the predictor model within the controller accordingly. The dual HP failure phase begins at t = 500 with the failure of HP C. Two primary benefits of the adaptive MPC (A-MPC) control are observed during this phase. The first benefit involves accurate reference tracking. When the reference power output level drops at t = 600, the non-adaptive MPC controller is incapable of following the reference power output trajectory despite that trajectory being within the performance envelope of the system even in the failed HP state. However, as was the case with a single HP failure, the A-MPC controller accurately tracks the reference trajectory from t = 600:900. This behavior can be seen in Figure 4. The second benefit is constraint adherence. At t = 1060, the non-adaptive MPC controller allows the evaporator temperature of HP at intermediate positions (labeled as HP B in the figure) to significantly overshoot, ~1330 K, above the upper constraint value of 1200 K as shown in Figure 4. In contrast, the A-MPC controller which does not produce this overshoot behavior and maintains HP B evaporator temperature within the higher limits [3].

Summary

This work presents scalable technology for the autonomous load-following operations of microreactors. This work uses hybrid modeling (physics-based and AI techniques) and MPC methods to achieve faster-than-real-time prediction and decision-making capabilities during normal and abnormal conditions. A software named ACORN [4] is developed with a graphic user interface for human-machine interaction evaluations. The anticipatory control strategy is also applied to a generic gas-cooled microreactor, where the control rod position and core inlet flow rates are controlled for achieving user-defined power setpoints while satisfying constraints in upper and lower bounds fuel temperatures, the maximum changing speeds of control rods and flow rates. Verification, validation, and uncertainty quantification are needed to assure the functionality and safety of the control system. Hardware in the loop test, cyber awareness evaluation, and system stability are also needed.

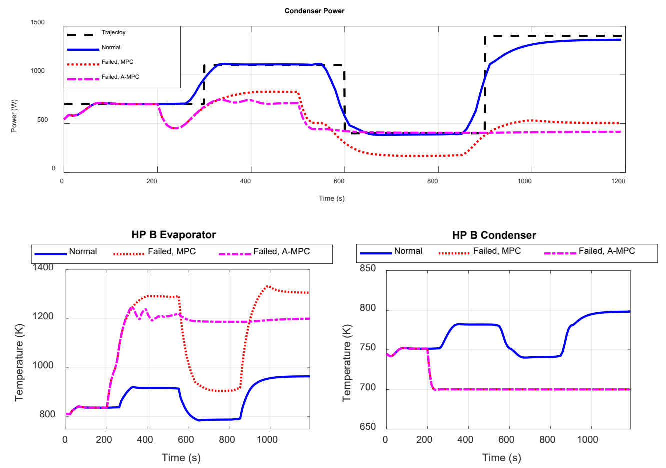

***Figure 8**. (top) Average heat pipe condenser power output and (bottom) temperatures at evaporator and condenser regions with two HP failures.*

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Workshop Session 3 Details - Challenges and Opportunities for Advanced Control

Rick Vilim
Argonne National Laboratory

In the third session of the DOE-NE sponsored workshop Rick Vilim moderated several presentations providing updates on the Challenges and Opportunities for Advanced Controls.

Session 3 presentations included:

- Surrogate Models for Real-Time Multi-Asset Control by Haoyu Wang (ANL)
- Synthesizing Advanced Reactor Control Systems: Achieving Security and Reliability by Daniel Cole (University of Pittsburgh)
- Intelligent, Risk-Informed Asset-Management Decision-Making and Maintenance Optimization by Vera Moiseytseva (ANL)
- AI/ML for a Digital Twin of the Purdue Reactor PUR-1 by Lefteri Tsoukalas (Purdue University)
- Reinforcement Learning for Performance Optimization by Akshay Dave (ANL)
- Unattended Operation of Fission Batteries by Vivek Agarwal (INL)
- Autonomous Controls for Nuclear Thermal Propulsion by Dianne Ezell (ORNL)
- A Path to Semi-Autonomous Operation by Roberto Ponciroli (ANL)

Haoyu Wang
Argonne National Laboratory

Dr. Haoyu Wang is a Principal Nuclear Engineer Nuclear Science & Engineering Division of Argonne National Laboratory.

Dr. Wang delivered his second presentation of the workshop, this time providing an overview of "Surrogate Models for Real-Time Multi-Asset Control." Dr. Wang provided examples of a novel data-driven method to derive surrogate models from high-fidelity digital twins, using advanced control algorithms for real-time multi-asset control.

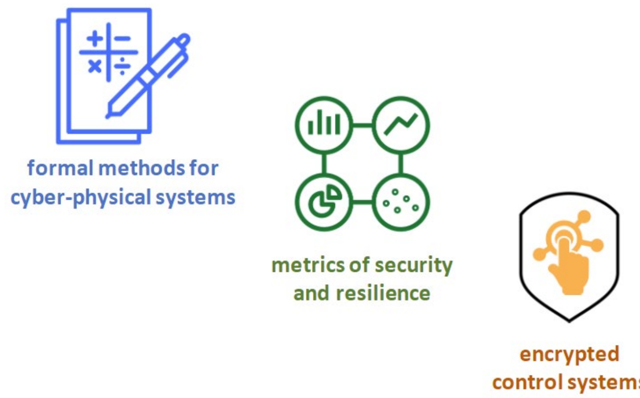
During this research, it was determined that by training the surrogate model on cold-start and steady data on key process variables, the computational burden could be reduced by 6,000 to 7,000 times. There is evidence that such surrogate models can be deployed in advanced control loops, which would aid real-time performance optimization and improved efficiency and flexibility of operation.

This presentation can be found on the ASI website following this Link → (Wang2).

Dan Cole
University of Pittsburgh

Dr. Daniel G. Cole is an Associate Professor in the Department of Mechanical Engineering and Materials Science at the Swanson School of Engineering at the University of Pittsburgh.

Dan presented an overview on Synthesizing Advanced Reactor Control Systems: Achieving Security and Reliability. During this presentation, Dr. Cole provided insights on:



This research provides examples of design methods leveraging better system verification tools, ultimately yielding secure-by-design control systems. By using formal methods, designers can verify safety properties ensuring secure-by-design goals and leverage homomorphic encryption for better command control and communication. All of these will improve security reduce development costs.

This presentation can be found on the ASI website following this Link → (Cole).

Vera Moiseytseva
Argonne National Laboratory

Dr. Vera Moiseytseva is a Nuclear Engineer in the Nuclear Science and Engineering Division at Argonne National Laboratory.

Dr. Moiseytseva provided a presentation on "Intelligent, Risk-Informed Asset-Management Decision-Making and Maintenance Optimization." During this presentation, Dr. Moiseytseva provided an overview of her efforts to develop an asset-management decision-making approach into an integrated analysis structure.

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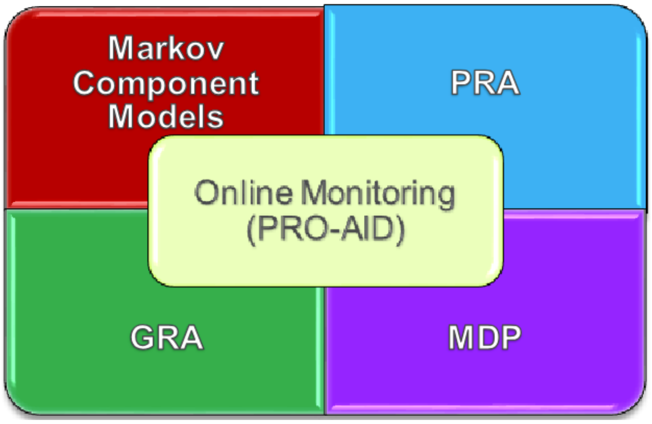
This approach includes:

- Utilizing online monitoring to create real-time generation and probabilistic risk assessments
- Utilizes Markov models at a component level to inform diagnostic software
- Utilizes the Markov Decision Process (MDP) to rank possible action pathways.



Integrated Decision Making Analysis Structure

The results of initial analyses for using the integrated MDP approach are positive and provide a preliminary level of confidence in the solution scheme and overall framework.

This presentation can be found on the ASI website following this Link → (Moiseytseva).

Lefteri Tsoukalas
Purdue University

Dr. Lefteri Tsoukalas is a professor in the School of Nuclear Engineering at Purdue University

Dr. Lefteri provided an overview of the efforts to experimentally validate semi-autonomous control and demonstrate its use in Purdue University Reactor Number One (PUR-1) using a modular digital twin platform with various levels of automation.

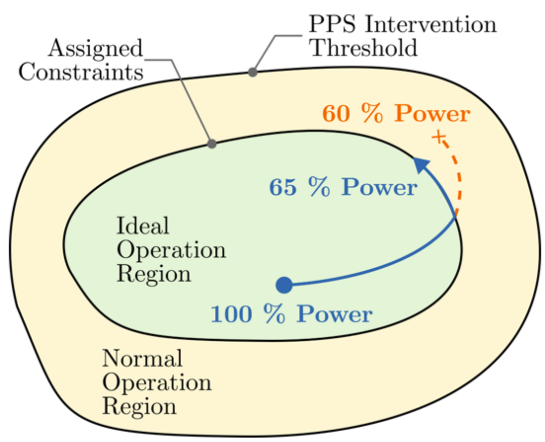
Dr. Tsoukalas provided updates on efforts to train AI/ML using physics-based microreactor models using real-time data collection from PUR-1. This included an overview on the results of the testing.

This presentation can be found on the ASI website following this Link → (Tsoukalas).

Akshay Dave
Argonne National Laboratory

Dr. Akshay Dave is the Group Manager (Innovative Systems) in the Plant Analysis & Control and Sensors Department within the Nuclear Science and Engineering Division at Argonne National Laboratory.

Dr. Dave's presentation on "Reinforcement Learning for Performance Optimization" provided an overview of efforts to design physics-constrained multi-objective agents to provide supervisory control for nuclear plant operation. Key challenges had to do with computational costs.



Control During Autonomous Operation

A separate newsletter article provides more detail in the next section below. Also, this presentation can be found on the ASI website by following this Link →(Dave).

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Vivek Agarwal
Idaho National Laboratory

Dr. Vivek Agarwal is a Distinguished Staff Scientist and Technical Lead for the Fission Battery Initiative at Idaho National Laboratory.

Dr. Vivek provided an overview of efforts to assess if we can leverage artificial intelligence/machine-learning (AI/ML)-informed digital twins to enhance the resiliency of remote monitoring and operations. Ultimately, this would achieve autonomous control of micro-reactors and include developing resilient, secure communications architecture designed using consequence-driven cyber-informed engineering principles.

This work introduced a novel framework for a digital twin-based data certification system, providing an additional layer of security and assurance. This approach attempts to:

- Mitigate unauthorized, unsafe, and unallowable commands received by the microreactor.
- Increases the trustworthiness of the system state information, such as sensor data or component status, sent from the microreactor to the remote operations center.

This presentation can be found on the ASI website following this Link → (Agarwal)

N. Dianne Bull Ezell
Oak Ridge National Laboratory

Dr. Ezell is the group leader of the Nuclear and Extreme Environment Measurement Group, in the Nuclear Energy & Fuel Cycle Division, at Oak Ridge National Laboratory (ORNL).

Dr. Ezell introduced the ORNL support of the NASA's space program, specifically in the area of autonomous controls for nuclear thermal propulsion. The work supports developing a testbed to experimentally test and trial sensors, control elements, and control algorithms for the optimization of a nuclear thermal propulsion (NTP) rocket engine.

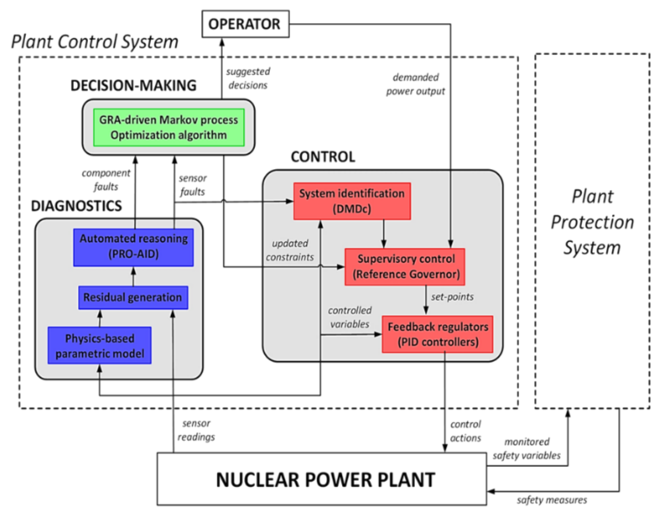
To interface the NTP reactor model with hardware in the loop test bed, ORNL researchers developed a surrogate model: Functional Mock-Up (FMU), which packages the NTP simulation with numerical solvers in a convenient black box, providing calculated responses based on the first principles model.

This presentation can be found on the ASI website following this Link → (Ezell)

Roberto Ponciroli
Argonne National Laboratory

Dr. Roberto Ponciroli is a Principal Nuclear Engineer at Argonne National Laboratory. His research interests include dynamic simulation of nuclear unit operation, power system planning and economics, autonomous operation control system architectures design, and physics-informed diagnostics.

Dr. Roberto provided an overview of the role of autonomous operation in improving nuclear units' profitability. ANL research indicates the most dramatic savings can be accomplished by optimizing nuclear plant's maintenance schedules, and this can best be accomplished through a diagnostic-informed Markov Decision Process (MDP).



Example of AI Algorithms Enabling Autonomous Control.

As shown above, algorithms fulfilling control, diagnostics, and decision-making tasks need to "talk" to each other, and ultimately, the process needs to ensure the plant operators can override the Supervisory Control layer.

Research also identified the need to monitor and control operations within an "Admissible Region" accomplished through leveraging a reference governor that optimizes operation set-points ensuring safe and economic operations.

This presentation can be found on the ASI website following this Link → (Ponciroli).

Workshop Session 3 Article: A Safe Reinforcement Learning Algorithm for Supervisory Control of Power Plants

Akshay Dave
Argonne National Laboratory

Rui Hu
Argonne National Laboratory

Yixuan Sun
Argonne National Laboratory

Rick Vilim
Argonne National Laboratory

Introduction

Nuclear power plants (NPPs) are complex systems, mandating careful design of a control system and control strategy. Within a hierarchical control framework, supervisory actions require concurrent assessment of feedback from the plant. Decision-making on feedback requires domain knowledge, experience, and the capability to forecast. Currently, supervisory decisions at NPPs require human intervention.

Reinforcement learning (RL) is an artificial intelligence (AI) framework to address Markov Decision Processes where an agent seeks a goal, despite uncertainty, and actions require foresight or planning. Because RL is a data-driven approach, it has the potential to learn control policies whose performance surpasses human-engineered policies. The RL agent learns these functions by interacting with an environment (Figure 1). Therefore, we require a suitable environment to design RL algorithms for supervisory NPP control.

The Nuclear Science and Engineering Division at Argonne National Laboratory's (ANL) is the developer of the System Analysis Module (SAM), a physics-based tool to simulate entire advanced NPPs [1]. SAM incorporates state-of-the-art methods in fluid dynamics, heat transport, and neutron transport. SAM is used for best-estimate modeling of molten salt reactor designs and hybrid nuclear energy systems. Thus, SAM would be the ideal RL environment to advance autonomous control of next-generation NPPs.

In this work, there were two primary objectives. First, we developed an RL interface for SAM called "SAM-RL." The interface facilitated data transfer between SAM and RL algorithms. Second, we utilized SAM-RL to design physics-constrained multi-objective agents to provide supervisory control during a Fluoride High-temperature pebble-bed Reactor (FHR) load-follow. The latter objective was addressed by modifying the state-of-the-art on-policy RL algorithm, Proximal Policy Optimization (PPO) [2], to accommodate constraints placed on the plant during operation.

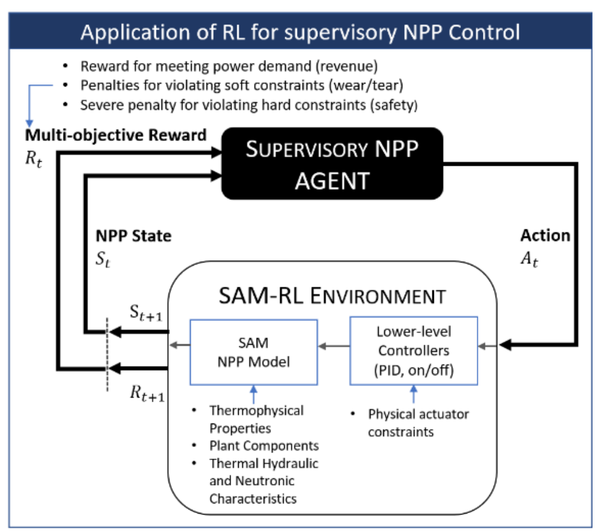


Figure 1. Application of RL for supervisory NPP control using the SAM-RL environment.

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Results

A subset of results from the project are presented in Figure 2. Where a comparison between a classical supervisory control algorithm, the Reference Governor (RG), and the RL algorithm designed in this project, the λ-PPO algorithm, is presented. The RG algorithm [3] is a model-based supervisory control algorithm that relies on the accuracy of a model of the plant to operate correctly. In contrast, the RL algorithm is a model-free, data-driven control policy that learns from interactions with the plant. When the model used by the RG algorithm is a perfect surrogate of the plant, we expect the RG algorithm to represent the best performance available.

In the power transient studied, the reactor load is requested to be reduced in two steps from 100 % rated capacity. Constraints are imposed on the secondary-side intermediate heat exchanger's inlet and outlet temperature ($T_{s,in}$ and $T_{s,out}$, respectively). There is no intervention from either algorithm for the first reduction in power as the constraints are not violated. However, both algorithms intervene in the second request to reduce the power. It is noted that further reducing the power would violate a constraint on $T_{s,in}$. The performance of the RL control policy is on par with the RG control scheme. However, a benefit of the RL approach is that continuous improvements to its performance are achieved through more experience operating. On the other hand, the RG would require a manual update to its model when the dynamics of the system change (e.g., component degradation). Additionally, the RL algorithm produces an end-to-end differentiable control policy that allows global optimization in a larger autonomous operation framework (i.e., impose other global factors to optimize for).

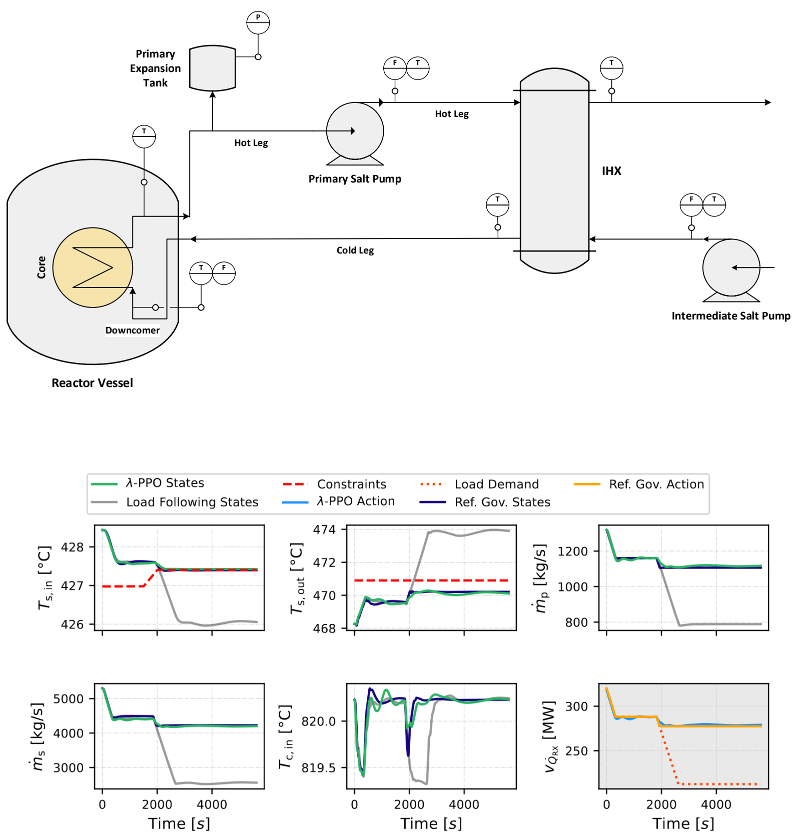

Figure 9. Top: A simplified layout of the studied model: a 320 MWth pebble-bed FHR. Bottom: A comparison of the performance of the λ-PPO RL algorithm and the Ref. Gov. algorithm during a load-follow transient.

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Concluding Remarks

In this work, we proposed the λ-PPO algorithm, which applied the RL framework to the supervisory control of NPPs. This required a reformulation of the PPO algorithm, which is the current state-of-the-art on-policy RL algorithm. We developed a physics-based RL environment on which the algorithm was demonstrated. The environment embedded SAM, ANL's system code for next-generation NPP designs. The λ-PPO algorithm performs on par with conventional model-based control algorithms yet provides two key advantages: (1) a data-driven path for continuous improvement (learning) during the operation of the NPP and, (2) an end-to-end differentiable control policy that can be easily embedded and optimized in a larger autonomous operation framework.

Acknowledgments

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