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SAFETY ASSURANCE FOR ATR IRRADIATIONS

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1. Introduction

The Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL) is the world's premiere test reactor for performing high fluence, large volume, irradiation test programs. The ATR has many capabilities and a wide variety of tests are performed in this truly one of a kind reactor, including isotope production, simple self-contained static capsule experiments, instrumented/actively controlled experiments, and pressurized water loop testing. Along with the five pressurized water loops, ATR may have gas (temperature controlled) lead experiments, fuel boosted fast flux experiments, and static sealed capsules all in the core at the same time. In addition, any or all of these tests may contain fuel or moderating materials that can affect reactivity levels in the ATR core. Therefore the safety analyses required to ensure safe operation of each experiment as well as the reactor itself are complex. Each test has to be evaluated against stringent reactor control safety criteria, as well as the effects it could have on adjacent tests and the reactor as well as the consequences of those effects. The safety analyses of each experiment are summarized in a document entitled the Experiment Safety Assurance Package (ESAP). The ESAP references and employs the results of the reactor physics, thermal, hydraulic, stress, seismic, vibration, and all other analyses necessary to ensure the experiment can be irradiated safely in the ATR. The requirements for reactivity worth, chemistry compatibilities, pressure limitations, material issues, etc. are all specified in the Technical Safety Requirements and the Upgraded Final Safety Analysis Report (UFSAR) for the ATR. This paper discusses the ESAP process, types of analyses, types of safety requirements and the approvals necessary to ensure an experiment can be safely irradiated in the ATR.

2. ATR core configuration and experiment types

A cross section of the ATR core showing the experiment irradiation locations is shown in Figure 1. The ATR includes 40 fuel elements arranged in a serpentine configuration, which results in 9 neutron "flux traps" arranged in a 3 x 3 array. Five of the nine flux traps (designated in Figure 1 as NW, N, W, SE, and SW) are currently used for Pressurized Water Loop (PWL) experiments. The remaining four flux traps are currently used for either static capsule experiments or instrumented lead experiments. Other irradiation positions within the flux trap regions are designated as inboard and outboard "A" and "H" positions. Additional irradiation positions lying outside of the flux trap regions include the "B" and "I" positions (inside of the core tank) and the outer north and south irradiation tanks. The ATR control system includes 16 vertical control drums (outer shim control cylinders in Figure 1) that rotate neutron poison/reflector materials toward or away from the reactor core. This system provides a constant neutron flux profile symmetric about the horizontal mid-plane of the core throughout each reactor operating cycle and over the duration of experiment programs requiring years of irradiation. Other control components in the core region include 22 neck shim rods, 2 regulating rods, and 6 safety rods. Experiments are required to not interfere with the normal operation of these control elements. The temperature and void reactivity coefficients are negative in the ATR fuel and reflector areas but are generally positive in the flux trap regions. Safety assurance reactivity issues, for example, can be quite different for experiments, depending on the locations of the experiments and experiment design details.

Three major types of irradiation experiments are performed within the irradiation positions in the ATR core. The simplest and least expensive type is a static capsule with only passive instrumentation. Static capsule experiments are (typically) self-contained sealed experiment encapsulations surrounding the irradiation specimens with 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. These capsules typically include passive instrumentation (e.g. flux wires, melt wires for temperature monitoring, etc.) as well as possibly passive temperature control through the use of a small insulating gas jacket (filled with an inert gas) between the specimens and capsule wall.

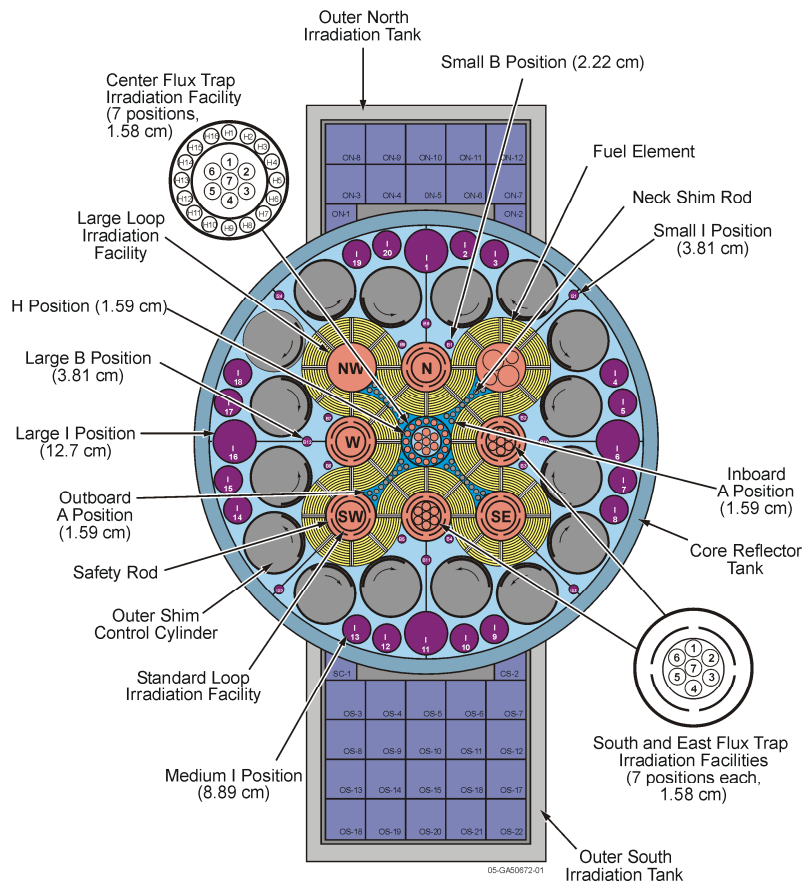


Figure 1 ATR Core Cross-Section

The next level of complexity in testing incorporates active instrumentation for continuous monitoring and control of certain experiment parameters during irradiation. These actively monitored and controlled experiments are commonly referred to 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 control system outside of the reactor vessel that provides active monitoring and control of experiment parameters (e.g. temperature, pressure, etc.) during irradiation. The umbilical tube is used to house the instrument leads (thermocouples, pressure taps, etc.) and temperature control gas lines from the irradiation position within the reactor core to the reactor vessel wall.

The last and most complex method is accomplished in the PWLs, which are connected to an In-Pile Tube (IPT). An IPT is the reactor in-vessel component of a PWL, and it provides a barrier between the reactor coolant system water and the PWL 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 closure plugs and seals at the reactor's top and bottom heads. This allows the top seals to be opened and each experiment to be independently inserted or removed. Each IPT is connected to its own PWL that provides the specific water temperature, pressure, flow rate, chemistry, etc. required for the experiment.

3. Experiment safety assurance package and the experiment safety assurance process

The ATR has many capabilities and a wide variety of experiments are performed in it, and therefore the safety analyses required to ensure safe operation of each experiment, as well as the reactor itself, can be complex. The analyses applicable to the safety of each experiment are summarized in a packet referred to as the "Experiment Safety Assurance Package" (ESAP). The ESAP addresses the reactor physics, thermal, hydraulic, stress, seismic, vibration, radiological, and all other analyses necessary to ensure the experiment

can be irradiated safely in the ATR. The requirements for reactivity worth, chemistry compatibilities, pressure limitations, material issues, etc. are specified in the ATR Technical Safety Requirements (TSR) and the Upgraded Final Safety Analysis Report (UFSAR) for the ATR. Each applicable requirement in these documents is addressed in the ESAP, and supporting documentation (i.e. analyses, evaluations, etc.) is referenced to demonstrate how the experiment complies with the requirement. If necessary, mitigating features such as reactor power limitations, additional safety systems, double encapsulation design, etc. must be provided to reduce the consequences of any postulated accidents to acceptable levels and therefore ensure safe irradiation of the experiment in the ATR. The ESAP is prepared and then submitted for several levels of review and approval prior to the project being granted permission to insert the experiment in the reactor. The following sections provide a description of the process utilized at the INL to assure the safe irradiation of the experiments within the ATR.

3.1 General safety analysis considerations

The current ATR safety basis establishes the risk envelope for operating the reactor, including operation of the experiments within the reactor. General safety analysis considerations must therefore include recognition that postulated reactor accidents can impact an experiment and conversely, postulated experiment accidents can impact the reactor. Postulated experiment accidents must, whether or not they impact the reactor, exhibit consequences within the risk envelope for the reactor. A proposed experiment that would be outside of the existing reactor risk envelope would require a change to the ATR safety basis. A change to the ATR safety basis to expand the risk envelope would require review and approval by the United States (US) Department of Energy. Not all conceivable experiments can be described in the reactor safety basis and therefore, as part of the experiment safety assurance process, each experiment is assessed relative to the risk envelope for the reactor per the US Code of Federal Regulations (CFR) for Unreviewed Safety Questions (USQ). 10 CFR 830 contains the requirements for USQs, and requires application of the USQ process in situations where there is a “test or experiment not described in the existing documented safety analysis” [1]. The current ATR safety basis has been developed to provide flexibility in being able to accommodate a variety of experiments. Part of this flexibility has been achieved by defining several “Plant Protection Criteria” that must be satisfied during the irradiation of an experiment, and a fundamental function of the ESAP is to demonstrate compliance to the Plant Protection Criteria. These criteria limit direct radiological consequences and potential damage to plant barriers that prevent or mitigate radiological releases. The criteria are divided into four categories (Condition 1, 2, 3, and 4) that address a range of conditions from normal operational events to extremely unlikely faulted conditions. They are abbreviated, for illustrative purposes, as follows:

- Condition 1 (Normal operation) – Radiation exposure limits of: 1.00 mSv/year effective dose equivalent (EDE) and 0.10 mSv/year EDE from airborne release to off-site public and 0.05 Sv/year total effective dose equivalent (TEDE) to workers. Reactor fuel source term protection limit: The integrity of the reactor fuel cladding is not challenged except for limited clad defects.
- Condition 2 (Anticipated faults) – Radiation exposure limits of: 5 mSv /year TEDE to off-site public and 50 mSv/year TEDE to workers. Reactor fuel source term limit: No rupture of the reactor fuel plate cladding is allowable unless the clad failure is the initiating fault. For canal accidents no melting of the fuel plate cladding is allowed.
- Condition 3 (Unlikely faults) – Radiation exposure limits of: 62.5 mSv whole body and 0.75 Sv thyroid dose to off-site public and evacuating workers (excluding personnel considered directly at the location of the accident). Reactor fuel source term limit: No large releases of uranium or fission products to the reactor primary coolant system will occur.
- Condition 4 (Extremely Unlikely faults) – Radiation exposure limits of: 0.25 Sv whole body and 3.00 Sv thyroid dose to off-site public and evacuating workers (excluding personnel considered directly at the location of the accident). Reactor fuel source term limit: The reactor primary coolant pressure boundary must be maintained (unless this failure is the initiator) and the reactor confinement must not be damaged.

The predominant risk associated with the ATR is the radiological source term confined within the reactor fuel. The ATR safety basis includes a comprehensive set of accident analyses that include different reactor fuel-related releases. Since most individual experiments include relatively small radiological source terms

relative to that represented by the ATR core, it is often possible to demonstrate compliance to the Plant Protection Criteria by making simple fissionable material mass comparisons between the two.

3.2 Safety assurance throughout all experiment phases

A total safety culture demands safety assurance throughout all experiment phases. The experiment irradiation phase generally represents the greatest risk; however, other phases must not be overlooked. Experiment components often include fissionable materials that must be stored and handled during experiment fabrication or assembly. The associated fabrication or assembly may take place in a facility or location outside the ATR and therefore be subject to a different safety envelope. Criticality safety issues need to be addressed during assembly as well as storage of experiments containing fissionable materials. Post-irradiation conditions can also present unique safety issues that must be addressed. Adequate post-irradiation cooling of experiments is a typical issue for consideration, both for experiment storage and experiment shipping. In a general sense, experience has proved the necessity of a procedural requirement for “cradle-to-grave” safety assurance of all phases of an experiment, both prior to and following the actual experiment irradiation.

Experiment sponsors and project personnel change from experiment to experiment and experiment designs may be developed by engineers not routinely associated with the ATR. In addition to potential lack of detailed knowledge of the ATR and its accident scenarios, experiment project personnel are typically pre-dispositioned to thought processes in “success space,” rather than “failure space.” For these reasons, experience has shown that it is important to involve safety analysis personnel throughout all phases of new experiment design and development. Safety analysts, pre-dispositioned to thought processes in “failure space,” can sometimes provide insights to help guide experiment designs. This guidance can prevent last minute surprises or minimize them when the experiment safety analyses are actually conducted and documented in the applicable ESAP. Safety assurance for the irradiation phase in the ATR requires not just the assessments be documented in the individual experiment ESAPs, but also on another safety document that is prepared for every reactor operating cycle. This second document is the Core Safety Assurance Package (CSAP) and it is developed to assure safe performance of the reactor given all installed experiments, the specific reactor fuel loading, the projected reactor cycle power, and the projected cycle length. The CSAP demonstrates, among other things, that the reactor control devices will meet specified reactivity requirements, that the nominal excess reactivity is acceptable, and that the fuel will perform within specified limitations. In general, the CSAP addresses reactor safety given the total effects of all installed experiments, whereas the ESAPs address individual experiments. The combination of the CSAP and all applicable ESAPs assures safe operation of the ATR and the experiments being irradiated during each reactor cycle.

3.3 Experiment safety assurance package requirements

A management control procedure is used to provide guidance for the preparation and approval of each ESAP. This control procedure requires the ESAP to include the “cradle-to-grave” concept of addressing all phases of an experiment and it specifies the minimum requirements for the outline of the ESAP. The required sections of an ATR ESAP are discussed in the following paragraphs.

3.3.1 Scope

The “Scope” section of an ESAP provides a brief discussion of the purpose of the ESAP along with the scope of activities encompassed. The facilities to be involved are also identified, along with the activities to be performed within the facilities. Pre-irradiation and post-irradiation activities may involve facilities other than the ATR and a “cradle-to-grave” experiment assessment needs to address all of these associated activities as well. Due to scheduling challenges there are occasions when the scope of an ESAP must be initially limited to preliminary phases of an experiment program, e.g., limited to just the receipt of an experiment or experiment specimens. The scope can then be revised when additional assessments and analyses are developed to support the further steps in the experiment program.

3.3.2 Hazard classification

ESAP hazard classifications of experiment activities serve to assure that hazards are identified and appropriately controlled. When an experiment is inside the ATR facility but not necessarily in the reactor vessel, the hazards associated with the experiment are generally enveloped by the reactor hazard. During experiment activities outside the reactor facility, however, the reactor hazard and associated controls do not apply and experiment hazards need to be recognized. Prior to irradiation, many experiments do not represent hazards other than routine industrial hazards, however other experiments may include fissionable or other radioactive material, machining of pyrophoric materials, or liquid metals that react with air that require appropriate hazard controls. Following irradiation, most experiments represent significant radiological hazards that need to be identified and controlled.

3.3.3 Process description

Each ESAP is required to include a flowchart, which is an important tool to help assure that all experiment process steps are recognized and assessed for accident conditions. It also helps to provide order in an ESAP and facilitates definition of process boundaries and applicable safety envelopes. A description of each experiment process step is also included that contains information on the physical location, applicable facility, materials involved, equipment used, applicable procedures, individual tasks, pertinent facility and experiment parameters, any associated alarm or mitigating action set-points, special personnel requirements, and any associated hazards with the step being addressed. The ESAP process description includes the governing safety envelope for each identified process step. Different process steps frequently have different safety envelopes and it is important to recognize the differences. The safety envelope during irradiation of an experiment is different, for example, than the safety envelope during movements of the irradiated experiment outside of the ATR. A safety envelope typically consists of the applicable facility controlling safety documentation. The safety envelope for irradiating an experiment consists of the ATR UFSAR and the Technical Safety Requirements, whereas the safety envelope for shipment of the irradiated experiment may consist of the applicable Department of Transportation and Nuclear Regulatory Commission safety documentation for the chosen shipping container (e.g. Type A or Type B container).

3.3.4 Demonstration of compliance

The fourth section of the ESAP demonstrates that an experiment complies with the applicable safety envelope requirements. This "Demonstration of Compliance" is typically expected to consist of tables of applicable requirements with associated statements that demonstrate how each requirement is satisfied. Although this part of the ESAP is not actually safety analysis, it does assure that applicable safety analysis commitments and technical safety requirements are not overlooked. The aforementioned management control procedure lists the minimum set of commitments and requirements that must be included in the Demonstration of Compliance section of an ATR ESAP. An example of these commitments and requirements is the reliability of the experiment containment boundaries. Experiment containment that experiences an internal pressure of greater than 1.62 MPa or that contains material that can generate pressure pulses greater than 2.96 MPa must have a design that meets the intent of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section III, Class 1 standards. Proto-type testing or other approved means may also be used to demonstrate the experiment boundary will not fail during service conditions. Quite often experiments will not experience internal pressures above these threshold values, and consequently, the associated containment boundaries are often not designed in accordance with these requirements. However, in such cases it then becomes necessary to demonstrate in the safety analysis section of the ESAP that the consequences of containment failure will be acceptable when the probability of failure is anticipated. Another example of the most fundamental requirements for experiments (as well as the IPT surfaces of a PWL in contact with the reactor primary coolant) is the assurance that no flow instability will occur during a flow decrease caused by a loss of all operating primary coolant pumps during reactor operation. This type of accident is anticipated to occur as a result of a loss of off-site power (ATR primary coolant pump motors utilize commercial electrical power). A loss of primary coolant pumps results in an immediate reactor shutdown and a decrease in reactor primary coolant flow. As the primary coolant pumps coast down, the emergency pumps maintain primary coolant flow, but at a significantly reduced flow rate. Two different types of heat transfer crises could potentially occur during this transient and therefore the requirement is divided into two parts. The first part of the requirement is the Departure from Nucleate Boiling (DNB) ratio must always be greater than two (or that the heat flux at the hottest spot is lower, by at least three standard deviations, than the DNB heat flux computed for the coolant conditions)

during the flow transient. The second part of the requirement is the rise in bulk reactor primary coolant temperature along the experiment hot track must be less than half the value that would cause flow instability (or the highest reactor primary coolant temperature is lower, by at least three standard deviations, than the value that would cause the flow to become unstable) during the flow transient. A very conservative approach to this analysis is achieved by assuming either the maximum rated power for the reactor at the beginning of the transient or by assuming an initial reactor power that is significantly above the maximum operating power level that will be allowed during irradiation of the experiment.

The Demonstration of Compliance section of an ESAP also includes a number of constraints related to experiment materials. These material constraints are directed toward assuring safety of the experiment and the reactor, both during normal operation and during accident conditions, especially accidents in which the experiment containment boundary fails and internal materials become exposed to the reactor primary coolant water. For example, it is required that fueled experiments will not melt during experiment handling and when forced coolant flow is terminated in the reactor. It is therefore necessary to determine the associated minimum time for which coolant flow must be maintained following reactor shutdown. In some cases no continued forced coolant flow may be required, while in other cases an extended decay time beyond flow termination may be needed to assure that an accidentally dropped experiment will not melt. The demonstration of compliance to this requirement will often be documented by specifying the required minimum time that the given experiment must remain in its irradiation position in the reactor before it is allowed to be moved to the adjoining water-filled storage canal.

3.3.5 Safety analysis

The actual safety analysis for each ATR experiment is to be documented in a safety analysis section of the ESAP. The safety analysis is to address at least the most limiting postulated event for each of four probability levels and is to demonstrate that the Plant Protection Criteria will be satisfied throughout all steps of the experiment process. Experiment steps not taking place within the boundaries of the ATR facility may, of course, have different applicable acceptance criteria for consequences of postulated accidents. The comprehensive set of PWL experiment accident analyses documented in the ATR safety basis typically makes it possible for the safety analysis for a PWL experiment to easily demonstrate that the experiment falls within the existing safety envelope. Conversely, the radiological source terms associated with capsule experiment accidents are typically small in comparison with the different source terms associated with the ATR safety basis assessments regarding accidents involving the ATR fuel. Therefore, fueled capsule experiment accidents are often compared to ATR fuel accidents by merely comparing fissile material masses. The safety analysis for each capsule experiment is tailored to the experiment, and is expected to address a variety of reactor abnormal operating conditions including, for example, such items as reactor overpower and overpressure (110% and 120%). The accident conditions for capsule experiments are varied but almost always involve some human error related events.

3.3.6 Unreviewed safety questions

Each ESAP is required to include a section that addresses the USQ issue. Typically this section simply states the conclusion from a referenced specific USQ evaluation (or screening) that supports the conclusion.

3.3.7 ESAP conclusions

Each ESAP is required to include a recommendation as to whether the experiment, as presented in its process steps, should be conducted. The recommendation is basically a conclusion regarding the acceptability of the risk for conducting the experiment.

3.4 Experiment safety assurance package development

ESAPs are usually authored by engineers familiar with the experiments and who are frequently involved in the development and/or analyses of the experiments. Early involvement of nuclear engineering personnel familiar with the ATR safety basis and experiment safety issues is encouraged. Experience has shown that involvement of these personnel early in the development of experiment designs contributes to successful development of the ESAP. Development of all the supporting analyses for conducting a given experiment is

usually an iterative process. There are some analyses, however, that must be finalized before other analyses can be completed. Successful ESAP development hinges around recognition of the critical analysis sequences that are required. The typical design and analysis sequence is as follows. The experiment design forms the basis for performing the neutron and gamma heating analysis during reactor operation. The results of this analysis become inputs for thermal-hydraulic analyses of the experiment. The results of the thermal-hydraulic analyses then feed into stress analyses that are needed to demonstrate adequate experiment containment. Thermal and reactivity analyses can also be tied together, for example, in cases involving experiments located in the flux trap regions, where the positive reactivity coefficient can cause significant reactor control issues. The level of conservatism used in analyses supporting experiment safety assurance packages may vary depending on the nature of the experiments. Some experiments are clearly more simple and benign than others and may warrant less conservatism in the associated analyses. In some cases, such as the coast down of primary coolant flow described in Section 3.3.4, the level of conservatism is prescriptive.

3.5 Experiment safety assurance review and approval

The first step in gaining approval of an ESAP is obtaining a peer review that is typically performed by an engineer in the ATR experiments engineering group. In addition to the required peer review, a review is also required by the ATR nuclear safety engineering unit, which is typically performed by an engineer familiar with both the ATR safety basis and experiments conducted in the ATR. Each ESAP must also be given line management approval by the ATR experiments organization. Final approval of each ESAP is based on review by an independent safety review committee with a high level of authority and broad review coverage relative to the operation of the ATR. This committee is composed of senior personnel with a variety of technical backgrounds and nuclear experience. Approval by this committee is required before any experiment can be irradiated.

4. Conclusion

Application of the safety assurance methodology described in this paper has supported and resulted in the safe operation of a wide variety of experiments in the Advanced Test Reactor over a period of many years. Successful safety assurance of both the experiments and the reactor itself are key to the continued operation of test reactors everywhere.

5. Acknowledgments

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6. References

[1] 10 CFR 830, "Nuclear Safety Management," Code of Federal Regulations, Office of the Federal Register, January 2001.