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Optical Measurement Technologies for High Temperature, Radiation Exposure, and Corrosive Environments—Significant Activities and Findings

In-vessel Optical Measurements for Advanced SMRs

PICS WP# SR-12PN050207

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September 2012

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Optical Measurement Technologies for High Temperature, Radiation Exposure, and Corrosive Environments—Significant Activities and Findings

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1.0 Introduction

Development of advanced Small Modular Reactors (aSMRs) is key to providing the United States with a sustainable, economically viable, and carbon-neutral energy source. The aSMR designs have attractive economic factors that should compensate for the economies of scale that have driven development of large commercial nuclear power plants to date. For example, aSMRs can be manufactured at reduced capital costs in a factory and potentially shorter lead times and then be shipped to a site to provide power away from large grid systems. The integral, self-contained nature of aSMR designs is fundamentally different than conventional reactor designs. Future aSMR deployment will require new instrumentation and control (I&C) architectures to accommodate the integral design and withstand the extreme in-vessel environmental conditions. Operators will depend on sophisticated sensing and machine vision technologies that provide efficient human-machine interface for in-vessel telepresence, telerobotic control, and remote process operations. The future viability of aSMRs is dependent on understanding and overcoming the significant technical challenges involving in-vessel reactor sensing and monitoring under extreme temperatures, pressures, corrosive environments, and radiation fluxes.

Based on a long history of success in other applications, it is likely that optical sensing technology can play an enabling role in future aSMR designs. The nuclear power industry I&C needs have largely been met by existing technology and the demand for specialized optical-based I&C systems has been modest. The new design architectures of aSMRs are likely to change this trend. New optical-based I&C systems are likely to evolve from prior technology, as well as follow a revolutionary design path; however, significant challenges lie ahead to realize the benefit potential of optical-based Instrumentation, Control, and Human-Machine Interface (ICHMI) systems for this application.

The scope of our effort will establish the preliminary requirements and assumptions for ICHMI systems for the leading aSMR designs. Important measurement parameters for aSMRs include thermal power, temperature, pressure, coolant inventory, coolant level/flow, and neutron flux, as well as component and coolant failure monitoring. The technical readiness of commercial off-the-shelf (COTS) optical-based sensing and monitoring technologies will be determined and gaps established. Our study results will provide input to help guide the R&D program phase, which will be required to address technology gaps and develop optical-based ICHMI systems that are broadly applicable to Generation IV (Gen IV) aSMRs. R&D could lead to important advancements in optical-based ICHMI that improve the viability and deployability of future aSMRs. Both engineering concepts and innovative technology R&D solutions will be required to reach this objective. Engineering concepts, such as optical ports for reactor vessels, will be developed to enable standoff optical measurements (possibly using modestly modified COTS systems) such that equipment is protected from the in-vessel environment. Innovative R&D will be used to adapt current optical measurement techniques for in-vessel deployment and develop or identify the potential for new sensing methods and advanced optical materials. Innovative R&D of this nature could lead to significant technology advancements, such as advanced optical materials that have prolonged damage resistance to high temperature, radiation, and corrosive environments, and new optical system designs and techniques for remote inspection, system control, and process monitoring. Innovative R&D requires a longer-term investment, consistent with the planned aSMRs development timetable, while promising engineering concepts may provide near-term opportunities to fast track evaluation and field trial studies.

This report summarizes the information survey approach and significant findings obtained during the first quarter of this project (July 23 to September 28, 2012) and outlines future study (planned in FY2013) to determine and address the optical-based ICHMI technology gaps.

2.0 Research Methods

A project team was assembled to include experienced laser and optics, nuclear engineering, and technical library staff. A wide array of in-house resources and external resources has been reviewed to survey aSMR design details, ICHMI requirements, and optical-based COTS technology. The in-house resources include the Hanford Technical Library and leveraging the abilities of its research librarians, consulting resident nuclear engineering experts at PNNL, searching the archives of the fast flux test reactor (FFTF), and exploiting synergies of relevant research at PNNL, which includes other aSMR projects. External resources included both key word and category searches in electronic journals and other databases, as well as consulting with external experts and organizations. The database survey used keywords designed to retrieve documents on a very broad range of topics, including ICHMI used in LWRs, design and operational characteristics of SMRs and aSMRs, optical materials for harsh environments, and design of optical sensors for parameters pertinent to nuclear power plants, as well as optical components and technologies from other harsh environment industries such as magnetic confinement fusion research (i.e., International Tokamak Physics Activity), oil drilling, foundries, and aerospace technology industries. These efforts resulted in a large body of documents that we were able to use to refine our search techniques. These searches yielded a significant number of journal articles (on the order of 150 and counting), which are currently being organized into categories based on reactor type, measurement type, instrument technology, and fundamental optical research direction. These are being sorted and entered into commercial bibliography software (Endnote) for future reference purposes. About 20 to 30 references discuss optical materials in extreme environmental conditions (radiation, temperature, and pressure). Roughly 20 additional articles focus on optical-based sensing and measurement of neutron flux, temperature, and pressure. Some of these articles discuss the optical sensor development for extreme environment applications, but this appears to be an under-researched category. Additional focused Gen IV reactors queries produced many papers and reports that discuss aSMR designs specifically, operational concerns, and less frequently, aspects of I&C. Publicly available government reports and documents have also been an extremely important resource specific to nuclear reactor designs and I&C. Several NUREG documents published by the U.S. Nuclear Regulatory Commission provide useful I&C information. Several reports produced by Idaho National Laboratory and Oak Ridge National Laboratory contain useful Gen IV reactor design information. Subject matter experts at some of the national laboratories and industry have been contacted. This effort has led to ongoing dialogue and the pursuit of non-disclosure agreements as needed to promote collaborative information sharing.

3.0 Significant Activities and Findings

In this section we report a brief summary of the FY2012 significant activities and findings in bulleted format. A summary of the preliminary aSMR design survey is provided in Section 3.1. Gen IV aSMR designs were evaluated, as well as relevant information from earlier generation reactor designs. Key reactor process monitoring and measurement parameters are summarized in Section 3.2. Prominent aSMR ICHMI measurement applications are also listed. Section 3.3 provides an outline of our COTS optical technology survey. Advanced optical materials and coatings, which could enable future deployment within high temperature, corrosive, and radiation environments, are presented in Section 3.4. A synopsis of optical measurement systems and aSMR applications, and important aSMR ICHMI engineering concepts to enable standoff optical measurements, are found in Sections 3.5 and 3.6, respectively.

3.1 aSMR Design Query

- A preliminary background review of the six key Gen IV aSMR designs (gas-cooled reactors, very high temperature reactors, lead-cooled reactors, sodium fast reactors, molten salt reactors, and supercritical water reactors) was conducted and the unique in-vessel conditions have been summarized in tabular format.
- A preliminary review of I&C sensor systems used in integral pressurized water reactors (iPWRs) has been conducted to baseline requirements and techniques that potentially could be extended to future aSMR designs, given engineering or scientific advancements needed to adapt or extend current performance.
- Many of the I&C sensor systems used in Gen II reactors are the same (or very similar to) technologies as those being adapted for use in modular Gen III+ reactors under development by NuScale, Westinghouse, B&W, and others. It follows that these systems and techniques could be extended to future aSMR designs, given engineering or scientific advancements needed to adapt or extend current performance.
- Supercritical water, gas cooled (fast and thermal), and molten salt reactors are likely to be the best candidates for optical-based ICHMI systems because of the largely transparent optical nature of the cover gases and coolant media, and the requirements to monitor parameters below the coolant, near the core. Optical-based ICHMI systems have minimal impact to liquid metal cooled reactors because of the optically opaque coolant. However, headspace process monitoring and refuel activities could benefit from optical ICHMI solutions.
- Optical sensing methods and systems have been reported in the literature for the primary list of reactor ICHMI requirements; however, for the most part, their application under harsh aSMR environments has not been evaluated.

3.2 aSMR ICHMI Measurement Parameters and Applications

Future aSMR designs will include thousands of sensors for reactor process monitoring, predictive maintenance, diagnostics, telepresence, telerobotic control, and remote process operations.

- Key ICHMI measurement parameters include:
  - Neutron flux
  - Temperature
  - Pressure
  - Flow

  - Liquid level
  - Contamination
  - Coolant level
  - Mechanical integrity
- Important aSMR measurement and monitoring applications include:
  - Coolant linear/volumetric flow rates
  - Coolant temperature levels (in-core, at core inlet/outlet, coolant loops, gas head-space)
  - Primary/second coolant loop cross-contamination detection
  - Headspace gas contamination monitoring
  - Sodium-cooled reactor rotating plug monitoring
  - Coolant impurity monitoring (e.g., oxygen in helium-cooled reactors, water vapor in gas- and salt-cooled reactors)
  - Cherenkov radiation monitoring to measure fission rates
  - Visual telepresence, telerobotic human machine interface processes
  - Mechanical crack and porosity monitoring
  - Mechanical vibration monitoring
  - Vessel and coolant-line pressure monitoring
  - Graphite dust monitoring (particle counting) in pebble-bed reactors
  - Power and temperature distribution anomaly monitoring
  - Component deformation and failure monitoring

3.3 Commercial-of-the-Shelf Investigation

- Several companies, including Luna Innovations, have been identified as important sources of expertise and technology relative to high-temperature or radiation-resistant optical devices. A non-disclosure agreement negotiation has been initiated with Luna to gain access to propriety sensor performance data.
- A list of commercial optical equipment/camera vendors targeting the nuclear power market has been drafted (and updated as needed). Diakont, Mirion/IST, and Ahlberg have been contacted for input.

3.4 Advanced Optical Material and Coatings

- High temperature optical material
  - Common commercial optical materials (except fused quartz (silica glass) and some single crystals such as sapphire) have glass transition temperatures or melting points lower than 1000°C. Some glass groups have optical transparency in the mid- and long-wave infrared and therefore are useful for thermal imaging and thermography applications. Many infrared optical materials have unsuitable glass transition temperatures, such as chalcogenide glass (glass transition temperatures

  at 200–400°C). Other materials become optically opaque at high temperature, such as germanium. As a result, they may not be suitable for use in high-temperature aSMR environments.

  - Optical materials data suggest that high-purity silica glass is a good candidate for high-temperature applications. Pure silica glass has a glass transition temperature above 1200°C and is transparent from UV to 3 μm in wavelength. It can be pulled into optical fibers and is insoluble in water near room temperature. However, silica becomes soluble as the temperature and pressure increases (i.e., in supercritical water-cooled reactor environments) and it is reactive to molten alkaline solution, so protective coatings are needed when used in liquid-metal cooled reactors. Dopants are added to pure silica glass to optimize the optical and mechanical properties, but this usually reduces the glass transition temperature.
  - Single crystal scintillators such as BaF_2, BGO, and $PbWO_4$ are typical high-temperature materials. Scintillators are used to convert high-energy particles, ions, or gamma radiation to UV/visible light. If the fluorescent or luminescent light is filtered, they can also be used as optical windows because of their broadband optical transmission in visible and near IR wavelengths. BaF_2 cleaves easily, so it may not have enough mechanical strength for this application.

- Radiation-resistant optical material and coatings
  - Almost all commercial optical glasses, except high-purity silica, are subject to radiation-induced darkening through color center formation and subsequent increases optical absorption at the visible wavelengths (~400–700 nm).
  - Commercial silica optical fibers are also subject to radiation darkening due to the dopants added during the manufacturing process and likely other factors.
  - The dose level threshold to trigger darkening in high-purity silica has not yet been uncovered in our survey to date.
  - The mechanism responsible for radiation-induced darkening is the creation of “non-bridging oxygen hole centers” (NBOHC).
  - The fundamental absorption frequency for the NBOHC is at 610 nm, with overtones at 660 nm and 760 nm.
  - The NBOHC process can be mitigated using a pre-irradiating phase and “hydrogenising” treatment. Adding hydrogen to the glass network creates hydroxyl groups that prevent the formation of NBOHCs. The associated absorption of hydroxyl group now occurs in the near infrared at 1.38 μm, rather than at visible wavelengths.
  - All radiation-darkening effects surveyed in the current literature review were studied at temperatures less than 100°C. It has been reported that transparency in radiation-darkened glass can be recovered by thermal annealing at temperatures near 400°C.
  - It was reported that radiation-induced absorption decreases as the operation temperature increases. These results suggest that further study should be directed at high-temperature annealing (self-healing) of radiation-darkened glass.
  - UV laser photo bleaching of glass or doping of glass with Ce may also reduce radiation-darkening effects.

  - It is possible that radiation-induced darkening can be sidestepped by using optical wavelengths distant from the color center absorption band. The absorption of 1550-nm light has been reported to be orders of magnitude lower than in the visible.
  - Metallic coatings (such as Cr and Al), some dielectric coatings (Ta_2O_5 and SiO_2), and some optical epoxy (Norland NOA 61) are resilient against radiation damage at extreme doses.
  - Fusion science programs have developed optical mirrors that have excellent radiation resistance properties. These metallic mirrors are made of stainless steel, or polycrystalline or single crystalline materials like molybdenum, tungsten, or nanocrystalline films on metal substrates such as molybdenum and rhodium.
  - Dielectric protection films such as ZrO2 were also demonstrated to survive high radiation exposures.
- Protective coatings
  - Aluminum nitride is an effective coating to protect metal and optical substrates from mechanical wear, as well as corrosion. AlN is resistant to most salt baths, even at elevated temperatures; however, it can undergo phase transformation at high temperatures and pressures. AlN also has a high transmission from 300 nm to greater than 900 nm.
  - Tungsten, nickel, and aluminum are also used as protective coatings for optical fibers to improve mechanical strength and decrease thermal stress.
- Photonic bandgap fibers
  - The radiation-resistance properties of photonic bandgap optical fibers are currently under investigation by a number of research groups. Photonic bandgap optical fibers can be made with a hollow core and intricate hole patterns surrounding the core, which control the mode propagation properties. Radiation damage is reduced because the light propagates through air and not within the optical material.

3.5 Optical Instrumentation

- Optical sensors to detection contaminants and impurities in the coolant will be important to control impurity-induced corrosion.
- Fiber optic-based sensor systems will be useful for monitoring in-vessel I&C parameters if the high-temperature and radiation-damage limitations can be resolved.
- Fiber optic-based borescopes will be useful for monitoring in-vessel crack, porosity, and other visual measurements, if the high-temperature and radiation-damage limitations can be resolved.
- Laser ultrasound can inspect for mechanical integrity such as cracks or component weakening using acoustic and resonant analysis.
- Video and still image cameras will be important for in-vessel diagnostics, characterization, and human-machine interface monitoring during reactor operation, telerobotic manipulations, and refueling processing. Engineering solutions to enable in-vessel ICHMI will be required to enable remote, external to the vessel, positioning of the system hardware.
- Remote laser techniques can be used to determine coolant levels.

- Laser-induced breakdown spectroscopy (LIBS) could be used for element composition and microstructure characterization.
- Among these technologies, fiber optic temperature sensors are perhaps the most mature. Measurements that can typically be made with fiber optics sensors are pressure, flow, acoustic emission, blast waves, strain, temperature, displacement, acceleration, and radiation dose. Fiber optic systems compatible with temperatures up to 450°C are commercially available. Limited research has been conducted to advance the high-temperature and radiation performance of optical fiber systems.
- The presence of water vapor in gas and sodium reactors could pose a serious threat to reactor safety; therefore, water vapor sensors could be an important optical focus.
- In pebble bed reactors, the rapid flow of graphite pebbles can produce graphite dust contamination; therefore, particle counting optical sensors could be an important focus.
- The rotating shield plug in some sodium-cooled reactor designs could be monitored remotely with camera systems.
- Continuous monitoring of headspace gas composition in liquid-cooled metal reactors could be useful for online diagnostics to detect water vapor and impurities.

3.6 Important aSMR ICHMI Engineering Concepts

- In-vessel optical ports: Allows remote viewing of in-vessel environment using external COTS optical systems. Will require careful placement and selection of window materials. Optical windows will require extended resistance to corrosion, high temperature, and radiation exposure.
- Optical/mechanical seals: Robust optical/mechanical seals designed for large thermal excursions, thermal gradients, pressure differentials, and corrosion resistance.
- Standpipe optical port designs: Standpipe port designs will reduce thermal and radiation exposure and coolant condensation and corrosion effects. This approach may provide access via existing instrumentation access ports. May allow optical access to difficult-to-reach areas like lower plenum.
- High radiation-resistant first-surface relay mirrors: First-surface mirrors that provide free-space optical paths for remote sensing. Possibly leverage fusion science R&D or develop new optical materials through R&D efforts.
- Periscope concepts for core imaging and sensor pod designs: Periscopes and sensor pod designs will allow in-vessel core instrumentation and process monitoring. These concepts may provide solutions to the problems associated with line-of-sight imaging systems (optical line of sight will otherwise coincide with gamma ray line-of-sight). Mechanical designs must maintain precise optical alignment under large temperature ranges and mechanical disturbances from flow and vibration. Engineering solutions for in-vessel designs will require experienced mechanical engineering staff.

4.0 Summary

This report summarizes the information survey approach and significant findings obtained during the first quarter of this project (July 23 to September 28, 2012). We have made good progress at establishing the preliminary requirements and assumptions for ICHMI systems for the leading aSMR designs. Review of COTS technology and establishing collaborative partnerships with industry and other national laboratories is underway. Key optical-based ICHMI applications have been established and will be updated, as new aSMR design information is uncovered. Initial aSMR ICHMI engineering concepts are under consideration for future development.

This investigation effort will continue during FY2013 and lead to identifying technology gaps in the areas of advanced optical materials, component designs, sensing systems, and relevant optical-based ICHMI systems. Our study results will be documented to support planning the R&D program phase, which will be required to address technology gaps and develop optical-based ICHMI systems that are broadly applicable to Generation IV aSMRs. Preliminary engineering concepts will be developed to enable standoff optical measurements, such that equipment is protected from the in-vessel environment. Advanced optical sensing materials and concepts will be prototyped and evaluated under simulated conditions (high temperature, high radiation) in the lab during out-year investigations.

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