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The Advanced Test Reactor Irradiation Capabilities Available as a National Scientific User Facility

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The Advanced Test Reactor irradiation capabilities available as a national scientific user facility

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Abstract

The Advanced Test Reactor (ATR) is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. The ATR is a very versatile facility with a wide variety of experimental test capabilities for providing the environment needed in an irradiation experiment. These capabilities include simple capsule experiments, instrumented and/or temperature-controlled experiments, and pressurized water loop experiment facilities. Monitoring systems have also been utilized to monitor different parameters such as fission gases for fuel experiments, to measure specimen performance during irradiation. ATR's control system provides a stable axial flux profile throughout each reactor operating cycle, and allows the thermal and fast neutron fluxes to be controlled separately in different sections of the core. The ATR irradiation positions vary in diameter from 16 mm to 127 mm over an active core height of 1.2 m. This paper discusses the different irradiation capabilities with examples of different experiments and the cost/benefit issues related to each capability. The recent designation of ATR as a national scientific user facility will make the ATR much more accessible at very low to no cost for research by universities and possibly commercial entities.

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1. Introduction

The Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL) is a valuable resource available for use in developing the materials and fuels necessary to support the next generation reactors and advanced fuel cycles. The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. The ATR core is completely replaced every 7 to 10 years, with the last replacement having been completed in January 2005. In addition, the ATR reactor vessel is constructed of solid stainless steel and is located far enough away from the active core that neutron embrittlement of the vessel is not a concern. These two major factors, combined with a very proactive maintenance and plant equipment replacement program, have resulted in the ATR operational life being essentially unlimited. The ATR has a maximum power of 250 MW and can provide maximum thermal neutron fluxes of 1E19 neutrons/m^2-second and maximum fast (E >1.0 MeV) neutron fluxes of 5E18 neutrons/m^2-second. This allows considerable acceleration of accumulated neutron fluence to materials and fuels over what would be seen in a typical power reactor.

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These fluences combined with the 77 irradiation positions varying in diameter from 16 mm to 127 mm over an active core height of 1.2 m make ATR a very versatile and unique facility.

The ATR core cross section consists of 40 curved fuel elements configured in a serpentine arrangement around a 3 by 3 array of prime irradiation locations in the core termed flux traps (see Fig. 1). The flux traps derive their name from the high-intensity neutron flux that is concentrated in them due to the close proximity of the fuel and the materials used in these "traps". The ATR's horizontal rotating control drum system provides stable axial/vertical flux profiles for experiments throughout each reactor operating cycle unperturbed by the typical vertically positioned control components. This stable axial flux profile, with the peak flux rate at the center of the core, allows experimenters to have specimens positioned in the core at different known flux rates to receive a range of neutron fluences during the same irradiation periods over the duration of the test program. This control system also allows the reactor to operate different sections of the core at different power levels. The ATR core is divided into five different operating lobes: the four corner lobes and the center lobe. Each lobe of the reactor may be operated at a different power level (within specific limitations) during each reactor cycle.

2. Experiment types

Three major types of irradiation testing are employed in the ATR. The simplest and least expensive type is a static sealed capsule with only passive instrumentation. The next level of complexity in testing includes active instrumentation for measurement and/or control of specific testing parameters, typically temperature and/or pressure. The last and most complex method is the pressurized water loops that are connected to in-pile tubes located in the flux traps. Each of these irradiation types and their relative cost, schedule and operation differences are discussed in detail in the following sections.

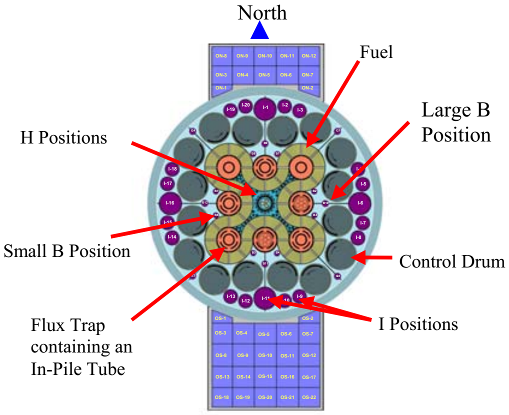

Fig. 1 ATR core cross section

2.1. Static capsule experiments

Static capsules experiments are self-contained (typically) sealed experiment encapsulations containing the irradiation specimens in an inert gas environment. However, occasionally the capsules are not sealed but allow the experiment specimens to be in contact with the reactor primary coolant to prevent excessive temperatures during irradiation. Static capsules may include passive instrumentation such as flux wires for neutron fluence monitoring and/or melt wires for temperature monitoring during irradiation. In addition, the temperature of a static capsule may also be controlled, within limits, by incorporating a small insulating gas jacket (filled with an inert gas) between the specimens and the outside capsule wall or pressure boundary. A suitable gas jacket width can usually be developed through iterative reactor physic and thermal analyses to provide the irradiation temperature desired by the experiment customer. The gas jacket is determined based upon the gamma and reaction heating characteristics of the specimens and capsule materials and proper selection of the insulating gas.

The static capsules may vary in length from several centimeters to full core height of 1.2 meters. They also may vary in diameter from 12-mm or possibly less for the small irradiation positions (or a portion of an irradiation position) to more than 120-mm for the larger irradiation positions. The capsules are typically constructed of aluminum or stainless steel, but zircaloy has also been utilized. Depending upon the contents and pressure of the capsule, a secondary containment may be necessary to meet the ATR safety requirements. The capsules are normally contained in an irradiation basket, which radially locates the capsules in the irradiation position and vertically positions them within the ATR core. Occasionally due to space limitations, a static capsule has been used to also serve the function of the basket, but in these cases, the capsules must fill the entire irradiation height and have a similar handling feature at the top of the capsule for installation and removal from the core.

The benefits of utilizing static capsules for irradiation testing include the ease of insertion into and removal from the reactor vessel to support specimen or capsule replacements or to avoid one of ATR's short high power cycles. This ease of insertion and removal can also be utilized to shuffle (or vertically relocate) capsule experiments within the irradiation position during reactor outages to even out fluences or fuel burn-up between different irradiation specimens. One last benefit of the ease of insertion and removal is the ability to possibly move the capsules to a higher power irradiation location to compensate for fuel burn-up and maintain the desired temperatures during the overall irradiation campaign.

Static capsules are less expensive than the other types of irradiation testing and due to their simplicity; they require the least amount of time to initially get the experiment into the reactor. However, static capsule testing has less flexibility and control of operating parameters (such as specimen temperatures) during the irradiation and greater reliance is made on the design analyses since passive instrumentation can only provide snap shot values of the operating parameters during irradiation (i.e. a melt wire can provide the maximum temperature attained during an irradiation but not the amount of time or when the maximum temperature was achieved).

2.2. Instrumented lead experiments

The next level of complexity in testing incorporates active instrumentation for continuous monitoring and/or control of certain experiment parameters during irradiation. These actively monitored and controlled experiments are commonly referred to at ATR as instrumented lead experiments, deriving their name from the active instrument leads (such as thermocouples or pressure taps) that they contain. An instrumented lead experiment containment is very similar to a static capsule, with the major difference being an umbilical tube connecting the experiment to a monitoring and/or control system outside of the reactor vessel. The umbilical tube is used to house the instrument leads (thermocouples, pressure taps, etc.) and temperature control gas lines (if utilized) from the irradiation position within the reactor core to the reactor vessel wall. The instrument leads and gas lines are then routed outside the reactor vessel to the control and data collection/monitoring equipment. An instrumented lead experiment may contain several vertically stacked capsules, and each experiment is specifically designed to meet the experimenter's needs. This is accomplished by selecting a suitable irradiation position, which will provide the necessary gamma and/or reaction heating as well as the total neutron fluence within the available schedule, and then designing the experiment capsule(s) and umbilical tube routing necessary to connect the experiment to the reactor vessel wall.

The most common parameter to be monitored and controlled in an instrumented lead experiment during irradiation is the specimen temperature. The temperature of each experiment capsule is independently controlled by varying the thermal conductivity of a gas mixture in a very small insulating gas jacket between the specimens and the experiment containment. This is accomplished by blending a conductor gas with an insulator gas. Helium is used as the conductor gas and neon is typically used as the insulator gas. However argon has also been used as an insulator gas (with helium as the conductor) when a larger temperature control band is needed or when the activity from the activated argon gas (Ar-41) does not affect the experiment data collection (i.e. monitoring of the experiment temperature control exhaust gas for fission gases, etc.). During normal operation, the gases are blended automatically to control the specimen capsule temperature based upon feedback from the thermocouples. The computer controlled gas blending system permits a blend range of 0 to 98% of the insulator gas to maximize the temperature control range for the experiments.

Temperature measurements are typically taken with at least two thermocouples per capsule to provide assurance against an errant thermocouple and to also provide redundancy in the event of a thermocouple failure. The control system also provides automatic gas verification to assure the correct gas is connected to the supply ports in the system to prevent an uncontrollable temperature excursion resulting from a gas supply mix-up (i.e. insulator gas connected to a conductor gas port or vice versa). Monitoring of the temperature control exhaust gas is quite common to sense for different materials as a measure of the specimen performance or experiment conditions. There are several options available for monitoring that have been employed on previous experiments conducted in the ATR. The most common monitoring has been for fission gases in fueled experiments to monitor fuel performance during irradiation. However, other monitors have also been utilized such as a gas chromatograph to monitor for chemical changes in an experiment cover gas due to oxidation of the specimens, and monitoring for supplemental gases to detect leakage through a test barrier during irradiation. Alarm functions are provided to call attention to circumstances such as temperature excursions or valve position errors. A helium purge to each individual specimen capsule is automatically actuated in the unlikely event of the ability to measure or control the temperature is lost. In order to minimize response time between a gas mixture change and a change in temperature in the experiment specimens, the gas system maintains a continuous flow to the experiment through very small internal diameter tubing. Manual control capability is provided at the gas blending panels to provide a helium purge of the experiment capsules in the event of a computer failure. Data acquisition and archive are also included as part of the control system function. Real time displays of all temperatures, gas mixtures, and alarm conditions are provided at the operator control station. All data are archived to removable media, with the data being time stamped and recorded from once every ten minutes to as often as once every ten seconds. The control processor will record these values in a circular first-in, first-out format for at least six months.

The benefits of performing an instrumented lead experiment are more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the temperature control exhaust gas to establish specimen performance during the irradiation. However, this type of experiment has the detriments of higher total experiment costs and a longer lead time to initially get an experiment into the reactor than a static capsule experiment. There are also higher costs and risks associated with removal and re-installation of an instrumented lead experiment in the reactor for specimen replacements or to avoid a short high power ATR operating cycle.

2.3. Pressurized water loops

Five of the ATR flux traps contain In-Pile Tubes (IPT), which are connected to pressurized water loops. The other four flux trap positions currently contain capsule irradiation facilities, and have also contained lead experiments as mentioned above. An IPT is the reactor in-vessel component of a pressurized water loop, and it provides a barrier between the reactor coolant system water and the pressurized water loop coolant. Although the experiment is isolated from the reactor coolant system by the IPT, the test specimens within the IPT are still subjected to the high intensity neutron and gamma flux environment of the reactor. The IPT extends completely through the reactor vessel with a closure plug and seal at the reactor's top head, while loop coolant flow enters and exits the IPT through the reactor bottom head. This allows the top seals of the IPT to be opened and the experiment to be inserted or removed. The experiments are suspended from the top closure plugs using a hanger rod, which vertically positions the experiment within the reactor core and provides an exit pathway for test instrumentation leads. Anything from scaled-down reactor fuel rod bundles to core structural materials can be irradiated in these pressurized water loops. Each IPT is connected to a separate pressurized water loop, which allows material or fuel testing at five different pressure, temperature, flow rate, water chemistry, and neutron flux rate combinations (dependent of the location within the ATR core) with only one reactor. The loops are connected to a state-of-the-art computer control system, which monitors, controls, and provides emergency functions and alarms for each loop. The system controls all aspects of loop operations (flow, pressure, and temperature) for all five loops simultaneously.

There are two Powered Axial Locator Mechanism (PALM) drive units that can be connected to specially configured tests in the pressurized water loop facilities so that complex transient testing can be performed. The PALM drive units move a small test section from above the reactor core region into the core region and back out again either very quickly, approximately 2 seconds, or slowly depending on test requirements. This process simulates multiple startup and shutdown cycles of test fuels and materials. Thousands of cycles can be simulated during a normal ATR operating cycle. The PALM drive units are also used to precisely position a test within the neutron flux of the reactor and change this position slightly as the reactor fuel burns.

The benefits of performing a pressurized water loop experiment are (as with the instrumented lead experiments) more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the loop water chemistry to establish specimen performance during the irradiation. However, this type of experiment has the detriments of the highest total experiment costs and the longest lead time to initially get an experiment into the reactor.

3. Experiment examples

The following sections provide several examples of the different types of experiments conducted in the ATR. Unfortunately, an example of a pressurized water loop experiment was not available; however examples of a static capsule and a lead experiment are provided.

3.1. Advanced fuel cycle initiative and Gen IV gas fast reactor irradiations

The Advanced Fuel Cycle Initiative (AFCI) is currently irradiating different fuel types in the East Flux Trap of the ATR, and plans to continue to irradiations for at least several more years. The fuel is being irradiated in static capsule type experiments, consisting of short internal capsules (called rodlets – see Fig. 2) containing the fuel specimens. The rodlets are filled with sodium to provide good heat transfer and temperature equalization within the capsule and fuel. An inert cover gas plenum is also included in the top of the rodlet to provide room for swelling and collection of any fission gas releases. Several rodlets are loaded in an outer capsule with a precisely designed gas gap between the rodlets and the capsule wall. The gas gap is filled with a suitable gas to control the heat transfer from the rodlets to the capsule wall and on to the ATR primary coolant, which determines and controls the temperatures within the rodlets. The capsules are loaded into an open top basket that positions the capsules in the proper vertical location within the selected position of the East Flux Trap (seven positions are available in the East Flux Trap). Since the experiments are being conducted in one of the high thermal flux positions of ATR and have a maximum linear heat generation rate similar to existing power reactors, a cadmium lined basket is utilized to reduce the thermal flux and therefore reduce the fission rate in the fuel. This approach also increases the fast to thermal flux ratio to a more representative value of future fast reactors.

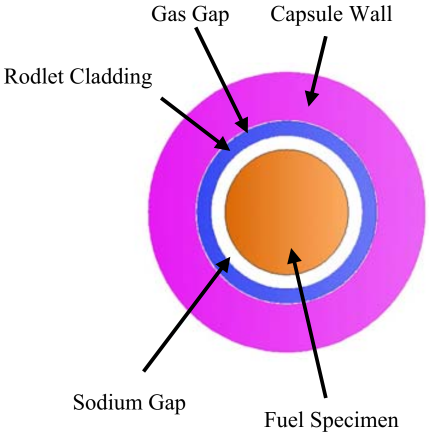

Fig. 2 AFCI capsule cross section

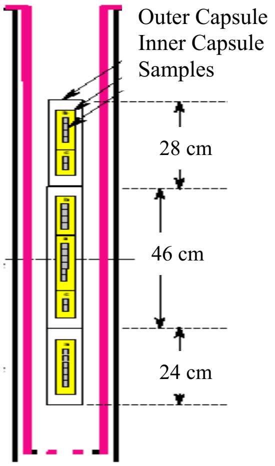

Fig. 3 GFR basket elevation

The Generation IV Gas Fast Reactor (GFR) program is utilizing the same hardware and approach used in the AFCI irradiations to irradiate materials being considered for the GFR type reactors (see Fig 3). The major differences between the AFCI and the GFR experiments are the heat source and heat transfer medium in the capsules. Since the GFR capsules only contain structural materials and no fuel, the main heat source in the GFR experiments is gamma heating of the materials in contrast to the AFCI irradiations where the main heat source is neutron reaction heating in the fuel. Therefore, the GFR irradiations utilize a gas or gas mixture inside the rodlet instead of sodium as a heat transfer medium in order to attain the desired temperature in the specimens. The GFR irradiations share not only the experimental hardware configuration, but they are also irradiated in the ATR East Flux Trap irradiation position. Future GFR fuel irradiations are also planned for the ATR along with future AFCI irradiations.

3.2. Advanced gas reactor fuel experiments

The DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is currently irradiating gas reactor particle fuel in the ATR in support of the DOE Next Generation Nuclear Plant program. The design of the first experiment test train, temperature control gas system modifications, and fission product monitors for this irradiation program were completed in 2005, and the first experiment (designated AGR-1) was inserted in the ATR core in December 2006. A horizontal cross-section of one of the six capsules in the experiment test train is shown in Fig. 4.

Eight different fuel irradiations are planned (Petti et al. 2005) for the program, with the first experiments being irradiated in the large (38 mm diameter) B positions. The test train for AGR-1 consists of six separate capsules vertically centered in the ATR core, each with its own custom blended gas supply and exhaust for independent temperature control. Each of the six capsules is approximately 35 mm in diameter and 130 mm long, and contain 12 prototypical fuel compacts approximately 12.5 mm in diameter and 25 mm long. The fuel compacts are made up of 780 μm diameter TRISO-coated fuel particles, graphite and a binder to hold the compacts together. The compacts are arranged in four layers in each capsule with three compacts per layer nested in a triad configuration. A nuclear grade graphite spacer surrounds and separates the three fuel compact stacks in each capsule and also provides the inner boundary for the insulating gas jacket. The graphite spacer also contains boron carbide as a consumable neutron poison to limit the initial fission rate in the fuel, providing a more consistent fission rate/power production during the planned two-year irradiation.

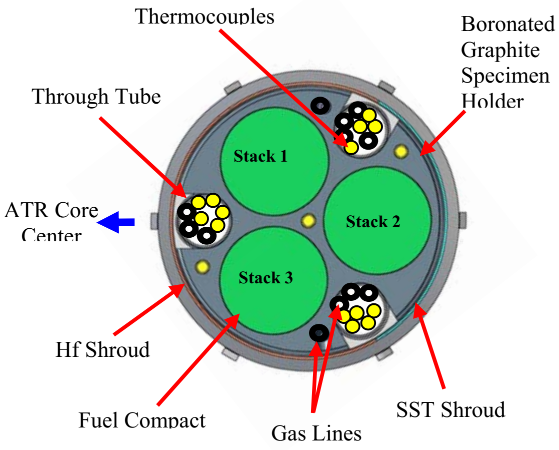

Fig 4 - AGR Capsule Cross-Section

In addition to the boron carbide in the graphite, a thin hafnium shroud is located around the outside portion of the capsule located toward the center of the ATR core to provide additional neutron absorption and provide more control of the experiment fission rate. As the boron carbide is completely consumed in the graphite, the fission rate in the fuel actually reaches a peak at about mid-point of the irradiation. Controlling and somewhat flattening the fission rate in the early portion of the irradiation provided better control of the temperatures in the fuel over the irradiation period, especially at the end of the long irradiation.

The Large B positions were chosen due to their neutron energy spectrum being very similar to the spectrum anticipated in the high temperature gas reactors as well as the flux rates in these positions would provide the AGR irradiations with an irradiation acceleration factor of approximately 1.5. This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough as to avoid possible premature particle fuel failures similar to those experienced in earlier highly accelerated particle fuel tests. Of course the length of irradiation was ultimately determined by the fuel burn-up or Fissions per Initial Metal Atom (FIMA) requirement established by the AGR Fuel Development and Qualification Program.

In addition to the acceleration factor, other precautions were required to prevent possible premature fuel particle failures including preventing the fuel compacts from contacting with each other in the radial direction (only axial contact was allowed) or allowing the fuel to contact any material other than graphite and the inert temperature control gas.

In addition to protecting the fuel, the graphite specimen holder has machined features to accommodate the thermocouples for measuring temperature within the capsule and for three tubes that provide a pathway for gas lines and thermocouples to the lower experiment capsules. The placement of the three tubes was also utilized to center the graphite holder in the capsules and space it at the proper distance from the capsule wall to provide the necessary gas jacket for temperature control. There are typically three thermocouples in each capsule located in the top, middle, and bottom of the graphite holder to measure temperatures during irradiation. However, the top capsule has five and the bottom capsule has only two thermocouples due to space limitations. The thermocouples could not have direct contact with the fuel since attaching or touching the fuel with thermocouples could induce fuel particle failures. Therefore, the thermocouples measure the graphite temperature, and the corresponding fuel temperatures are calculated. Flux wires were also installed in the capsules to measure both the thermal and fast neutron fluences.

Gaseous fission products are the most common isotopes monitored in fuel lead experiment temperature control exhaust gases, and these experiments are no exception. The outlet gas from each capsule is routed to an individual fission product monitor with the capability to be rerouted to an online spare if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors include a High Purity Germanium (HPGe) spectrometer for identifying specific fission gases and a gross gamma (sodium iodide crystal scintillation) detector to provide indication when a small cloud or wisp of fission gases passes through the monitor. This small cloud or wisp of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification of the specific isotopes, the spectrometer can be used to determine the birth to release ratio of the fission gases being detected. This determination can establish whether a new TRISO fuel coating failure has occurred or if the fission gases are merely being released from an existing failure or possibly tramp contamination on the outside surface of the fuel particles. These details can be very important in the qualification of fuel especially in small TRISO particle fuels, where a few random particle failures are anticipated and need to be tallied very accurately to support statistical qualification of the fuel. By utilizing the combination of a spectrometer and a gross gamma detector and having both items monitoring continuously on-line, the gross gamma detector results can be scanned quickly to establish which portions of the voluminous spectrometer data need to be closely scrutinized.

4. National scientific user facility designation

The ATR was designated a National Scientific User Facility (NSUF) by the U.S. Department of Energy (DOE) in April 2007. The concept for the user facility is to provide broader and easier access as well as additional support for use of the ATR by experimenters from universities, government and industry. In addition, access to the Hot Fuels Examination Facility (HFEF) located at the INL was included as part of the NSUF experiments to provide post irradiation examination of the ATR irradiation experiments. Under the NSUF designation, the ATR and HFEF facilities, as well as the necessary user support, will be provided at either no or very little cost to experimenters performing non-proprietary work.

The pilot process for selecting the first group of experiments for the NSUF program during the U.S. government fiscal year 2008 (October 1, 2007 to September 30, 2008) was initiated in November 2007. The process was started by issuing a solicitation for experiments, which included well defined criteria for the experiment proposals to ensure the research would benefit the DOE and the nuclear industry. The experiments were to be led by universities, and teaming between universities and possibly industry partners was encouraged in the solicitation. The program schedule called for the experiments to be completed within a three year time frame, including the post irradiation examination, but the experiments could be considered for renewal after conclusion of the initial three years if the technical merit of the experiment and results warrant additional research.

The proposals for the experiments were due in January 2008, and were subjected to several reviews including an independent peer review that included reviewers from both academia and industry. The criteria for the reviews included technical feasibility, scientific merit, and resources and capabilities of the experimenter group. Based upon these reviews, four experiments were selected to be performed under the NSUF program and are currently in the early planning phase.

The current plan for the NSUF is to incorporate lessons learned from the first round of experiment selection, and issue yearly solicitations for new experiments. A summer school will also be conducted annually at the INL to provide information and knowledge to potential interested NSUF experimenters that will assist them in identifying research opportunities and preparing successful proposals for the ATR NSUF program.

5. Conclusion

The ATR has a long history in fuel and material irradiations, and will be fulfilling a critical role in the future fuel and material testing necessary to develop the next generation reactor systems and advanced fuel cycles. The capabilities and experience at the ATR, as well as the other test reactors throughout the world, will be vitally important for the development of these new systems to provide the world with clean safe energy supplies in the future. In addition, the recent designation of the ATR as a National Scientific User Facility will make the ATR more accessible for experimenters to utilize this resource in meeting the future plans of the nuclear industry.

Acknowledgement

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