# Summary from the Innovation Workshop for Integrated System and I&C Testing

On June 4-5, 2015, over 40 nuclear energy specialists from industry, laboratories, and academia came together for an Innovation Workshop and Webinar for Integrated System and Instrumentation and Controls (I&C) Testing, hosted by the Center for Advanced Engineering and Research (CAER) in Forest, Virginia. The non-profit CAER is home to two major nuclear research programs, the Integrated Systems Test (IST) facility and the Integrated Control Room and Operator Performance Laboratory (INCONTROL). The objective of the CAER program was to leverage the momentum generated from the March 3-5, 2015, Nuclear Innovation Workshop hosted by the Idaho National Laboratory (INL) to specifically target national research and development[1] (R&D) infrastructure gaps related to nuclear power plant design and operation.

With investments by BWX Technologies, Inc. formerly The Babcock & Wilcox Company (B&W) and Virginia Region 2000 Partnership, the IST is a heavily instrumented pilot-scale light water reactor (LWR) prototype. To support its original mission as a design test bed for the BWXT mPower™ small modular reactor (SMR), it fully integrates balance-of-plant (minus turbines and power generation) and a state-of-the-art digital control system. Similarly, INCONTROL was the inspiration of an industry-university collaboration benefiting from contributions by AREVA, GSE Systems, and regional universities. This laboratory consists of a reconfigurable control room platform with over 50 consoles (including three 90" displays) emulating the data acquisition and presentation required of nuclear power plant.

This Innovation Workshop for Integrated System and I&C Testing was organized to address the R&D challenges and opportunities for utilizing the IST and INCONTROL at CAER as a platform incorporating interfaces for process-scale thermal-hydraulic investigations and cyber-physical systems. As a workshop, the principal end product is this summary of the discussions among participants. The primary motivation of the workshop was to prepare a document package containing information recommending investment by the U.S. Department of Energy (DOE) as responses to the DOE Request for Information (RFI) for Competitive Work Scope Development DE-SOL-0008246 and Potential Infrastructure Investments DE-SOL-0008318. In addition, this summary will be submitted to the INL Innovation Workshop website.

## Workshop Agenda and Orientation

The workshop[2] began with an introduction of participants and review of the agenda, appearing in Attachments A and B, respectively. The group was reminded of the DOE RFI objectives of spurring nuclear innovation in support of the current and new reactor technology (see "Day 1 Workshop Information" and "Integrated System Testing & Licensing: CAER INCONTROL & IST"). As a cyber-physical systems (CPS) platform incorporating interfaces for process-scale thermal-hydraulic investigations, the CAER-IST and INCONTROL capabilities were next summarized with the intent to stimulate discussion on the broader agenda topics. Workshop organizers then presented to the participants five focus areas of discussion specific to nuclear power plant design, operation and R&D:

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[1] The term research, development and demonstration (RD&D) appeared in materials used by workshop participants. For continuity, only "R&D" is used in this summary.

[2] Presentations delivered during the workshop are available for download at http://www.caer-ist.org/

- Focus Area 1: Integrated Testing Concept: LWR / SMR Operational testing
- Focus Area 2: Instrumentation and Controls, Cross Cutting Technology
- Focus Area 3: Novel Applications of the CAER-IST as a Cyber-Physical System Platform
- Focus Area 4: Integrated Testing Processes / Licensing
- Focus Area 5: Cost-effective R&D of the CAER-IST

A premise underlying the initial workshop discussion was a recognition that progress in the deployment of nuclear power has coincided with large-scale safety and operational testing programs. During the developmental years of nuclear energy, federally supported large-scale test facilities were commonplace. As those facilities completed their mission, they were decommissioned, with many of these programs concluding in the late 1980s and early 1990s. The data from these programs has since served the interests of both the R&D and industry communities to resolve technical issues.

These integral investigations provided the foundational database supporting both the existing operating LWRs and the advanced LWR designs currently under development. As the insights from these programs were captured and applied, the value of this data to further serve R&D and systems operations missions has been largely exhausted. Notably, thermal-hydraulic uncertainties remain significant, such that among other physical domains, including reactor physics and materials, the largest uncertainties remaining in these areas are thermal-hydraulics.

Insights from those early large-scale thermal-hydraulic tests inspired study of the revealed phenomena. Fast computers and efficient evaluation methods has led to computational fluid dynamics resolving fluid conditions at the scale of bubbles and droplets. Subsequently, instrumentation has been needed to provide data at those scales. This incompleteness and inconsistency of the existing thermal-hydraulic database was the first national R&D infrastructure gap identified by the workshop participants.

To be consistent with “design practices,” this introduction was followed by a conversation on requirements setting for eventual in-depth discussions. The principal requirement was the identification of national R&D infrastructure gaps, supplemented by an assessment of the current state of nuclear CPS R&D, including basic technology research, transition, and adoption roadblocks.

## Focus Area 1: Integrated Testing Concept: LWR / SMR Operational testing

Focus Area 1 explored unresolved LWR/SMR/BWR reactor technology challenges that could benefit from a pilot-scale power plant research center such as the CAER-IST. Several topics, including natural circulation initiation, two-phase natural circulation, two-phase flow instability (with simulated reactivity feedback), were proposed; however, the trajectory of the discussion eventually settled on the observable domain of modern instrumentation for thermal-hydraulic investigation. Such instrumentation includes optical probes, conductivity or capacity probes, film probes, wire mesh sensors, hot wire or hot film anemometry, steady and transient X-ray or Gamma tomography, absorption and scattering methods, laser Doppler anemometry, particle image velocimetry (PIV), laser induced fluorescence, nuclear magnetic resonance, ultrasonic methods, etc. Examples of successful demonstration of such instrumentation in thermal-hydraulic applications were cited, including optical probes at University of Michigan, gamma densitometers at Imperial College, and PIV at Texas A&M.

Drawing on their experience with the CAER-IST, Focus Area 1 leaders explained to workshop participants that to support its original mission as a design test bed for the BWXT mPower SMR, the IST was constructed to be flexible. This flexibility extends beyond the study of system-scale single- and two-phase thermal-hydraulics. Adaptable interfaces include a removable five-foot section above the core and a five-inch blind flange at the inlet to the steam generator. In addition, piping runs of the interfacing systems (i.e., safety and secondary) are configurable for instrumentation or slip-stream diversions of liquid or steam to accommodate study objectives.

Of particular interest for two-phase flow investigations is the removable five-foot section above the core. Beyond its use as an instrumentation access port, several ideas were offered by workshop participants during the Focus Area 1 discussion and assessed for feasibility. This included component or systems tests interfacing either directly or via a heat exchanger. While cleanliness of the primary and secondary systems at the CAER-IST is a requirement, the latter option could facilitate interests in chemistry testing or the introduction of particles for tracking fluid behavior. This section could also be served by a heat exchanger interfaced to another fluid system. The five-inch blind flange at the inlet of the steam generator can accommodate instrumentation or serve a plenum for materials and structural testing under high temperature. Lastly, I&C systems is programmable to support algorithmically-defined control over heater and system conditions to emulate coupled-physics such as nuclear reactivity feedback.

Workshop participants then turned their attention to consideration of level and flow measurement, which are tightly coupled to core cooling safety metrics. Historically, these have been inferred from surrogate measures of pressure drop and/or thermocouples. A Fukushima lesson-learned is that these instruments are vulnerable to distortion under extreme conditions. Contemporary instrumentation have shown promise over limited testing domains; however, qualification and survivability under the full range of possible environmental conditions, including severe accidents, needs to be established.

The only significant advancement of instrumentation into nuclear power plants has been the introduction of ultrasonic flow meters for justifying power upgrades. Implementation of these instruments bypassed several stages of technology readiness and has, subsequently, run into several unanticipated problems delaying the benefit they were originally implemented to resolve. The inability to independently test and qualify advanced instrumentation over the full application domain of operational conditions was cited as the second national R&D infrastructure gap.

As a counter-point, it was noted that often thermal-hydraulic phenomena occurring at low pressure following an accident is of greater interest for safety. Nonetheless, this is not a conservative assumption in all settings. High pressure process-scale investigation is uniquely challenging as certain solutions possible at low pressure are not available at high pressure, particular optical probes. It was noted that Sapphire windows can handle "fairly" high pressure and if implemented in the CAER-IST, could provide a unique instrumentation interface. This capability would be essential in the study of pressure-sensitive phenomena, including two-phase flow stability, reflux condensation, and flow regime structure and transition. Previous experience has focused on void fraction; however, crediting the IST's coupled I&C, it offers fine control of conditions to drive desired fluid conditions.

This latter point was identified as the third national R&D infrastructure gap, that is, the need for fine control over thermal-hydraulic conditions to minimize epistemic uncertainties in measurements associated with the conduct of testing. With variable-drive motor-operated pumps and valves under algorithmic control, target fluid conditions can be established at the CAER-IST with minimal variability. Such fine control is essential to characterizing flow regime structure and transitions.

From the group discussion, the following cooperative research opportunities reflecting workshop participant's immediate interests and requiring minimal modification to the IST were advanced:

- Critical heat flux (CHF) testing (evaluation of heater temperature prior to CHF conditions)
  - The IST heater bundle consists of 60 heaters with a total of 160 thermocouples (TC) internal to the heater pin sheathing. Precursors to CHF are indicated by a rapid heatup measured by the TCs. When rapid heatup is sensed (heatup range and time can be set for each test) the IST digital control system can be set to trigger multiple actions. In previous tests, boil off conditions were secured by removing power to the heaters and closing a boil-off valve.

 - Installation of viewing window along the 5' removal test section. This window would allow for optical measurement to the test section where a heater pin capable of attaining departure of nucleate boiling to CHF conditions would be installed. The heater pin would be energized to create boiling conditions to be observed by external measurements through the optical port.
 - Dry-out test where the safety margin case for fluid height required above the core is established at pressures from atmospheric to over 1000 psia.

- Thermal Hydraulic Testing
  - LWR/SMR thermal hydraulic testing including primary to secondary heat transfer evaluations.
  - OECD LWR UAM: Exercise III-2: Thermal-hydraulics system performance steady state and selected transient data.
  - Nuclear Energy Knowledge and Validation Center (NEKVAC), access to novel instrumentation concepts for the compilation of process-scale data covering the operational domain of various light water reactor designs.
  - Light Water Reactor Sustainability; facilitate testing to meet beyond 60 year licensing efforts.

In compiling this list, a workshop participant added that no platform currently exists for validating regulatory evaluation methodologies. This was recognized as a fourth national R&D infrastructure gap.

### Focus Area 2: Instrumentation and Controls, Cross Cutting Technology

The integration of thermal-hydraulic and I&C was a natural segue to the broader subject of I&C as a cross-cutting technology, Focus Area 2. To stimulate discussion, a presentation (see "Instrumentation and Control Systems (I&C)") was delivered describing the current state-of-the-practice and how programs sponsored by the DOE and others support this research. The particular CPS cross-cutting technology topics include Fault Tolerance, Resilience, Cyber Security, Human Factors, User Interfaces, Equipment Qualification and Survivability, and Digital I&C. While the data sought for these purposes is disparate from process-scale thermal-hydraulic phenomena, this community shares a common nuclear safety objective, measured by the same margins to safety criteria employed by the thermal-hydraulics safety community. This research serves to improve the capacitance of structures, systems, and components to physical loads, thermal-hydraulic or otherwise, through automation and "human-in-the-loop" frameworks. Insights improve human reliability assessment (HRA), a contributor to the development of control room architecture, staffing programs, emergency operating procedures, probabilistic risk assessment (PRA), severe accident management guidelines, etc.

With respect to specific I&C, considerable discussion focused on embedded I&C and smart sensors as a means for fault-tolerant control. Canned motor pumps and control rod drive mechanisms were offered as candidates benefiting from improved monitoring and control. Such technology has not progressed beyond the laboratory-scale for nuclear applications. Experience gained from other industrial applications of embedded I&C and smart sensors suggests that this technology may have an advantage over conventional I&C for extreme environments. In particular, high fidelity local information, accounting for assessed plant state, could be applied at the component-scale to assure responses appropriate during more challenging (e.g., multiple-failure, high temperature/pressure, etc.) events.

A workshop participant explained that the DOE's NEET program coordinates research efforts on common issues confronting the DOE-NE R&D programs to advance technology development. Of particular interest to NEET are the development of advanced sensors and instrumentation and modeling and simulation. They also facilitate applications of DOE's Advanced Test Reactor (ATR) in Idaho, DOE-

NE's only Nuclear Science User Facility (NSUF). Among the NEET R&D themes is robust, adaptive, and inherent optimal plant response. Comparisons of measured and modeled or calculated values of plant parameters can be used for diagnostic and prognostic purposes, and in particular to monitor and improve the human performance and the performance of specific plant functions or systems under a spectrum of threats and failures.

To date, the United States has few advanced control room R&D facilities equipped with full-scope plant simulators, and human performance monitoring systems. The most notable are the INL's Human System Simulation Laboratory (HSSL), and the CAER's INCONTROL reconfigurable main control room simulation facility. Outside the U.S., the most prominent facility for conducting human performance and human-machine interface (HMI) research is the Halden Man-Machine Laboratory (HAMMLAB) at the OECD Halden Reactor Project (HRP) in Norway. The CAER's INCONTROL facility aims to complement the capabilities of HAMMLAB and SSL and add research capacity to investigate technology design and regulatory matters associated with nuclear power plant (NPP) control rooms that could be validated with the CAER-IST. Such facilities are invaluable in the U.S. for enabling applied research input to the technical basis for technology design and regulatory guidance in areas such as alarm systems, control room design, display navigation, and human performance. INCONTROL, coupled with SSL and HAMMLAB also provide platforms for comparative testing of new digital technologies as well as resiliency research of digital platforms performing same or similar computing and control functions.

While the HSSL and HAMMLAB are supporting basic research in these I&C cross-cutting technology areas, currently there is no CPS test bed to advance and demonstrate research conclusions. With design and operational flexibility built into the CAER-IST and the INCONTROL, resilience tests could be conducted by defining scenarios from sets of tiered challenges and tracking various diagnostic measures. Such challenges would include both human- and hardware-in-the-loop issues. Resulting insights are expected to have a "cross-cutting" connection to PRA that could support decision-making on topical issues such as post 60 year lifetimes, emergency planning zone sizing, multiple-unit siting, etc.

As with the Focus Area 1 discussion, the following cooperative research opportunities reflecting workshop participant's immediate I&C interests and requiring minimal modification to the IST and INCONTROL were advanced:

- Rulemaking and licensing support for digital I&C systems. Utilize current quality program and quality instruments to vet new I&C platforms.
- Control system anomaly detection (e.g., control system operational and security techniques, strengthen resiliency, etc.). Includes development of metrics for resiliency and evaluation of techniques using a simulator and the CAER cyber-physical system.
- Level measurements capable during operation and accident scenarios, incorporating Fukushima scenarios (sensing lines evacuated, etc.) to test new, mitigating technology.
- Level instruments for SMR applications (integral design requiring minimal or no protrusions, water submerged, etc.) verified against traditional measurements.
- Embedded I&C to improve component performance, evaluation of component response during operational and accident scenarios.
- Integration of operations technology concept for remote, real-time data evaluation by industrial experts to reduce staffing loads at NPP sites.

## Day 1 Closeout / Day 2 Restart

At the conclusion of Day 1, a brief review of the day's accomplishments was provided. Regarding the need for data, DOE-NE's Consortium for Advanced Simulation of Light Water Reactors (CASL) and the Light Water Reactor Sustainability (LWRS) programs have noted that to resolve remaining thermal-hydraulic and process control uncertainties, such as those appearing in **Table 1**, data is needed over the spectrum of integral, component and process scales, re-inspiring the need for a large-scale test facility.

**Table 1**. Process-Scale Thermal-Hydraulic Phenomena Important to Safety and Performance

| **Fluid-dynamic** | **Heat transfer** |
|---|---|
| Pressure loss | Forced convection |
| Turbulence and Mixing | Natural convection |
| Thermal stratification | Mixed convection |
| Flow Instabilities | Radiation |
| Flow regimes and interfacial area evolution | Conduction |
| Interphase forces | Two-phase evaporation and condensation |
| Entrainment | Boiling |
| Cavitation | Thermal striping |
| Flow-induced vibration | |

Capability to study process-scale phenomena and qualify advanced sensors and instrumentation at conditions aligning with LWRs addresses only part of the power system technology deployment challenge. Practical demonstration of power plant control and, thus, safety requires a complete assessment of thermal-hydraulic process uncertainties, including the role of automation and manual control. Resolution of process-scale uncertainties requires fine control of conditions influencing the measures revealed by instrumentation. As assessment includes verification and validation, demonstration of derived regulatory evaluation methodologies requires capability to manufacture conditions representative of design-basis or beyond-design-basis events.

Regarding testing, an insight drawn from the Day 1 discussion was that a crucial part of roll out of technology is demonstration. Specifically, a pilot-scale CPS is necessary to show functionality / proof-of-concepts beyond basic science level. Notably, no domestic, public domain pilot-scale test bed exists to support thermal-hydraulic and advanced I&C concepts. Recently, a survey was completed of compiling information about existing university-based thermal-hydraulic facilities. **Table 2** was prepared following the workshop as an action item to better characterize existing thermal-hydraulic test beds in the U.S. The information appearing in the report is presented against a typical pressurized water reactor and the CAER-IST.

**Table 2.** Overview of University LWR Thermal-Hydraulic Test Facilities

| **Test Facility** | **Typical PWR** | **IST** | **UCLA** | **CCNY** | **Florida** | **Maryland** | **MIT** | **Ohio State** | **Oregon State** | **Penn State** | **Purdue** | **Texas A&M** | **Wisconsin** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water? | | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Transient Mode? | | Y | N | Y | N | N | Y | N | Y | Y | N | N | Y |
| Power, kW | | 1800 | 125 | | | | 1 | | 400 | 750 | 45 | | 200 |
| Pressure, MPa | 17 | 17 | 50 | 1.2 | 0.15 | 0.1 | 1 | 0.1 | 11.4 | 0.55 | 1.0 | 0.1 | 25 |
| Temperature, °C | 330 | 343 | 500 | Amb | Amb | 100 | 180 | 90 | 330 | 154 | 180 | Amb | 600 |
| Flow, kg/s-m$^2$ | 2200 | 2426 | 7300 | pool | | pool | 3000 | 1500 | 2000 | 200 | 200 | | 2000 |

Workshop Day 2 was restarted with a review of the day's agenda and focus topics (see "Day 2 Workshop Information") .

## Focus Area 3: Novel Applications of the CAER-IST as a Cyber-Physical System Platform

Building on the previous day's discussions assessing thermal-hydraulics and I&C testing, workshop participants were asked to characterize the concept of CPS for nuclear application-oriented frameworks. Focus Area 3 leaders provided a presentation (see "Novel Applications of the IST") emphasizing the importance of a balanced R&D plan within the strategic direction of the DOE and other R&D investors and highlighting that a primary objective of current DOE-sponsored R&D are the next generation safety analysis codes under the CASL and LWRS programs (e.g., RELAP7). Notably, mission success will not only be measured by predictive capability but also by enabling simulations for supporting engineering decision-making.

Such research requires a CPS like the CAER-IST complemented by INCONTROL, one characterized by physical hardware coupled with control and data acquisition systems that can be used for verification, validation and uncertainty quantification (VVUQ). Subsequent demonstration of the predictive maturity of new analysis capability relies on derived experimental data to bridge computer models to physical processes. A unique focus area of contemporary VVUQ R&D is the characterization of probabilistic aspects of complex systems. Related analysis involves data of a different nature, e.g., reliability of systems, structures, and components, and human actions. Integration of probabilistic and mechanistic simulations, including treatment of aleatory and epistemic uncertainty, is being pursued in the Risk-Informed Safety Margin Characterization (RISMC) / RELAP7 project in the LWRS program. Realism in this setting serves a primary role in associated decision-making settings that require more than that traditionally informed by computer simulation. **Figure 1** illustrates the necessary CPS domain.

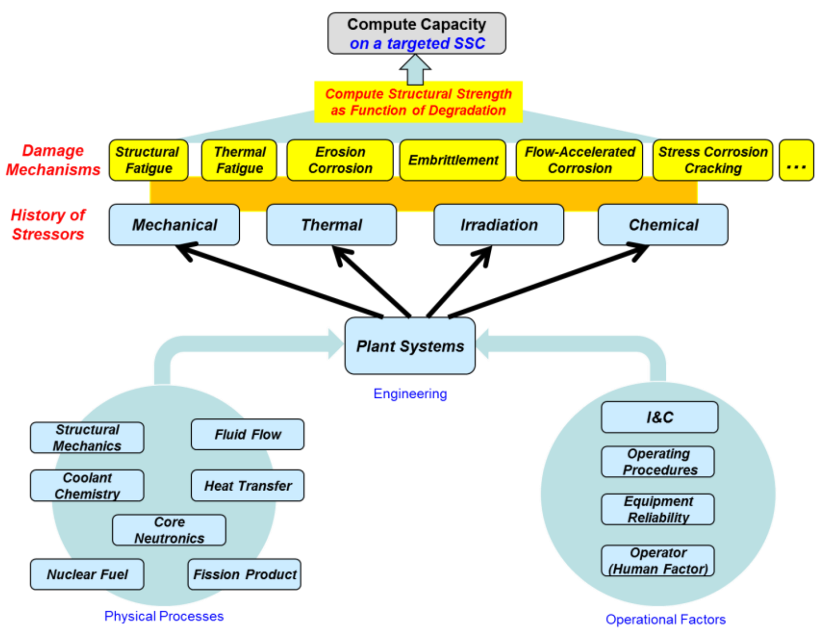


**Figure 1.** Nuclear power plant as a cyber-physical system

With a pilot-scale CPS, like the CAER-IST, related operations issues such as the assessment of age-related stressors (such as those appearing in **Figure 1**), the demonstration of "inherent security" and validation of emergency operating procedures and severe accident management guidelines, can avoid the uncertainty associated virtual emulations (i.e., computer codes), which is the current practice. V&V in these areas may rely more on confidence-building exercises rather than conformance to strict quantitative measures.

There remains a major lack of relevant experimental data, especially when it comes to validation of models for integral-effect, multi-physics and process-scale phenomena. Further, the VVUQ value of previous experiments is diminished by scaling distortion and incomplete characterization of data uncertainty. In particular, in a special issue of “Science and Technology of Nuclear Installations” reporting on an OECD-NEA program involving the benchmarking of subchannel analysis codes (e.g., COBRA) characterizes this gap with following statement:

> *“Of note also is the relative scarcity in the literature of experimental data covering heat transfer, critical heat flux, and local subchannel void fraction distribution for full-scale assemblies under the same thermalhydraulic conditions as a PWR and utilizing water.”*

New code development seeks predictive capability at or below this scale of resolution. Only a large-scale VVUQ platform using known I&C technologies and advanced sensors will be able to provide the necessary realism for VVUQ on multi-physics analysis software such as RELAP7 and simulation tools created under the CASL program. Whereas such tools may be currently too immature to fully benefit from such data, the long-lead times required to make the requirements for such data is motivation for the immediate establishment of such a test bed.

In the U.S. the most advanced facility available for this purpose is the Rod Bundle Heat Transfer facility at Penn State, which is only capable of operation below 5.5 bar. An international workshop participant mentioned that outside the U.S. a consortium network entitled Significant Light & Heavy Water Reactor Thermal-Hydraulic Experiments Network for the Consistent Exploitation of the Data (SILENCE) is the principal working group coordinating efforts among owners of various thermal-hydraulic test beds to support similar R&D. SILENCE[3] currently has nine members, with access to long-standing and highly-regarded facilities such as the PKL in Germany and ATLAS in South Korea. As a DOE-sponsored user facility, the CAER-IST would be a natural additional to SILENCE.

Another workshop participant suggested that a valued form of engagement with this international community would be to host an experiment to serve as the next International Standard Problem (ISP). ISPs are traditionally sponsored by OECD/NEA. There has not been a thermal-hydraulic related ISP in several years. As useful exercise capable of serving both an ISP objective and the national R&D objective for generating data in a manner mirroring computer code development and modeling might involve the particular challenge of integrating 0-D, 1-D and 3-D models. For the CAER-IST multi-dimensional representation would require an engineered replacement for the five-foot section above the heater region designed specifically for this investigation. Other active thermal-hydraulic investigations being considered by the international community include collaborative counter-part testing, loss-of-coolant-accident initiated severe accidents (inspired by the Fukushima event), load follow or grid disturbance scenarios, and some non-nuclear applications.

Given the cross-cutting nature of the CAER-IST as a CPS, engagement with DOE’s NEET program was recommended. The coordination of diverse disciplines remains a major objective, which is reflected in evolution of this young program to date. Notably, it has little experience working with industry; however, the 2015 research solicitation is recognizing industry contributions.

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[3] SILENCE appears to be a reformation of the OECD/NEA Working Group on Analysis and Management of Accidents (WGAMA), which has been relatively inactive since 2008.

## Focus Area 4: Integrated Testing Processes / Licensing

Whereas the previous focus areas encouraged deep-dive discussion on specific R&D activities and logistics, the emphasis in Focus Area 4 was on the role of CPS R&D in policy-making and licensing (no formal presentation accompanied this discussion). Among the many missions of the DOE-NE is to promote industry sustainability through the reduction of uncertainties related to nuclear power plant safety and security. Management of those uncertainties through the application of the technology is the role of the regulator. For highly regulated industries, the success of any new technology is correlated with rapid licensing action. As such, the nation's nuclear power industry, supported by scientists and engineers residing at national laboratories and universities, receives tangible benefits from evolving processes and methodologies more so than disruptive technologies requiring extensive regulatory review. Coincident with safety and security enhancements, the industry has extended operational and lifetime performance of the existing fleet of nuclear power plants and revealed insights for next generation designs.

Several examples of current licensing challenges were mentioned, including safety-related digital I&C, evaluation methodologies updates, new plants, PRA, HRA and cyber security. Despite decades of engagement between the industry and regulator, the regulatory path for these issues appears to be in a continuous state of change. A few examples were mentioned where existing regulatory guidance imposes unnecessary limit, such as conventional-LWR-specific rule language. Some workshop participants noted that leadership in resolving these issues is worked through subcommittees established by the Nuclear Energy Institute (NEI) that meet as-needed with similar teams at the U.S. Nuclear Regulatory Commission (NRC). Progress tends to be slowed by large utility sensitivity to changes that might dismantle past practice. Further, with the current fleet of commercial power plants nearing the end of their planned lifetimes, industry investment in new technology has little chance of returning a substantial benefit.

Accepting that there are many players in cyber security regulations, the discussion was narrowed toward identifying high impact HRA and cyber security R&D and implementation methods – particularly that regarding consequences of highly automated SMRs with monitoring and even remote control operation. Being the least developed (among the candidates mentioned previously) with respect to regulatory opinion, the evolution of cyber security issues have the highest potential benefit from ongoing R&D. It was noted that coincident with this workshop, the International Atomic Energy Administration was sponsoring their first "International Conference on Computer Security Conference" in Vienna, an acknowledgement of the evolving interest in this and related issues.

Workshop participants then turned their attention to assessing the current R&D and regulatory framework to implement HRA and cyber-security ideas. It was acknowledged that the DOE NEET program specifically targets this question; although, there is parallel attention at the National Science Foundation, Department of Homeland Security, and the DOE Office of Science. Regardless, progress appears to be still at the idea stage. As an emerging science, there does not appear to be an established path for providing technical basis for HRA and cyber rule making. For example, consensus on requirements, acceptance criteria and a set of useful measures remains to be resolved. The NEI/NRC engagement has resulted in proposed guidelines. The release of NRC RG 5.71 in 2010 and a recent update to RG 1.152 captured existing position.

The review of sponsorship and development of HRA and cyber-security R&D led to a tangential discussion on technology readiness. As explained by one of the Focus Area 4 leaders, the primary challenge of advancing research through the various technology readiness levels (TRL) appears after the laboratory benchtop testing and prototyping stages, a so-called "valley of death" for many projects. The unique integration of nuclear, thermal, hydraulic, mechanical, chemical, vibrational, and structural loads characteristic of production-scale systems is often inaccessible at the laboratory-scale. The DOE-NE has characterized nine stages of technology development in their Technology Readiness Assessment Guide (DOE G 413.3-4A, see http://www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf). The early stages (TRL 1-3) of technology readiness include the idea and "proof of concept" stages. The latter stages (TRL 7-9) are the realm of demonstration, commercialization and regulation. Eroding the natural inertia between the early and late stages is the principal challenge of technology transfer.

With this framework, workshop participants considered categorization of the CAER assets. As previously acknowledged, the CAER-IST is a pilot-scale facility, firmly residing at TRL 6. The INCONTROL laboratory is not at the stage. To characterize the asset gap, workshop participants reviewed a generic HRA and cyber-security framework by beginning with the question of how can threats (either intentional or human performance) affect the physical system. Since public safety is the principal objective, existing safety measures and criteria are well established; however, it is the human- and hardware-in-the-loop role that defines the interface between human reliability and cyber security to the safety objective. A laboratory such as INCONTROL, outfitted with audio-video recorders, wearable eye-trackers, and wireless physiological monitors, synchronized with a data integration and analysis software application, seeks to optimize both automation and the HMI and, in doing so, aid in establishing associated regulatory guidance.

With respect to existing CAER assets, workshop participants with INCONTROL experience offered that a component missing from at the CAER that could take it to TRL 6 is a cyber-lab for adapting a cyber-security infrastructure. The cyber-lab design begins with people with expertise on computer/software vulnerability and related automation/control hardware/software. Further, it could serve as the principal means to couple INCONTROL and the IST. The envisioned cyber-lab could then provide an environment to explore the characterization, design, implementation, and safety of using computation, networks, software, embedded microprocessors, sensors, and robotics to link production and manufacturing assets with industrial control systems, enabling businesses to more efficiently manage physical systems. For example, this is the idea behind General Electric's "Industrial Internet" that has the goal of making industrial machines smarter, through the adoption of sensors, software and big data analytics.

To closeout this focus area, workshop participants expanded on the potential for this platform by returning to some of the challenged areas mentioned at the start of the discussion, in particular, digital I&C and PRA. For these issues, V&V is process-oriented, with common cause failure & cyber-security being significant hurdles. Advanced sensor, signal processing, and automation R&D appear to have the greatest potential in reducing uncertainties associated with anticipated threats and failures. As demonstrated in other industries, real progress is being done in the field. Consequently, a hardware interface between CAER-IST and INCONTROL via such a cyber-lab should be a goal.

## Focus Area 5: Cost-effective R&D of the CAER-IST and Workshop Closeout

As led by workshop organizers, the last focus area addressed the funding model to support the CAER-IST and INCONTROL facilities (presentation content appears as part of "Day 2 Workshop Information"). The financing model has gone through a significant evolution, beginning as a university consortium managed asset. Through the sponsorship of several information meetings, culminating in this workshop, the CAER will be proposing to the DOE through its response to DOE RFI DE-SOL-0008318 that its IST and INCONTROL facilities be established as a NSUF. It is envisioned that research, development, and demonstration efforts would be overseen by a Research Control Board. This would be comprised of DOE-NE, national laboratory, university, industry and international research partners.

The control board would develop the research strategy, approve modifications to the facility, and communicate with NSUF leadership and direct CAER staff. Subsequently, the CAER staff will be responsible for operations, maintenance, modification, testing and engineering support of the facility. Tests for research partners will be conducted by trained and qualified CAER personnel in accordance with test requirements and test matrices provided by research partners.

Since the facility is already available, investment by the DOE-NSUF program would support staff and operating expenses. Experiments by research partners would be funded by public and private sources. Typical expenses would address researcher time and materials and test-specific costs such as electricity and unique facility modification costs. **Figure 2** shows how the proposed user facility would be organized.

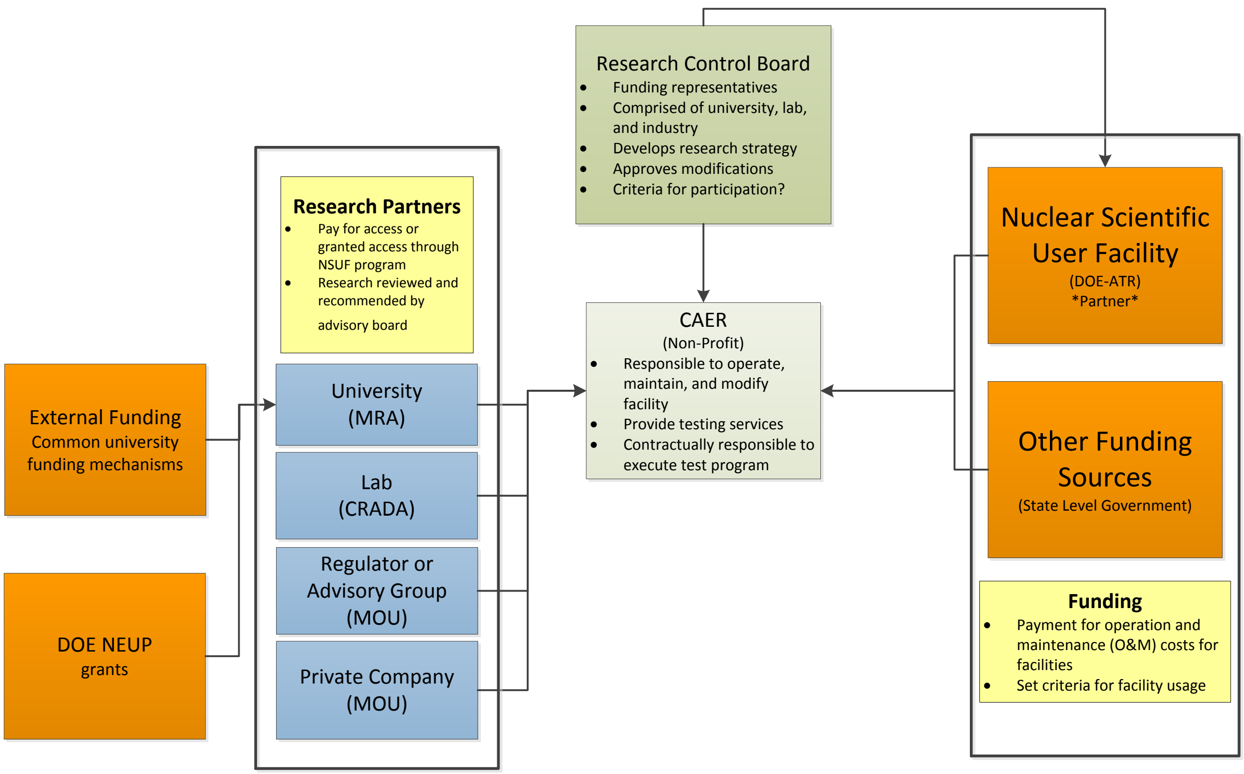


**Figure 2. Proposed Funding Model.** Model highlights synergy between research partners, CAER & DOE-NE

The IST and INCONTROL have been constructed, tested, and proven operable at high levels. This substantially reduces the cost and schedule for the capabilities. The start-up cost and duration can be evaluated and documented based on experience of operation and usage therefore eliminating first of a kind schedule and cost uncertainties associated with new platforms. Although the systems and equipment are complex, they are well documented from instrument output to data storage. The flow of data, known as the IST "data-stream" has been fully characterized in accordance with NQA-1 requirements (Figure 3).

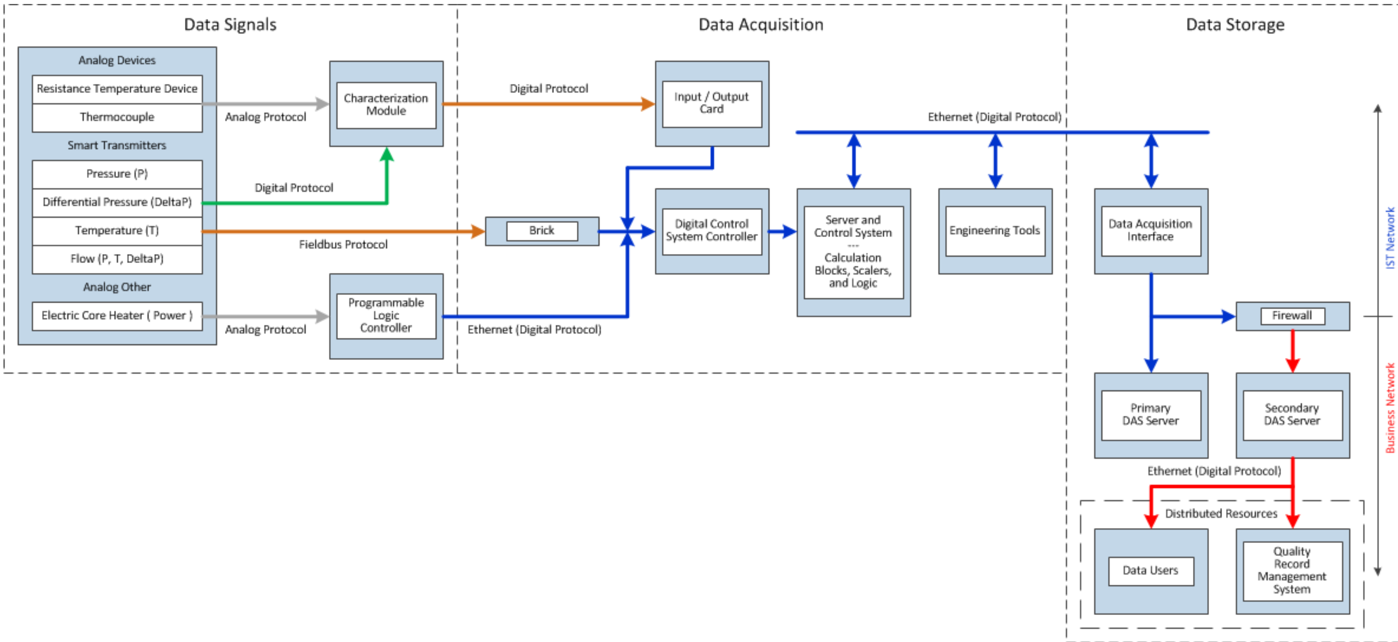


**Figure 3. Integrated System Test Facility Data-Stream**

The CAER facility exists so construction costs are not required. An enduring mortgage to the DOE-NE is not required, nor do the facilities carry any debt. Only operational (including staffing) and maintenance costs are required. Proposed modifications can be funded by complimentary programs such as NEET, nuclear energy university program (NEUP), research councils United Kingdom energy programme (RCUKEP), and traditional university funding mechanisms as part of the costs to conduct research.

The funding strategy was well received by workshop participants, noting that this is similar to the ATR at the INL and the HFIR at Oak Ridge National Laboratory.

A couple short-comings were noted by workshop participants 1) the IST is a water loop (interest is high for gas or molten salt concepts) and 2) detailed attributes of the IST would need to be made available to universities so they can hone their R&D ideas.

## Summary and Conclusion

The principal conclusion from the two-day workshop was the identification of several national R&D infrastructure gaps. The perceived gaps are—

- the incompleteness and inconsistency of the existing thermal-hydraulic database required for continued modeling and simulation improvements;
- full-range qualification testing platform for advanced sensors and instrumentation;
- fine and programmable system control providing simultaneous resolution of process and phenomenological uncertainties; and
- validation platform for regulatory evaluation methodologies.

To efficiently leverage previous DOE-NE technology successes, a pilot-scale CPS capable of replicating the design and operation of existing and proposed new reactors is required to overcome these gaps. The CAER-IST and INCONTROL facilities offer a readily available asset being offered to thermal-hydraulic and I&C/HMI communities.

It's in the U. S. national best-interest to support and sustain the current generation of plants through improvements in reliability, safety, and lifetime issues. In particular, sustainability of an aging nuclear industry requires attention to immediate industry needs that improve their ability for expedited licensing. The lack of access to test beds like the CAER-IST and INCONTROL is preventing innovative solutions from realizing their full potential, which must be demonstrated under conditions applicable to their envisioned applications to ensure safety and reliability in nuclear reactors. The CAER-IST test bed, in particular, is a one-of-a-kind facility capable of supporting both fundamental, separate-effects thermal-hydraulic research and to a fully functional pilot plant for demonstrating operational performance of maturing technology for commercialization. Public investment in the CAER-IST and INCONTROL promises to bridge the existing gulf between laboratory inspiration and industrial innovation.

# *CAER-IST Workshop Agenda June 4-5, 2015*

**Day 1: June 4th 11:00-4:00**

**Meet and Greet, Lunch: 11:00- 12:30**

Workshop Introduction, Doug Lee, B&W mPower

CAER introduction, Bob Bailey, CAER Director

INCONTROL, Nathan Lau, Human Factors Engineer, CAER

IST introduction, Joe Miller, B&W mPower

Computer Code Modeling, Erik Nygaard, B&W mPower

Thermal Hydraulic Research and Scaling Background at IST, Bob Martin, B&W mPower

**Focus Area 1, Lead: Joe Miller, Erik Nygaard** – Integrated Testing Concept: LWR / SMR Operational testing **(12:30-2:00)**

- *How would the RD&D activities at CAER help resolve technical challenges thus enabling the deployment of new reactor technologies and promote LWR / SMR Technology? Improve existing technologies?*
- *What instrumentation, test assemblies, and/or inspection equipment could be installed in the 5' spool piece directly above the electrically heated core? What analysis would be associated with its installation?*
- *What instrumentation, test assemblies, and/or inspection equipment could be installed in the 5" blind flange in the spillover area above the steam generator and below the pressurizer? What analysis would be associated with its installation?*

**Focus Area 2, Lead: Carl Elks, Yang Liu** – Instrumentation and Controls, Cross Cutting Technology **(2:10-4:00)**

- *What potential advanced sensors and instrumentation could be installed for testing that would improve physical measurement accuracy of nuclear system process parameters and minimize uncertainty?*
- *What types of control system setup could be created and tested to increase plant safety?*
- *Identify and conduct research into monitoring and control technologies, including human factors, to achieve control of new nuclear energy processes, and new methodologies for monitoring to achieve high reliability and availability.*

**IST, I&C LAB and INCONTROL Tour (4:00- )**

**Day 2: June 5th 10:00 – 1:30**

**Focus Area 3, Nam Dinh, Xiaodong Sun** – Novel Applications of the CAER IST as a Cyber-Physical System Platform (**10:00-11:00)**

- *What technologies exist at universities, national laboratories that, if adapted to the CAER IST, would make a significant and favorable impact? Alternatively, what technologies could the CAER IST be adapted to in order to make a significant and favorable impact?*
- *What are the biggest obstacles or unique challenges in adopting the CAER IST to envisioned technology R&D (e.g., thermal-hydraulics, advanced M&S, digital I&C, etc.)?*

**Focus Area 4, Dan Cole, Bob Martin** – Integrated Testing Processes / Licensing **(11:00-12:00)**

- *What Thermal-Hydraulic research platforms could exist at the IST and how would this research be used to further current R&D projects?*
- *How could INCONTROL and IST enhance communications and data transmission needed for digital technologies, their licensing and regulatory qualification, and security issues?*
- *How can the IST be used to streamline regulatory rulemaking?*

**Lunch / Break (12:00-12:30)**

**Focus Area 5, Doug Lee, Bob Bailey** – Cost-effective RD&D at the CAER **(12:30-1:15)**

- *What are attributes to a cost-effective use of the CAER IST as a R&D user facility?*
- *What are the most effective programmatic arrangements to achieve initiatives established in the focus areas discussed?*
- *What physical attributes are necessary to minimize the cost of R&D at the CAER IST? How could the CAER IST be best managed for efficient conduct of R&D?*

**Summary and Close-out – Final review of input (1:15-1:30) – Doug Lee**

**Post-workshop tours, further small-group discussions 1:30 - (B&W and CAER staff)**