TRENDS IN NUCLEAR INSTRUMENTATION AND CONTROL SYSTEMS 2025

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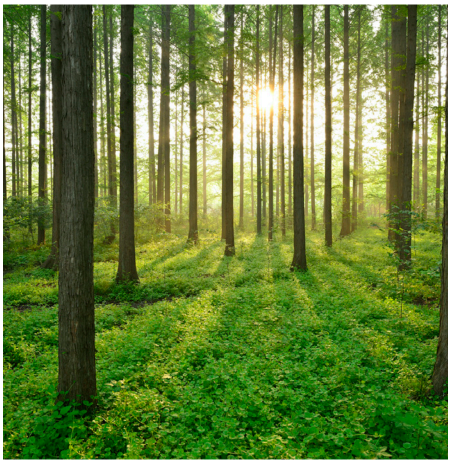

ENERGIFORSK NUCLEAR SAFETY RELATED I&C, ENSRIC

Energiforsk

TRENDS IN NUCLEAR INSTRUMENTATION AND CONTROL SYSTEMS 2025

Report from ANS conference NPIC & HMIT 2025

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Foreword

This report forms the results of a project performed within the Energiforsk Nuclear Safety Related I&C (ENSRIC) Program.

The ENSRIC Program aims to increase the knowledge of aspects affecting safety, maintenance and development of I&C systems and their components in the Nordic nuclear power plants. Part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

The U.S. conference NPIC & HMIT is one of the larger conferences covering the nuclear instrumentation and control area. Covering this conference is an efficient way of picking up international trends and tendencies.

The conference was covered by senior experts Emil Ohlson (Forsmarks Kraftgrupp AB) and Jonas Olandersson (Ringhals AB). The project was performed within the Energiforsk ENSRIC Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This report summarizes impressions and reflections from a major I&C and HMI conference organized by the American Nuclear Society This year the conference was an embedded part of the 2025 ANS Annual Conference that besides from I&C and HMIT also included a conference on Probabilistic Safety Assessment and Analysis (PSA).

Characteristic themes for the conference were the rapid development of new reactor technologies and the hopes and expectations that comes with it. Other major areas where the use of AI for different areas as well as cyber security other types of data analytics for NPP use.

Keywords

Nuclear, I&C, Advanced reactors, Cyber Security, ANS, Innovation, AI

Kärnkraft, I&C, Avancerade reaktorer, cybersäkerhet, ANS, Innovation, AI.

Sammanfattning

Denna rapport sammanfattar intryck och reflektioner efter en större I&C och MMI konferens anordnad av American Nuclear Society. Årets konferens var en integrerad del av 2025 års årliga ANS konferens, som förutom I&C och HMIT även inkluderade en konferens om probabilistisk säkerhetsbedömning och analys (PSA).

Karakteristiska teman för konferensen var den snabba utvecklingen av nya reaktortyper och de förhoppningar och förväntningar som följer. Andra viktiga områden var användningen av AI för olika områden samt cybersäkerhet och andra typer av dataanalys för kärnkraftverk.

List of content

1 Abbreviations

ANS	*American Nuclear Society*
CCF	*Common Cause Failure*
COTS	*Commercial-Off-The-Shelf* - Soft- or hardware which can be bought or licensed from an open market contrary to custom made solutions.
EMC	*Electromagnetic Compatibility*
EPRI	*Electric Power Research Institute*
FPGA	*Field Programmable Gate Array*
I&C	*Instrumentation & Control*
IAEA	*International Atomic Energy Agency*
IEC	*International Electrotechnical Commission* – A standards and conformity assessment body within Electrical and I&C
LLM	*Large Language Model*
ML	*Machine Learning*
MLM	*Machine Learning Model*
MMI / HMI	*Man Machine Interface / Human Machine Interface* – The interface between operator and the process facility.
NPP	*Nuclear Power Plant*
OEM	*Original Equipment Manufacturer*
OLM	*On-Line Monitoring*
PSA	*Probabilistic Safety Assessment*
SMR	*Small Modular Reactor*
US NRC / NRC	*United States Nuclear Regulatory Commission*

2 Conference

2.1 GENERAL

During week 25 in 2025, a major conference concerning I&C and HMI within nuclear power was hosted. The organizing unit was the ANS (American Nuclear Society) and the conference is a recurring event in which different areas of focus are addressed. This year's conference was the 14th in this topic.

The conference was an Embedded Topical Meeting to ANS Annual Meeting 2025, which deals with nuclear power at large and addresses much more areas than just I&C and HMI. Besides from the embedded I&C and HMIT conference there was also an additional embedded conference on Probabilistic Safety Analysis (PSA) in parallel with the ANS and I&C conference.

Each conference usually has a slogan that reflects the location, situation and mood for both the actual meeting and the industry as a whole. The slogan for this year's conference was " Energizing The World" and referred to the major expansion in nuclear power and capacity that currently is planned in the USA as well as other countries. In USA, the aim is to increase nuclear energy capacity from 100GW to 400GW by 2050, and where a large part is planned to come from Advanced Reactors and SMR´s but also conventional large reactors.

ANS is an international non-profit organization for research, education and organization in nuclear power. It was formed in 1954 and today has about 10,000 members from more than 40 countries (most from USA) representing over 1,600 companies, research institutes, universities and government agencies. The purpose of the organization is to work for understanding and knowledge in nuclear power technology. For more information on ANS different divisions, see www.ans.org or more specifically www.new.ans.org/about/committees/

ANS conferences are usually divided into two different ways; It is either a larger meeting with several different technology areas involved (e.g. I&C, Materials Technology, Calculation Program, etc.) or only one area represented. This year's conference was of the large sort and comprised both nuclear power in general and specifically conferences on I&C and HMI as well as PSA.

The NPIC & HMIT conference was divided into two main tracks - I&C and HMI, which in turn were divided into several different technical areas. This meant that there were always up to six presentations and sessions that took place in parallel at the NPIC & HMIT meeting, along with the additional up to fourteen parallel sessions from the ANS Annual Meeting and PSA conference. This meant a lot of planning to participate in the sessions and presentations that were considered relevant and interesting to one's own.

Apart from the sessions there was also a larger exhibition going on where vendors and company’s within the nuclear area showed new technologies and equipment invited to dialog and technical discussions. The exhibition was in parallel with the conference during most of the week and was located just besides the meeting rooms. There were also a number of different demonstrations and smaller “workshops” ongoing where the exhibition visitors could try different tools, applications and simulations SW.

During the weekend before the meeting several training course was also organized and addressed different topics related to nuclear I&C and HMI, advanced reactor safeguards etc. These workshops where led by engineers and experts from the different companies or laboratories at the conference and is aimed to provide a deeper knowledge and understanding within different areas.

Approximately 1450 people representing different organizations and companies from around the world attended the ANS conference and embedded conferences.

This year’s conference followed a trend from recent years with a larger part of the presentations was from National Labs or research institutes, and there were fewer presentations from vendors and utilities. This trend was notices during the 2021 meeting and continued also this year. This also reflected the content of the conference as many presentations focused more on future technologies then on what could be implemented right now.

The reason is believed to be related to the pandemic and the virtual conference, as many vendors and utilities attend such conferences for the possibility to meet and interact with peers and other utilities, and that possibility is largely limited in a virtual meeting.

In total, just over 200 reports (so-called "papers", meaning a shorter summary reports) were sent to the NPIC & HMIT conference, and about an additional 100 at the PSA conference and several hundred more on the larger annual general ANS conference. This makes the number of papers and sessions very extensive which could be expected at such a 3-leg conference.

During the week the authors combined were able to listen to over 80 different technical presentations, overall lectures and panel discussions.

The conference with all presentations, panels and plenary sessions is seen as a very good opportunity to get a hint of what is going on within the industry.

3 Content

As mentioned, the NPIC&HMIT part of the conference was divided into two main tracks – I&C and HMI, and under these main areas there were technical sessions with presentations and panel discussions according to the list below. Certain sessions are quite extensive and are therefore divided into different rounds (one round equals the morning or the afternoon).

In the morning prior to the first regular technical session, there were also so-called Plenary Sessions and Special Sessions, these sessions were hosted by the ANS Annual Meeting and continued as long as the ANS Annual Meeting. The speakers at the Plenary and Special sessions were often handpicked to address a certain topic or issue and was often people who had high positions in the industry (e.g. CEOs from different companies, people from the Department of Energy, Commissioners from NRC mm). Normally, these sessions comprised of a short presentation from each session member followed by a panel discussion and questions from the audience.

Each technical session then contains between 4-20 presentations. The different sessions at the conference were (without relevant order but divided into the different "tracks”):

- Human Machine Interface Technology
  - Considerations for HFE Activities: Function Allocation and Verification and Validation
  - HF Considerations for Artificial Intelligence and Machine Learning Systems
  - HF Considerations for Small Advanced Reactors and Multi-Unit Operations
  - HF for Cybersecurity, Computerized Procedures, and Digital Instructions
  - HF for Novel Concepts of Operations
  - Simulation and Decision Support
  - Transforming the Nuclear Industry: A Human Factors Perspective
  - Verification, Validation, and Uncertainty Quantification
- Nuclear Power Instrumentation & Control
  - Acceptance of COTS Digital Equipment - Panel
  - Advanced Reactors Instrumentation: Challenges and Opportunities- Panel
  - Advanced Sensor Technology: I-II

- Advanced Surveillance, Online Monitoring, Diagnostics, and Prognostics: I-III
- Autonomous Control and Operation of Nuclear Reactors: I-II
- Cybersecurity in I&C
- Cybersecurity in Nuclear Reactors
- Cybersecurity in Radiation Systems
- Cybersecurity in Wireless Technologies
- Digital Modernization of Plant Protection Systems - Panel
- Digital Twins and Their Applications: I-II
- Diversity, Defense in Depth and Artificial Intelligence
- DOE Office of Nuclear Energy Advanced Reactor Safeguards and Security Program - Panel
- Economics and Operation of Reactor Technologies
- I&C for Advanced Reactors and Small Modular Reactors
- I&C Regulations, Standards, and Guidelines: I-II
- I&C System Reliability
- Licensing of Advanced Reactor Instrumentation and Control - Panel
- Machine Learning and Artificial Intelligence for Nuclear: I-III
- Navigating Change: Young Engineers Shaping the Future of Nuclear Industry - Panel
- Operational Experience and Anomaly Detection
- Operator and Control Room Studies and Assessment
- Recent IAEA Activities on Safety and Security of I&C systems and Innovation to Support Operating Plants - Panel
- Remote Operation, Monitoring, and Maintenance
- Structural Health Monitoring
- Student Competition Papers
- Theory and Applications of Large Language Models in Nuclear Energy
- Wireless Technologies for Nuclear Facilities

- 19th International Conference on Probabilistic Safety Assessment and Analysis (PSA 2025) *[Note that most of these sessions are not covered by this report, only included as information about the PSA meeting content]*
  - Artificial Intelligence, Machine Learning, and Automation
  - Component Reliability
  - Digital I&C and Software Reliability
  - Dynamic PRA
  - External Hazards
  - Human Reliability Analysis: I-III
  - Multi-Hazard Risk Analysis
  - Multi-Unit and Other Modes Risk
  - Non-LWR PRAs
  - Operation and Generation Risk
  - PRA Development
  - PRA Software, Tools, and Methods: I-III
  - Risk Analysis of Hybrid and Integrated Energy Systems
  - Risk Metrics and Safety Margin
  - Risk-Informed Design and Construction
  - Risk-Informed Emergency Planning
  - Risk-Informed Security
  - Risk-Informed, Performance-Based Regulation
  - Safety Assessment
  - Setting Reliability Targets - Panel
  - Source Term and Consequence Analysis: I-II
  - Uncertainty Analysis
- ANS Annual Meeting (sub-divided into ANS Divisions) *[Note that these sessions are not covered by this report, only included as information about the ANS meeting content]*
  - Accelerator Applications (AAD)
    - Accelerator Applications: General
    - Lightning Talks: Material Science and Accelerator Applications

- Aerospace Nuclear Science & Technology (ANSTD)
  - Aerospace Nuclear Science and Technology: General
  - Lightning Talks: Operations, Power, Safety, Robotics, Space Applications and Non-proliferation.
- Decommissioning & Environmental Sciences (DESD)
  - General Decommissioning
- Education, Training & Workforce Development (ETWDD)
  - Nuclear Energy Sector - Academic Roadmap
  - Revitalizing Nuclear Infrastructure: Advancing Digital Twins, Cybersecurity, and Workforce Development - Panel
  - Innovations in Nuclear Curricula
  - Training, Human Performance, and Workforce Development
  - Lightning Talks: Education, Training, Workforce Development and Fusion Energy
  - Education, Training, and Workforce Development: General I-II
- Fuel Cycle & Waste Management (FCWMD)
  - Progress in Salt Reactors: Current Status and Key Considerations for Advancement - Panel
  - Progress Towards a Domestic Repository Program - Panel
  - Molten Salt Fuel Chemistry
  - Innovative Methods in SNF Disposal Research and Development
  - Scientific and Technical Advances in SNF Storage and Transportation
  - University Research in Fuel Cycle and Waste Management
  - Lightning Talks: Fuel Cycle, Waste Management, Radiation Protection and Shielding
  - Advances in Fuel Recycle
  - Fuel Cycle and Waste Management: General II
- Fusion Energy (FED)
  - Fusion Modeling and Simulation

    - Careers in Fusion - Panel
    - Fusion Materials and Technology
    - Lightning Talks: Education, Training, Workforce Development and Fusion Energy
  - Isotopes & Radiation (IRD)
    - Advances in Research Reactors and Isotope Production with High-Density LEU Fuel: I-III
    - Thermal Hydraulics and Multiphysics
    - Isotopes and Radiation: General III
  - Mathematics & Computation (MCD)
    - Current Issues in Computational Methods: Roundtable - Panel
    - Uncertainty Quantification, Sensitivity Analysis, and Machine Learning
    - Transport Methods
    - Computational Methods and Mathematical Modeling
  - Materials Science & Technology (MSTD)
    - High Entropy Alloys and Ceramics
    - Fast Reactor Fuels
    - Accident Tolerant Fuels
    - Fuels and Materials for Molten Salt Reactors
    - Advanced/Additive Manufacturing
    - AI and ML Applications in Nuclear Materials
    - Environmental Degradation of Materials
    - Nuclear Fuels: III
    - Lightning Talks: Material Science and Accelerator Applications
  - Nuclear Criticality Safety (NCSD)
    - ANS-8 Standards Forum - Panel
    - Reverse Knowledge Transfer – Bridging the Generational Divide - Panel
    - Updates/Revisions to Series 8 Standards

    - Sharing of Good Industry Practices and/or Lessons Learned in NCS - Panel
    - Lightning Talks: Operations, Power, Safety, Robotics, Space Applications and Non-proliferation.
    - Data, Analysis, and Operations in Nuclear Criticality Safety: II
  - Nuclear Installations Safety (NISD)
    - Lightning Talks: Thermal-hydraulics and Safety
    - Nuclear Installations Safety: General II
    - Lightning Talks: Operations, Power, Safety, Robotics, Space Applications and Non-proliferation.
  - Nuclear Nonproliferation Policy (NNPD)
    - Science, Technology, and Policy Advances in Nuclear Nonproliferation
  - Operations & Power (OPD)
    - Nuclear Energy Markets, Financing, and Economics: I-II
    - Advanced Nuclear Reactors and Power Systems: I-II
    - Lightning Talks: Operations and Power
    - Hybrid and Integrated Energy Systems: TES and Safety
    - Hybrid and Integrated Energy Systems: Hydrogen Production
    - Lightning Talks: Operations, Power, Safety, Robotics, Space Applications and Non-proliferation.
    - Hybrid and Integrated Energy Systems: Ammonia Production
  - Reactor Physics (RPD)
    - MARVEL Project: Lessons Learned Towards Demonstration - Panel
    - Early Career Reactor Physicist Award (ECRP) - Panel
    - Reactor Physics of Molten Salt Reactors
    - Reactor Physics Design, Validation and Operation Experience
    - Reactor Physics of Micro Reactors for Terrestrial and Space Applications
    - Reactor Physics of Fast Reactors

    - Lightning Talks: Reactor Physics, Mathematics, Computing and Criticality Safety
    - Reactor Analysis Methods: II
    - Reactor Physics: General
  - Radiation Protection & Shielding (RPSD)
    - Radiation Protection and Shielding in Spallation Neutron Facilities
    - Radiation Protection and Shielding: General
    - Radiation Protection and Shielding in Nuclear Power Plants
    - Computational Tools for Radiation Protection and Shielding
    - Lightning Talks: Fuel Cycle, Waste Management, Radiation Protection and Shielding
  - Robotics & Remote Systems (RRSD)
    - The Nuclear Industry's Connected Workforce in the Digital Transformation Era - Panel
    - Robotics and Remote Systems: General II
    - Lightning Talks: Operations, Power, Safety, Robotics, Space Applications and Non-proliferation.
  - Thermal Hydraulics (THD)
    - Memorial Panel -- John Kelly
    - High-Fidelity Computational Fluid Dynamics
    - Lightning Talks: Thermal-hydraulics and Safety
    - Thermal Hydraulic Education: Opportunities with AI
    - Thermal Hydraulics of SMRs and LWRs
    - Advances in Research Reactors and Isotope Production with High-Density LEU Fuel: I-III
    - Thermal Hydraulics Challenges and Opportunities for LWR Initiatives - Panel
    - Thermal Hydraulics of the High Temperature Test Facility
    - AI/ML Applications in Thermal Hydraulics
    - Thermal Hydraulic Testing for Advanced Reactors

    - Thermal-hydraulics Issues and Opportunities of Non-traditional Uses of Nuclear Energy - Panel
    - Enabling Deployment of Fast Reactors
    - Thermal Hydraulics: General
    - Thermal Hydraulics and Multiphysics
    - Experimental Thermal Hydraulics: I-II
    - Computational Thermal Hydraulics
    - Advanced Reactor Thermal Hydraulics: I-II
    - Experimental Multiphase Flow: I-II
  - Young Members Group (YMG)
    - Mentorship Matters: Building the Future Through Guidance and Support - Panel
    - AI as Your Career Co-pilot: Insights and Best Practices
    - Advancing U.S.-International Engagement in Nuclear Energy

Sessions with "I-III" after the title indicates that this session was divided into several round (3 rounds if "I-III" is indicated).

As can be seen from the list above, the Instrumentation and Controls Division was the division with far most presentations, and the Human Factors Division was also one of the larger.

Also noticeable from the list of sessions above is that AI as well as "Knowledge and Competence" related topics is common to many different divisions.

4 Larger topics and trends

This chapter contains a collection of topics and areas that either covered several rounds and thereby many presentations, topics that were smaller but still significant in its content, or was mentioned a lot during sessions, panels and plenary's.

4.1 A BRIGHT NUCLEAR FUTURE

The conference was located in Chicago just about 12 km north of the location of the Chicago Pile 1 where the first controlled chain reaction took place on December 2 1942, the event that in many aspects started the nuclear era and nuclear power. So it was perhaps a bit natural that large focus was nuclear expansion. No one wanted to say the words "Nuclear Renaissance" since that expression had a bit of "jinx" around it, but still many saw the close future as a very expansive period for nuclear energy. Matthew Marzano from the NRC said in the opening panel discussion the compared the "first nuclear renaissance" where it was mostly people from the nuclear industry that talked about it, this time there is a much wider interest and many more stakeholders involved (environment concerns, data centers, politicians etc). And that made it much more stable and ensuring.

Many plenary and panel discussions as well as technical presentations during the week addressed the planned nuclear expansion in USA and the world at large. In USA the aim is to increase the nuclear energy capacity from 100GW to 400GW by 2050. Large part of this expansion is planned to come from new advanced reactors, SMR's and micro reactors but also from conventional large reactors. With this expansion comes a growth in the business for both research laboratories, vendors, regulators and utilities. This can also be seen at the ANS where they now have more members under the age of 40 then older. And a lot of the members are students, meaning that nuclear now has grown large in the student/university community, something that has not been the case for several years.

And the expansion is growing faster than the industry and universities can provide competence. As ANS CEO Craig Piercy said is his opening plenary "*Where the challenge earlier used to be money, now its people and competence*". With the foreseen growth in nuclear capacity will require much more resources at national labs, OEMs, vendors, utilities, NRC etc and at this time there was no realistic plan as to how this should be handled. Matthew Marzano from US NRC also said that given all the planned licensing work ahead with both life time extensions and new builds (many of completely new advanced types with no prior experience at the NRC) the NRC could become a big bottleneck in this development if they do not find other ways to perform this work, e.g. with aid by AI.

Craig Piercy also said that the situation in the business right now is like when you start up a new plant, there is a lot of "start-up transients" since many players (both technologies and companies/people) are new to the business, and that these transients are "*expected, but not frightening*". Craig also emphasized that in this "start-up phase" there is a great opportunity to learn and gain experience. It was also mentioned that today there are as many countries that are looking at or aims to build their first NPP as there are countries that have operating NPPs.

Bryan Hanson, Executive Vice President and Chief Generation Officer at Constellation said however that he believed that the expected demand for electricity in the future was slightly exaggerated since many of those planned data centers etc won't be built and some of them are looking into several locations but will only build in one place. He made the metaphor to if a couple is planning to buy a house and go looking at 8 different houses, the 8 current house owner will tell their friends "*We are about to sell our house*" meaning that the "market" believe that 8 houses in the neighborhood will be sold. But in the end the couple will only buy one house, not 8, so the "market outlook" was exaggerated in this case. Bryan said that he believes that it will be similar with the planned electricity expansion, a lot will be built, but not everything that's included in today's forecast.

The public opinion on nuclear has also shifted in the USA where now 61% are pro nuclear according to a recent poll, and for ages under 35 more than 65% was pro nuclear. It was also addressed in one of the opening plenary that it used to be a little awkward to say that you worked with nuclear and that people working at a utility used to say that then worked for "electricity producing company", but nowadays they proudly say that they work in a nuclear power plant. So there is a whole new attitude towards nuclear in USA today compared to just a few years ago.

NPP's once in permanent shutdown are now starting to be scheduled for restart. One example is the TMI 1 plant that is planned to be restarted in 2028 through a cooperation between Constellation and Microsoft.

One thing that was addressed was the need for cooperation between stakeholders if the planned expansion is to happen. Nicole Holmes from GE Vernova Hitachi said that in order to make this work the industry must start to cooperate in matters of licensing/building/operation/competence in the same way that we cooperate within nuclear safety matters today. And that goes for regulators, vendors, utility etc. Nicole also said that GE today aims to design NPP for the world market rather than designing them for the US market and then adjust to regulatory markets, and therefor started to look a lot at the framework and guides from IAEA rather than just the NRC.

4.2 OUT WITH THE OLD, AND IN WITH THE NEW

One thing that sort of stood out on this year's conference was the high attention and focus on new advanced reactors, SMRs and future technologies. This has been present also during earlier conferences but it seemed more significant this time, and to some extent on the cost of current reactors and technologies that did not have as many presentations or focus during the week.

The vendor expo at the conference had both new and current technologies, and some of the vendors exposed equipment and systems for plant modernizations within I&C, showing that I&C modernizations is still a large part of the NPP everyday work. But it was fever utility and vendor presentations on the topic than usual.

One reason for this might be the "race to win the Advanced and SMR competition" where USA clearly wants to be the main player and puts a lot of effort and resources on this technologies. In earlier conferences the feeling has been that the initiative and leader position for designing and building large scale reactors has shifted from the western world towards China / Mid East / Russia that are designing/building way more plants then USA/Europe. And that the leader position for large scale reactors might be hard to retake for USA/Europe and instead the aim is to lead the next generation of reactor technologies. It was not said out directly in any plenary but the underlying feeling was that "If we want to be a global leader in nuclear technologies, we got to aim for the next generation and win that race". This does also reflect in that many presentations was from students and universities/national labs on future applications for tomorrows problems rather than from utilities on solutions for today's problems.

So the feeling was that the focus was more on reactors not yet built than on the existing ones. And even if many presentations was on content that perhaps could be used even in the current fleet one day in the future, that day is for away and the main field of application was for future reactors.

Still, USA aims to grow from 100 GW to 400 GW nuclear power by 2050 and this growth is most likely impossible without long life time extensions of existing plants and establishment of many new large scale reactors. If for example this expansion should be made with 300 MW SMRs it would require 1000 units, 10 times more in numbers then the current fleet. This is not seen as a likely scenario, rather it will probably be a mix of SMR, micro reactors, advanced reactors and large scale generation 3 reactors.

At this conference it was also the first time that fusion reactors was mentioned several times and also had a place at the plenaries. While fusion is still some time away, this time it was questioned if old saying "*fusion is always 30 years away*" was not going to the disproved within some years. There is an extensive research on fusion in the world and many facilities has proven that their fusion reactor can go critical. The main problem seems to keep the criticality in a stable, and long term state and to convert its energy to electricity in an effective manner.

One thing that also indicates that the conference is moving towards more future I&C technologies is that the next NPIC&HMIT meeting in 2027 will be held together with the "International Symposium on Future I&C for Nuclear Power Plants". And perhaps the two conferences will merge fully in some years given the current path.

4.3 CYBERSECURITY

Cybersecurity has been a large topic at the conference since digital I&C started to be discussed for safety applications, that means for the last 15-20 or so years. This year was no exception, and with 4 full sessions devoted to Cybersecurity and one session for "HF for Cybersecurity, Computerized Procedures, and Digital

Instructions", as well as one session in the ANS conference including Cybersecurity. So it was clearly one of the biggest technical topics of this year's conference.

The topic was presented and discussed in several different aspects such as basic strategies similar to defending an medieval fortress:

- Fortification: Physical barriers and cryptographic
- Chokepoints: Monitored access points (e.g., network intrusion detection).
- Access Control: Active: Session monitoring, biometrics, multi-factor authentication. Passive: Role-based access.
- Deception: Luring attackers into traps to expose their methods.

But also new threats such as quantum computing that pose a threat to current encryption methods due to their ability to break encryption codes quickly. Methods to handle such threats were presented.

Another aspect is that there are regulatory barriers that hinder the integration of advanced cybersecurity technologies into nuclear reactor systems, such as IEEE 7-4.3.2. Fraser Dougal from Sandia proposed a forward-looking framework that focus on a more performance-based approach to cybersecurity. He advocate for the use of Common Criteria (CC) Evaluation Assurance Levels (EALs) as a means to certify cybersecurity components, drawing parallels to how Safety Integrity Level (SIL) certifications are used for safety-critical systems. By aligning CC evaluations with the commercial-grade dedication process, he suggests a path to streamline regulatory approval, reduce costs, and enhance the cybersecurity posture of advanced nuclear reactors.

4.4 ARTIFICIAL INTELLIGENCE (AI)

Various forms of AI were by far the dominant theme at NPIC this year. Efforts have been made to leverage AI and related technologies such as machine learning, digital twins, and neural networks, to enhance safety and reduce costs for both traditional and advanced nuclear reactors. These technologies offer significant potential for improving the efficiency and reliability of nuclear systems by enabling more sophisticated monitoring and control mechanisms.

Dr. Nelli Babayan – AI Director, Microsoft, described the AI development phases:

1. Everyone has a personal assistant. (2021)
2. Human-led agents assist with tasks. (2024)
3. AI agents operate entire business processes, overseen by humans. (?)

This transformation requires complete trust in data handling. All data must be protected and accessible only to authorized users.

Throughout the conference AI appeared in everything from concrete applications for detecting anomalies in production facilities (see 1.3 for more information) to being discussed as a potential solution to the shortage of skilled professionals. For example, Tighe Smith from Paragon spoke about qualifying automated tools to review safety-critical components. He said "*Can we certify an AI-based engineer under the NQA-1 program?*"

Other use cases for AI discussed were:

- System-Level Prognostics
- Interpreting Nuclear Power Plant Documents
- Measure Plant Outage Resilience
- Cyber Attack Detection
- Cost-Benefit Analysis of Digital Upgrades
- Virtual sensors
- Operator Support System for Technical Specifications
- Non-destructive testing

AI affect the entire industry, including the regulator. The NRC is preparing to regulate AI applications and is committed to not becoming a roadblock to innovation. They have developed a strategic plan for AI oversight and are upskilling staff to create an agile workforce. A pilot project is underway using AI to perform and review a safety analysis, in collaboration with Argonne and Sandia national laboratories.

A common theme thorough out several presentations were explainable AI (XAI). Machine Learning Models (MLM) performs well but lack in explainability. Widespread adoption of MLM and LLMs in safety-critical industries such as nuclear will require some form of explainability to assure end users that the models response to a given query is valid.

A suggested way to handle this is to start with interpretable models and switch to complex (black box) ones only when justified. This is typically done by developing some kind of explainable model (e.g. physical), process the data through the model and then apply AI/ML technics. Finally use active learning to provide model-based context and explainable AI. There is a clear trade-off between performance and explainability. But trust and explainability are key to AI adoption. Typically is Human-in-the-loop essential.

When using unexplainable models such as Chat-GPT there are several known weaknesses. E.g. current LLMs lack good uncertainty quantification. It can be confident and still wrong. This can be showed by asking similar questions and get varied answers. It is important to ask AI how confident it is and request references. Typically GPT-4 hallucinates in ~1.5% of cases. LLMs must learn to say "I don't know" when uncertain.

4.5 ON-LINE-MONITORING (OLM)

In recent years, the nuclear power industry has increasingly embraced digital tools and AI-driven approaches to improve safety, reduce operational costs, and enhance predictive maintenance. Several presentations gave examples of how AI-driven predictive maintenance was implemented and showed the potential. The examples was generally only on portions of a plant (typically on one system) but still needed a large amount of work to develop and implement. The potential is tremendous but there are no plug and play solutions.

One example of how digital I&C can be used to reduce burden on operations and maintenance personnel is to reduce manual surveillance requirements. This by crediting the on-line monitoring and diagnostic capabilities of safety related digital platforms to perform the same activities on a real-time basis that are performed by manual surveillances.

To reduce manual surveillance requirements to inherently increase the safety of the plant through reducing the duration of how long the RPS system, for example, is at less than full redundancy. An analysis is performed to justify the elimination and/or automation of certain surveillance requirements. These surveillance requirements change take full advantage of the specific digital platform self-diagnostic features and application design, something not accounted for in the plant specific Technical Specification (TS). The elimination of surveillance requirements will also reduce the burden on operations and maintenance personnel, eliminate risks associated with human performance errors associated with these tests, as well as the generation and automation of procedures related to surveillance requirement testing.

This has been done at Vogtle 3 and 4 and more plants are looking into follow. By crediting the built in testing, around 100 periodic test was eliminated, saving thousands of hours annually. But also reducing human errors and less wear on equipment.

4.6 REMOTE AND AUTONOMOUS OPERATION

Remote or Autonomous Operation means to control or operate your equipment or entire plant either from a far location or that it runs entirely (more or less) independent of human interaction. The subject has been raised before but this time there was two sessions devoted to “Autonomous Control and Operation of Nuclear Reactors”.

The presentations comprised of both operation of a single component and test that had been done in this scale, or in some future applications showed the ability to run the entire plant from remote and often with large proportions or self-deciding or autonomous operation. The applications did vary a lot where one presentation showed a concept of a remote located (still fictional) micro reactor that preformed its own load following and produced just the amount of electricity that was required, and another used a digital twin to predict certain events that later controlled the plant. The autonomous load following concept did appear in several presentations with different application specific attributes.

Zeth duBois from the University of Idaho presented a paper for a hybrid control system for NPP that would form a Hybrid System Operation (HSO). This lets the human operators run the plant but is always supervised by the control system and like in many modern cars, if the operator initiates (or don't initiate) a certain operation that the control system does not agree with, the system gives feedback to the operator. Just like when a modern car takes control and steers the wheel if the car seems to be on its way out of bounds, but the car driver can override this intervention by pulling the steering wheel. This means that it is still the operator that makes all the final decisions but is aided by a supervising system to prevent errors. This is often referred to "Human in the Loop" systems. Many at the sessions seemed convinced that Human in the Loop systems would be the only acceptable solution for current plants, at least for the near future. And other presentations also addressed these hybrid and Human in the Loop system so it is likely that we will see them in some non-safety system in the near future.

Some of the presentations around autonomous operation involves only a smaller system or part of a system, meaning that only a limited function operates autonomous. One could then ask the question what the actual difference is between these systems and the control looped systems we have installed today in our plants. In some cases "autonomous" is just a buzz word for "control system".

A visionary look on the autonomous operation in the future was presented in several presentations where a centralized control room or control center supervised several remote located plants (mostly micro reactors and SMR type reactors). If something happened they would send maintenance personal or other staff to handle it but mostly the plants would operate in autonomous mode. The vision is very similar to the Swedish hydro power in Norrland where a central control center in Vuollerim controls a large amount of hydro plants along the Luleälven. A prerequisite for doing this in the nuclear business is of course that the plants must have passive safety functions and very slow accidents propagation, making small advanced reactors ideally for this type applications.

4.7 DIGITAL I&C AND SOFTWARE RELIABILITY

Digital l&C and Software Reliability was perhaps not one of the bigger topics at the conference, but it had one session in the PSA track and one in the I&C track. But since it has been a discussed topic within ENSRIC and an area where all Nordic plants have an interest it was decided to cover this session and similar presentations and include it in the conference report.

This an area where I&C and PSA could benefit a lot by cooperating. From the I&C perspective it is very hard to predict just how reliably a digital software based system is since it is much harder to predict why a component could fail compared to an analog component that could be analyzed by circuit board inspection and assessment. And from the PSA perspective it is often hard to understand how this complex equipment actually works and what failure mechanisms it has, and hence it is hard to model this equipment in a proper manner in a PSA analysis tool such as RiskSpectrum etc.

It is important to point out that software based components does not have any other failure modes from the plant perspective compared to hardware based systems. E.g. a digital software based transmitter might produce the wrong value, no value or go to a fault mode, just like an analog transmitter could. The difference is in what caused the fault and how easy vulnerabilities could be realized prior to use. This complexity and "hard-to-analyze" aspect makes software based systems harder to analyze and justify with regards to CCF, especially if it is a larger more complex system. Most presenters at the session agreed that when looking at a single software based component it has better MTBF and fault statistic (partly due to that is often has self-supervision and fault detection) than an analog component, but that is it much harder to "prove" that there is no CCF risk in a system with several redundancies (e.g. a 4 train safety system).

John Weglian from EPRI also addressed this in his presentation where he said "*There are no Software Common Cause Failure, just Common Cause Failure*". John also stated that SW does not fail, it simply does what it is told to do, and sometimes it might be told to do the wrong thing but that is an implementation error or a specification fault, but the SW does not change and fail.

Younghak Lee from Chung-Ang University presented a work where they have assessed IEC61508 and Safety Integrity Level (SIL) using PSA. Younghak said that SIL could be used to determine the reliability on demand and that PSA would give the plant risk if the assessed equipment did not function, and that these two methods together did provide a good way to analyze and justify your system. He also said the SIL and PSA in this matter could be a mean to justify COTS in nuclear applications. The project had also used PSA to determine what level of SIL that was required for a single train or on system level.

Antti Pakonen from VTT Technical Research Centre said in one of the I&C reliability session that when making digital I&C modernizations it was important to not only see to the requirements for diversity etc but also make sure that the end product is not over complex. Since too much complexity can make a system hard to analyze and fully understand, it can sometimes cause faults and therefor be negative for safety. A balance between function and complexity should be assessed when installing a new digital and software based I&C system in safety applications.

4.8 WIRELESS

Wireless systems are becoming an established technology used in the nuclear power industry, with applications including data communication, monitoring equipment conditions, and radiation monitoring. The leading advantage of selecting wireless systems over their wired counterpart is the reduced cost of construction, especially during retrofitting and refurbishment. Although wireless systems can be more cost-effective to implement for a monitoring application, they contain an inherent weakness due to their use of an open medium for transmitting information that relies on complicated integrated circuits to operate and are more susceptible to interference.

Some sort of redundancy is usually introduced into the architecture in industrial applications, to improve the reliability of wireless systems. Mesh networks utilize redundant communication pathways between the source devices to destination devices to better reduce the impact of disruptions to the network. The drawback to this solution is that fully formed mesh networks increase the system's cost to implement and complexity.

Studies and experience within the industry shows that the star network topology is roughly as reliable as a wired system. In fact the a meshed network usually results in less availability than of a star network due to more complex issues and requires more maintenance work.

Besides availability there are challenges such as cyber security, radiation tolerance and electromagnetic interference (EMI). Currently, wireless technology is mostly used to monitor and not control. In fact IEC 62988 limits its use to I&C systems performing Category C functions. Even in lower safety-criticality applications, robust cybersecurity measures and procedures must be in place, and the impact of EMI/RFI on other wireless infrastructures and their associated applications must be carefully evaluated.

Typically design engineers propose solutions; IT approves and maintains the network, but they often don't communicate. Instead it is important to early define who owns the wireless system and the spectrum. Ongoing monitoring of the spectrum is essential when implementing and expanding the use of wireless technologies.

Wireless spectrum management is something that are becoming much more important and relevant now when the different applications start being installed. And since in many cases applications are installed by different stakeholders (e.g. maintenance, IT, etc) it becomes very important that someone has the overall responsibility and overview of every different wireless network. Since this typically is a task that falls between the chairs of IT, Engineering, Maintenance it is many times forgotten or done fragmented at different departments.

EPRI has a report on Spectrum Management and it was recommended to look into this before starting to install wireless networks, or at least as soon as possible if you already have started wireless with any spectrum management.

According to Chad Kiger at AMS the tests that they have conducted in various plants shows that about 10% of all installed equipment is sensitive for EMC, but that it is very uncommon that any equipment is sensitive for signals above 1 GHz. The test conducted also showed that the calculated exclusion zones are often conservative and measurements often can decrease these zones if needed. There are several different protocols and standards for wireless and WiFi was the most common used according to Chad, but it was not always the best choice, rather an assessment of a plants/systems needs and function should be done prior to choosing your wireless standard.

Henry Kane from the University of Manchester presented a paper on Wireless Remote Sensing for Nuclear Material Storage Facilities where they had evaluated different ways of transmission; radio (e.g. WiFi), light (e.g. IR) and acoustic/sound.

The most common is of course radio but given different situations there are times when the other are better, so the advice way to assess your situation and prerequisites and make an educated choice and not assume from start the radio/WiFi will be your best option.

Chad Kiger also pointed out that EMC interferences in the plants are becoming a larger issue with the increasing instalment of different wireless equipment, drones etc.

Despite the risks, there are numerous examples of successful use of wireless technology in the nuclear industry, including remote sensors and handling systems in highly radioactive and inaccessible areas. These applications must be in systems where there is a safe state in the event of wireless failure, rather than applications in which continuous control was needed to maintain safety.

4.9 DIGITAL SAFETY SYSTEM UPGRADES

Surry and North Anna are replacing more or less all control and safety systems transitioning to Ovation and Common Q platforms. The project had been ongoing since 7,5 years and will be finished by replacing the safety systems in 2031-2032.

The Main Control Rooms (MCR) are upgraded by improving the operator interfaces, but the core functionality is maintained. Originally it was planned to be implemented for 3 outages per plant, but is now planned for 7 outages.

Even though they expect to half the maintenance costs, the project would not be feasible without the state of Virginia paying for half of the project costs.

The project builds control network infrastructure for the first time at the plants. The systems are standardized to be as equal as possible at all plants but requires new knowledge. Training the personal and develop the local workforce during the project is identified as keys to manage the systems after the project. It is important to identify all different aspects as early as possible. E.g. they had to build a special secure storage for cyber-compliant equipment waiting to be installed.

NRC anticipates all plants will need to upgrade protection systems to operate beyond 60 years. To handle this NRC have to do more with fewer people. One way to accomplish this is to consider generic reviews for common platforms and handle similar applications in parallel. Many plants have been talking about modernizing plant protection systems, but Surry and North Anna seems to be the first of many to come.

5 Other areas and conference notes

This chapter contains remarks and notes from presentations, panels or other sessions that is outside the scope of the larger areas presented in chapter four. They are reproduced without any order or priority.

- Mark Gusakov from International Data Center Authority addressed the electricity consumption for large data centers. Mark said that today large data centers require as much power to perform the calculations as it does to cool and remove heat from the racks.
  Mark also said that new data centers now consumes up to 40-50 MW, and that this is 3 times as much compared to just a few years ago. And that the worlds collective data centers consumes almost as much electricity as the UK (250 TWh data center compared to 288 TWh for UK).

- When building new large data centers today, grid capacity and reliability has become an issue. Some of the companies that planned to build data centers said that they must also build some small reactor in the close vicinity. "*We can't get that type of power from the grid, so we'll just have to bring it ourselves*".

- EdF struggled to find qualified safety related equipment to their ventilation systems. Eduardo Couto Montenegro presented a project where they designed and qualified their own components using FPGA. The project was carried out by EdF R&D lab in Chatou in Paris.

- During the plenary session "Breaking the Mold: How Innovation is Disrupting the Nuclear Industry" it was discussed the nuclear industry could meet the goal with 300 GW of nuclear power added by 2050. The panel said that it has been a "norm" that NPP takes a very long time and a lot of money to build, but if you look at the current fleet (build in the 1970-80) that is actually not the case. Only the most recent building projects in the western world has been "slow and expensive", and many other major civil constructions today are also "slow and expensive". Could it be that it is not "norms and traditions" that makes new NPP hard to build nowadays, and could it be connected to today's society and attitude? And that this will affect the planned SMR as well (that are believed to be "fast and cheap"). For example, many problems with larger NPP builds today have been around ground and concrete as well as on-site welding, this is also needed to be built on site even for SMRs. So perhaps even "factory made" SMR will face similar problems as large scale reactors has? Is it perhaps not possible with any sort of nuclear facility to achieve "fast and cheap"?

- The "Breaking the Mold: How Innovation is Disrupting the Nuclear Industry" panel also stressed that is should not be the industry and the current NPPs that drives the innovation process, that should be done by the national labs and universities. The operating NPP should focus on producing reliable electricity in a safe manner and to a compatible cost because if they fail doing so there won't be any plants to provide innovations to since they would have been forced to shut down. It is easy to forget the main objective if utilities focus too much on innovation and new technology. Also, labs and universities have the possibilities to test and fail before coming up with a good solution (and in many cases also have the task to fail with some ideas, so that the industry won't have to try and fail).

- False or counterfeit components is a grooving problem in the nuclear industry, not least from the fact that many OEM no longer provides some spare parts and these needs to be purchased from somewhere else, giving a growing market of counterfeit equipment. Jason Castro from EPRI presented a method of detecting counterfeit from genuine components using a method called "Hardware-Based Reference Signatures" that comprised four different tests:
    - Visual inspection
    - Impedance Signature analysis
    - Thermal Emission analysis
    - EMC emission analysis
- One motive for installing wireless in new installations that was mentioned is that decommissioning goes much easier with lesser cables.
- During one of the plenary sessions about advanced reactors a comparison was made with data collection from modern cars and airplanes where thousands on units send data every day to the OEM in order for them to learn and improve their systems and components. This is not really applicable to today's NPP in the same manner since very few NPP are copies or identical, making the collected data from one plant not necessarily useful for another plant. This might change if the next generation of nuclear plants more consist of standardized fleets of identical plants and SMR's.
- A question from the audience during one of the plenary was that many of the tech-giants (Google, Amazon, etc.) that are working toward innovative solutions within autonomous operation, AI, remote control etc. does not have the same consequence of a major failure as do nuclear plants. For a NPP an accident is a catastrophe, and it does not have to be core meltdown it could be a much smaller accident but it would still effect the whole industry for years to come. Is it therefor reasonable that NPP aim to follow in the "AI era" with arguments such as risk of losing staff if they are not keeping up with the latest technology? And do the NPP industry follow these new technologies because we need to do so for sake of plant reliability and effectiveness, or do we do it because it is cool and exiting right now? Lots of statistic indicates that modern plants do not have big issues with reliability or cost effectiveness of plant systems, yet lots of efforts are poured into the Digitalization and AI area.

- A comparison was made with autonomous cars as compared with autonomous NPP. autonomous cars are less likely to end up in an accident and therefor are safer for the overall driver/passenger. But, the car industry expect and can accept that every once in a while, there are some fault on a single car causing an accident. This is devastating to those involved in the accident but not for the society around it. With NPP it becomes something entirely different as not a single accident can be accepted even if the overall everyday operation becomes slightly better with more AI-driven systems and autonomous operation.
- Lots of new measurement techniques are developing and were presented at the conference. Two interesting examples are strain gauges for extreme conditions that were printed onto/into the structure on which it measured by use of 3D printing techniques, and fiber optic cables that are easily wrapped around object to measure temperature and strain for system health purposes.
- Hank Strahley from Southern Nuclear presented a quick solution for converting analog display instruments to digital information. They had developed a small "puck" that simply was mounted in the display instrument and read the instrument readout and then signaled this to the control room via a wireless network. "*Digitalizing without trespassing into the actual process*" was a term used. Collecting the signal from the analog display instrument meant saving to field technician rounds per day for these signals.
- Youndo Do from Georgia Institute of Technology presentation was about a robot that they were developing. (e.g. containment) as search for leaks, if a leak was found it could take video and measurements and send to the MCR and also repair the leak using patches and welding. This meant that leaks could be both investigated, assessed and repaired, giving the plant the ability to run to outage and make a final repair instead of shouting down in mid cycle. The robot was in development and test phase right now but the aim was to have a pilot robot for a real plant in a few years.

TRENDS IN NUCLEAR INSTRUMENTATION AND CONTROL SYSTEMS 2025

This report summarizes impressions and reflections from a major I&C and HMI conference organized by the American Nuclear Society This year the conference was an embedded part of the 2025 ANS Annual Conference that besides from I&C and HMIT also included a conference on Probabilistic Safety Assessment and Analysis (PSA).

Characteristic themes for the conference were the rapid development of new reactor technologies and the hopes and expectations that comes with it. Other major areas where the use of AI for different areas as well as cyber security other types of data analytics for NPP use.

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