PUBLIC SUBMISSION

SUNI Review Complete
Template=ADM-013
E-RIDS=ADM-03

ADD: John Lane, Mary Neely
Comment (8)
Publication Date: 4/21/2021
Citation: 86 FR 20744

As of: 5/25/21 1:14 PM
Received: May 21, 2021
Status: Pending_Post
Tracking No. koy-sgk9-n31t
Comments Due: May 21, 2021
Submission Type: Web

Docket: NRC-2021-0048
Role of Artificial Intelligence Tools in Nuclear Plant Operations

Comment On: NRC-2021-0048-0001
Role of Artificial Intelligence Tools in U.S. Commercial Nuclear Power Operations

Document: NRC-2021-0048-DRAFT-0007
Comment on FR Doc # 2021-08177

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General Comment

See attached file(s)

Attachments

001264 Xenergy NRC Response AI ML Applications

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21-May-2021 XE00-R-G1ZZ-GLZZ-G_001264_Rev 1

Docket No. NRC-2021-0048

U.S. Nuclear Regulatory Commission
ATTN: Mehdi Reisi Fard (Chief, Performance and Reliability Branch, Division of Risk Analysis, Office of Nuclear Regulatory Research)
Washington, DC 20555-0001

SUBJ: Response to U.S. NRC Request for Comment, Agency/Docket Number: NRC-2021-0048

"Role of Artificial Intelligence Tools in U.S. Commercial Nuclear Power Operations"

Ladies and Gentlemen,

The purpose of this letter is to voluntarily submit comments on the subject agency notice. X Energy, LLC (X-energy) is actively developing the Xe-100 high-temperature, gas-cooled reactor for deployment in the United States, Canada, and in international markets. The implementation of advanced technologies to improve the operational efficiencies of our design is of critical importance to us, to our prospective customers, and to the advanced reactor community and public we seek to serve.

Thank you to the NRC for this opportunity to discuss X-energy's views on AI/ML applications in the nuclear industry. We look forward to continuing this discussion with you through our on-going regulatory engagements and through future public opportunities. If you have any questions or concerns, please contact Mr. Ian Davis, Senior Digital Twin Systems Engineer, idavis@x-energy.com.

Sincerely,

DocuSigned by:
Eben Mulder
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Dr. Eben Mulder
Chief Nuclear Officer
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Cc:
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Travis Chapman

Enclosure: 1) X Energy, LLC Response to Request for Information

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Enclosure 1: X Energy, LLC Response to Request for Information

Role of Artificial Intelligence Tools in U.S. Commercial Nuclear Power Operations

Summary of Notice: The U.S. Nuclear Regulatory Commission (NRC) is requesting public comment on the current state of commercial nuclear power operations relative to the use of artificial intelligence (AI) and machine learning (ML) tools.

Discussion: The NRC is exploring the potential for advanced computational and predictive capabilities involving AI and ML in the various phases of nuclear power generation operational experience and plant management. The NRC is soliciting comments on the state of practice, benefits, and future trends related to the advanced computational tools and techniques in predictive reliability and predictive safety assessments in the commercial nuclear power industry.

Specific Request for Comment: The NRC requests comments from the public, the nuclear industry and other stakeholders, as well as other interested individuals and organizations. The focus of this request is to gather information that will provide the NRC staff with a better understanding of current usage and future trends in AI and ML in the commercial nuclear power industry.

Requested Information and Comments: AI and ML are emerging, analytical tools, which, if used properly, show promise in their ability to improve reactor safety, yet offer economic savings. The NRC requests comments on issues listed below in this solicitation to enhance the NRC's understanding of the short- and long-term applications of AI and ML in nuclear power industry operations and management, as well as potential pitfalls and challenges associated with their application.

1. What is status of the commercial nuclear power industry development or use of AI/ML tools to improve aspects of nuclear plant design, operations or maintenance or decommissioning? What tools are being used or developed? When are the tools currently under development expected to be put into use?
    a. X Energy, LLC (X-energy) is in the advanced reactor (AR) space, specifically small modular (SMR) high temperature gas reactors (HTGR). As such, these comments will focus on possible use cases for the AR community. The AR community is fully embracing AI/ML technologies for a wide array of applications. Examples include autonomous control systems, performance monitoring, predictive maintenance, additive manufacturing, design optimization, etc. Throughout this document, X-energy will provide examples of applications it is exploring, as well as knowledge of other applications being explored by the AR community in general.
    b. Nuclear Plant Design
        i. Fully Autonomous Control System: The AR community is seriously exploring fully autonomous control systems. In theory a fully autonomous control system would be able to handle all modes of operation from startup to full power to shut down.
        ii. Load following capabilities are integral to the Xe-100 design.
        iii. Optimized sensor placement: (on-going) Rick Vilim at Argonne National Laboratory gave a talk detailing how they are using ML combined with physics-

based models to optimize the placement of sensors in power plant systems. X-energy is interested in pursuing similar research.

iv. Dynamic Probabilistic Risk Analysis (PRA): (theory) With current computing power, it should be theoretically possible to build PRA models that provide results dynamically and can provide feedback regarding possible end states, given current plant conditions and trends. It would potentially also be possible to determine the plant's state on an event tree within the PRA model.

v. Expanded use of Operator Training Simulator: (on-going) The Xe-100 plant simulator is being used to create synthetic data that is used to build ML models.

vi. ML Surrogate models: (theory) Using synthetic data from the Xe-100 simulator it would theoretically be possible to build a surrogate ML model that can mimic the simulator behavior with limited increase in uncertainty.

c. Operations & Maintenance – current maintenance practices use many predictive tools through "rules" and "conditions." While these rules and conditions can be programmed into software, they are a translation of expert knowledge into logical statements. The future of maintenance programs will include truly predictive capabilities, where AI/ML models can tell an engineer the remaining useful life (RUL) of a component with quantified uncertainty bounds. These predictions will most likely come from neural networks trained on operational data.

i. Anomaly Detection – (on-going) using artificial data generated from systems analysis software, train a neural network to identify anomalies during operation and classify the type of "Initiating Event." The Initiating Events come from PRA.

ii. Sensor Drift – (theory/planned) Once the first Xe-100 unit is commissioned, operational data would be collected for a period of time. That data stored in the plant historian could be used to train ML models on sensor drift characteristics of the Xe-100 plant. Once trained, those ML models can be implemented in the Xe-100 Monitoring & Diagnostic (M&D) portion of the Maintenance Program. Finally, the sensor drift models would alert staff when significant drifts are identified that could impact plant operations. Note here that "staff" is the term used, and specifically not operators. X-energy recognizes the caution that must be applied in having AI/ML models directly influence operator actions. It is envisioned that such models would be able to be ported to other Xe-100 plants with minimal re-training. The Xe-100 design in general is meant to be as standardized as possible.

iii. Equipment Degradation – (theory/planned) The development of the equipment degradation models would mirror that of the sensor drift models. Furthermore, the level of criticality for equipment reliability (ER) would be considered, and the degradation models would be implemented in a graded approach. First, the ML models would provide supplemental indications of degradation for the equipment of lowest importance. Human oversight is assumed at this stage. Once trust has been established in the ML models' ability to detect degradation, control over the maintenance of said components could be gradually shifted to the ML models. It should be noted that this "trust" would be quantified. Only when trust is established, can equipment of more importance be considered.

d. Decommissioning – no comment
e. Tools being used or developed
    i. Programming language of choice: Python & Matlab
        1. For the Xe-100 Digital Twin, X-energy has been using Python to build custom AI/ML models. Many data science code packages are used, the most notable being Tensorflow.
    ii. Plant Historian – to collect, store, and visualize plant data. It is envisioned the ML models will be directly coupled to the plant historian. The plant historian will be the main source of data. AI/ML makes the plant historian more than just a database by organizing the data and developing relations between sub-sets of data. These connections and relations are what makes the data useful.
    iii. Operator Training Simulator – ideal testing ground for theoretical AI/ML models
    iv. PRA tools – if AI/ML models are meant to support PRA needs
    v. Control Systems – tools around the industry are being developed to improve control systems, identify the most efficient response to anomalies or method of performing a state transition.
    vi. Cyber Security – there are currently tools that exist to assist in network threat detection and diagnostics. Many router security packages, for example, use AI to automatically detect and defeat denial of service attacks. X-energy plans to build its IT and data infrastructure from a cyber security-centric approach.
f. Expected release and use
    i. For the Xe-100 this would be when the first unit is commissioned under the Advanced Reactor Demonstration Program (ARDP). Tentatively between 2025-2027.

2. What areas of commercial nuclear reactor operation and management will benefit the most, and the least, from the implementation of AI/ML? Possible examples include, but are not limited to, inspection support, incident response, power generation, cybersecurity, predictive maintenance, safety/risk assessment, system and component performance monitoring, operational/maintenance efficiency and shutdown management.
    a. X-energy chose to rate these sub-topics on a scale of 1-5 stars. One star for least beneficial and five stars for most beneficial.
    b. inspection support (****)
        i. Autonomous or drone assisted inspections.
        ii. Safety cases are made stronger anytime staff can be kept off ladder or out of a confined space.
        iii. Safety and cost savings from reduced dose to staff. This can be realized by not needing staff intervention, reducing maintenance activities, or reducing field time through better training with virtual reality (VR).

    iv. Continually building a dataset to compare new data to old data; AI models only get better with more data.
    v. Support for security inspections (e.g. vehicle inspections)

c. incident response (**)
    i. Incidents are rare, so data is rare. Models need data. It is difficult to postulate how one could synthesize useful data in this case.
    ii. Responses to Security issues and Emergency situations.
    iii. A potential use case could be identification of incidents and notifying the correct people to respond.
    iv. Following on the previous point, a specific example would be identification and required response to a fire. In theory an AI/ML model might be able to categorize small, medium, large fires, location, have an understanding of HVAC risks, have an understanding of sensitive equipment in buildings and rooms, etc.
    v. Fire Brigades use a lot of plant staff resources, especially for regular training and extra shift duties. Replacing some of that burden with AI/ML models could be beneficial.

d. power generation (***)
    i. Autonomous control systems could support load following capabilities, which are not typical for large LWR's.
    ii. AI/ML models could help optimize utilities that explore multiple applications: power generation, hydrogen generation, industrial heat, etc.

e. cybersecurity (*****)
    i. Needs no additional context. Cyber threats are widely known.

f. predictive maintenance (*****)
    i. Already discussed above.

g. safety/risk assessment (***)
    i. Safety concepts are built directly into the reactor and plant design.
    ii. Similar to applications mentioned above, AI/ML models that can determine the current plant's state within the context of PRA models would be very beneficial. One step further, AI/ML models that could predict future states, "front-running" the plant behavior, would have even more of an impact. This could give staff a leg up in understanding possible future states given current trends.

h. system and component performance monitoring (*****)
    i. Already discussed above.

i. operational/maintenance efficiency (**)
    i. Automation reduces workload, but you can automate without AI.
    ii. The real benefit would be Maintenance and Outage scheduling using the predictive maintenance tools. This would ideally help prevent failures of equipment, which affects both safety and cost.
    iii. For Operations AI/ML models could be used to automate testing of plant transients. Preventing a single trip leads to a savings of around ~$1million.

j. shutdown management
    i. No comment.
k. Physical Security (****)
    i. Facial recognition innovates on current access control practices.
    ii. Path tracing for individuals on-site.
    iii. Thermal imaging.
    iv. Intelligent security monitoring system could help security staff by providing the information they need to know, when they need to know it, and the procedure for how to deal with the threat. That could be significant in facilitating an effective and timely response to an incident/threat and in defeating against the threat.

3. What are the potential benefits to commercial nuclear power operations of incorporating AI/ML in terms of (a) design or operational automation, (b) preventive maintenance trending, and (c) improved reactor operations staff productivity?
    a. In general the potential benefits come from novel solutions that improve safety and security, reduce cost, reduce time burdens, and improve efficiency with resource usage.
    b. design or operational automation
        i. Using AI to optimize designs (e.g. core geometry, sensor placement).
        ii. ML can identify patterns unnoticed by humans.
        iii. ML models can sometimes run thousands or even millions of simulations in the time it takes a human to do conduct an analysis.
        iv. Use AI to suggest control strategies…including novel approaches not thought of beforehand.
        v. Simultaneously tuning multiple controllers in control loops.
    c. preventive maintenance trending
            1. Already discussed above.
    d. improved reactor operations staff productivity
        i. Reduction of human work load
            1. Control Room
                a. Autonomous/Automated control systems reduce decision making needs of operator
                    i. Startup/shutdown
                    ii. Normal operations
                    iii. Load following
                    iv. Off-normal transients
                b. Smarter alarm systems that only show the staff the information they need to know, when they need to know it, and the procedure for how to deal with the alarm. Relevant information would include the alarm itself, and any related process or control signals.

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4. What AI/ML methods are either currently being used or will be in the near future in commercial nuclear plant management and operations? Example of possible AI/ML methods include, but are not limited to, artificial neural networks, decision trees, random forests, support vector machines, clustering algorithms, dimensionality reduction algorithms, data mining and content analytics tools, gaussian processes, Bayesian methods, natural language processing, and image digitization.
    a. This question brings up a very different "problem" statement between the existing LWR fleet which has a data infrastructure in place vs. an advanced reactor company like X-energy who will design and build a data infrastructure from the ground up using state-of-the-art technologies. Many existing companies are embarking on a "Digital Transformation" and trying to implement the "Digital Thread." AR companies can build the Digital Thread among its tools with much more ease and without the inertia of a decades old existing data management system. This lack of inertia will allow AR companies to incorporate AI/ML into just about any tool where it is deemed beneficial and appropriate. Some examples might include Enterprise Asset Management (EAM), System and Component Health Monitoring (SCHM), Corrective and Protective Actions (CAPA), Predictive Maintenance, Master Equipment List (MEL), Energy Management, Planning and Scheduling, Enterprise Resource Planning (ERP), Equipment Reliability (ER), Learning Management System (LMS), Laboratory Information Management System (LIMS), etc.
    b. Artificial neural networks with and without Bayesian methods
        i. Convolutional Neural Network (CNN)
        ii. Bayesian Neural Network (BNN)
    c. Auto-Encoders (AE) – feature extraction
    d. Long-Short Term Memory (LSTM) – for temporal data
    e. ANN's have replaced Logistic Regression, Support Vector Machine (SVM), and K-Nearest Neighbors. More data available and increased computational power have led to rapid development of Deep Learning (DL) methods.
    f. Natural language processing – dealing with large work order databases.
    g. Image digitization – visual inspections could be completely replaced by images captured by drones. Neural networks have been shown to outperform humans in reviewing images for minute details. One specific example is inspecting for cracks in concrete.

5. What are the advantages or disadvantages of a high-level, top-down strategic goal for developing and implementing AI/ML across a wide spectrum of general applications versus an ad-hoc, case-by-case targeted approach?
    a. Top-down company strategy or top-down guidance from NRC?
        i. A good example of a top-down implementation from the NRC is the inclusion of risk-informed analysis criteria for all revised standards. There has been a significant challenge for some standards because there is no practical way to evaluate risk for some systems. Adding an AI/ML requirement in this manner

would be a similar challenge. The case-by-case basis is more natural and targets application to the systems which are most conducive to AI/ML methods.

ii. The top-down approach makes more sense within individual companies.

b. The biggest hurdle in data science is always the data. Models are only ever as good as the data. Most often, the data infrastructure for established companies was built before AI or ML was even a thought. As a result, the data is siloed, incomplete and filled with errors that must be dealt with before a ML model can be developed. Surveys among data scientists show that nearly 45% of their time is spent collecting, cleaning and organizing the data.[1] If data infrastructures are built with the intent for the data to be collected and analyzed, those challenges can be avoided. Unfortunately, this opportunity may only be available to advanced reactor companies who don't currently rely on existing infrastructures. With that said, it is imperative that new AR companies build their infrastructure from a top-down approach. If all of the data is meant to be used in the future, the infrastructure must be built in such a way that the data is readily available to new tools and technologies well into the future.

6. With respect to AI/ML, what phase of technology adoption is the commercial nuclear power industry currently experiencing and why? The current technology adoption model characterizes phases into categories such as: the innovator phase, the early adopter phase, the early majority phase, the late majority phase, and the laggard phase.
    a. From an outside perspective and from employees that have worked in the industry, X-energy would characterize the current nuclear power industry in either the "late majority" or "laggard" category in terms of AI/ML adoption.
        i. Again, consider the outsider perspective and compare the nuclear power industry at-large to other industries. The automotive and airline industries have adopted AI/ML technologies to enhance operator awareness and reduce human error. They both recognize the human as a safety risk and have made significant strides to removing the human from the loop. Contrast that with the nuclear power industry, which has traditionally relied on human action to ensure the safe operation of its plants.[2]
        ii. Another example would be the combined-cycle gas plants, which run nearly autonomously. They entire plant can be started up from the push of a button, including remotely.

[1] https://www.anaconda.com/state-of-data-science-2020?utm_medium=press&utm_source=anaconda&utm_campaign=sods-2020&utm_content=report

[2] INPO IER 20-4 highlighted "Operator-Induced Events" that occurred between March 2019 to March 2020. In the webcast INPO detailed how it found that operators contributed to or directly caused seven scrams from March 2019 to March 2020. This accounts for approximately 1/3 of all reported events in that same timeframe.

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b. X-energy sees itself in the "innovator" category. For all the reasons mentioned above, the AR community plans to integrate AI/ML as much as is feasible in both Design and Operations.

7. What challenges are involved in balancing the costs associated with the development and application of AI/ML tools, against plant operational and engineering benefits when integrating AI/ML into operational decision-making and workflow management?
   a. For advanced reactor companies, the costs of developing AI/ML tools are negligible compared to non-recurring design engineering and capital costs for building a nuclear power plant.
   b. Also, the benefits are hard to quantify right now. The potential benefits could be massive, or it could be marginal if other factors (like regulatory restrictions on execution of AI/ML derived products) dampen or prevent the tools from meeting their potential. A disadvantage for advanced reactor companies is that we do not have operational data and costs to which we can compare. The only quantifiable number we can compare to would be Levelized Cost of Electricity (LCOE), specifically for Fixed Operations & Maintenance (O&M) costs. Without subsidies, nuclear power is not competitive compared to combined-cycle plants and renewables. One way in which Fixed O&M costs can be reduced is to centralize the Maintenance staff, such that they can support multiple units and/or sites. To be able to centralize staff, the plant design must be absolutely optimal in terms of safety and efficiency. An inherently safe reactor design provides flexibility to the design of all other systems in the plant. Hypothetically speaking, if a reactor is meltdown proof, there could be an argument made that no safety systems are necessary. Designing commercial systems instead of safety systems reduces costs drastically. How do you design an inherently safe reactor? It can be done with brilliant engineers carefully working through their analyses. It might also be done by an AI/ML model. Theoretically, you could provide an AI/ML model a set of input parameters and ask it to provide the most optimal design in terms of neutronics performance, thermal performance and safety. Efficient plant design can take many forms: minimal materials and spacing used, construction time reduced, construction cost reduced, optimal sensor placement, maintenance considerations built-in to the design, operator tasks minimized, security tasks minimized, maintenance tasks minimized, etc. All of these things and more must be considered if a nuclear power plant is to run "lean" enough to be supported by a central maintenance facility. AI/ML models can play a part in just about every topic listed above. To give one hypothetical example, if the distributed control system (DCS) that runs the plant is completely autonomous, then the operator tasks are significantly reduced. If every major and minor component in the plant has diagnostic sensors attached that feed data to the plant historian, and if there are ML models trained to detect anomalies and degradation in those components, then maintenance schedules become more efficient and there are less inspections needed.

c. The existing nuclear fleet would have much higher costs.
d. Analogy: trying to turn a tugboat around vs. a cruise ship.

8. What is the general level of AI/ML expertise in the commercial nuclear power industry (e.g. expert, well-versed/skilled, or beginner)?
    a. The interest in AI/ML applications within the nuclear industry is growing rapidly. X-energy has communicated with a healthy number of individuals with engineering backgrounds who chose to explore the data science field. Graduate programs are starting to build more research around a broad range of nuclear engineering sub-disciplines, specifically around computational analysis and AI assisted design optimization. However, human factors and autonomous control systems expertise is less common.
    b. X-energy itself has put together a team (internally) to develop Digital Twin concepts, which also include AI/ML applications. Also, as part of the ARPA-E GEMINA project, X-energy is working with partners from industry and academia on the Digital Twin concepts. The team is comprised of experts in the fields of Operations, Maintenance, Security, PRA, HFE, and simulation. There are also experts on the team with mixed nuclear engineering and data science backgrounds tackling the AI/ML applications.

9. How will AI/ML effect the commercial nuclear power industry in terms of efficiency, costs, and competitive positioning in comparison to other power generation sources?
    a. Already discussed above.
    b. Commercial nuclear power will not survive in the U.S. energy market without one of two actions: (1) more top-down government control of the energy market, or (2) less top-down control of the energy market, coupled with adoption of dynamic analysis methods to ensure safety rather than strict conformance via layers of regulations. Continued updates to the regulatory framework (i.e. Part 53 development) and acceptance of the inclusion of AI/ML applications for nuclear reactors in the SMR and Advanced Non-LWR (ANLWR) space would be beneficial. Also, it should be noted that the adoption of NEI 18-04 for "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development" for ANLWR's is a step in the right direction. AI/ML technologies can and will help that process along.
    c. Currently, the nuclear industry lags behind other power generation sources in terms of technology adoption. That is not a secret.

10. Does AI/ML have the potential to improve the efficiency and/or effectiveness of nuclear regulatory oversight or otherwise affect regulatory costs associated with safety oversight? If so, in what ways?
    a. Natural Language Processing – In a previous virtual conference/webinar the NRC discussed an effort to make the ADAMS database more searchable and user friendly. The value of this effort cannot be overstated. There is decades of useful information and data locked away in documents within the ADAMS database, which itself is difficult to navigate. Unlocking that information would provide immense value to both the current fleet and AR companies.
    b. As far as how the industry's adoption of AI/ML applications might improve regulatory oversight, first consider the regulatory process itself. To oversimplify the process, a vendor submits a design for a new nuclear power plant to the NRC, and the NRC must evaluate that design. How does the NRC do this evaluation? One part of it is modeling and simulation. Furthermore, to make an informed decision the NRC must be comfortable with the provided results of many simulations run by the vendors. To be comfortable the NRC must accept the model as valid, and must also accept that an adequate number of test cases have been run to cover the operational envelope. In other words, the confidence in a reactor design is at odds with modeling error in the simulation results and the computational costs of running simulations. That begs the question, can AI/ML improve upon simulation error and computational cost. AI/ML models have their own challenges with simulation error, but computational cost could be an area of immediate improvement. The example of AI surrogate models is given in the next bullet.
    c. AI Surrogate model – AI models can be trained on output data from a simulation model, such that it re-creates the behavior of the simulation model. The AI surrogate can run many orders of magnitude faster, while losing minimal accuracy. Therefore, vendors could create such models and run through significantly more desired permutations of that model. An increased testing envelope might give the NRC more confidence in their decision making.

11. AI/ML typically necessitates the creation, transfer and evaluation of very large amounts of data. What concerns, if any, exist regarding data security in relation to proprietary nuclear plant operating experience and design information that may be stored in remote, offsite networks?
    - Cyber security and data security is a major concern. The reasons for this are clear. As more and more data is generated, the incentive for attempting to steal that data equally increases. X-energy plans to apply appropriate security controls to prevent unauthorized access of this data for illicit purposes. Echoing comments made earlier, because AR companies do not have decades old IT infrastructure in place, they are more flexible to adopting state-of-the-art cyber security tools. Moreover, the IT infrastructure can be built with cyber security in the forefront of design considerations.