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Aqueous Homogeneous Reactor Technical Panel Report

Stephen Bajorek, Allen Bakel, David Diamond, George Flanagan, Vinod Mubayi, Raymond Skarda, Joseph Staudenmeier, Temitope Taiwo Kotaro Tonoike, Christopher Tripp, Thomas Wei, Peter Yarsky,

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AQUEOUS HOMOGENEOUS REACTOR TECHNICAL PANEL REPORT

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Prepared by:

Stephen Bajorek, Nuclear Regulatory Commission/ Office of Nuclear Regulatory Research
Allen Bakel, Argonne National Laboratory/ Chemical Sciences and Engineering Division
David Diamond, Brookhaven National Laboratory/ Nuclear Science and Technology Department
George Flanagan, Oak Ridge National Laboratory/ Reactor and Nuclear Systems Division
Vinod Mubayi, Brookhaven National Laboratory/ Nuclear Science and Technology Department
Raymond Skarda, Nuclear Regulatory Commission/ Office of Nuclear Regulatory Research
Joseph Staudenmeier, Nuclear Regulatory Commission/ Office of Nuclear Regulatory Research
Temitope Taiwo, Argonne National Laboratory/ Nuclear Engineering Division
Kotaro Tonoike, Japan Atomic Energy Agency/ Nuclear Safety Research Center
Christopher Tripp, Nuclear Regulatory Commission/ Office of Nuclear Materials Safety and Safeguards
Thomas Wei, Argonne National Laboratory/ Nuclear Engineering Division
Peter Yarsky, Nuclear Regulatory Commission/ Office of Nuclear Regulatory Research

Prepared for:

Raymond Skarda, NRC Project Manager
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

ABSTRACT

Considerable interest has been expressed for developing a stable U.S. production capacity for medical isotopes and particularly for molybdenum- 99 (^{99}Mo). This is motivated by recent reductions in production and supply worldwide. Consistent with U.S. nonproliferation objectives, any new production capability should not use highly enriched uranium fuel or targets. Consequently, Aqueous Homogeneous Reactors (AHRs) are under consideration for potential ^{99}Mo production using low-enriched uranium. Although the Nuclear Regulatory Commission (NRC) has guidance to facilitate the licensing process for non-power reactors, that guidance is focused on reactors with fixed, solid fuel and hence, not applicable to an AHR. A panel was convened to study the technical issues associated with normal operation and potential transients and accidents of an AHR that might be designed for isotope production. The panel has produced the requisite AHR licensing guidance for three chapters that exist now for non-power reactor licensing: Reactor Description, Reactor Coolant Systems, and Accident Analysis. The guidance is in two parts for each chapter: 1) standard format and content a licensee would use and 2) the standard review plan the NRC staff would use. This guidance takes into account the unique features of an AHR such as the fuel being in solution; the fission product barriers being the vessel and attached systems; the production and release of radiolytic and fission product gases and their impact on operations and their control by a gas management system; and the movement of fuel into and out of the reactor vessel.

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BACKGROUND

The U.S. Nuclear Regulatory Commission (NRC) has received notification of intent to submit a license application for an aqueous homogeneous reactor (AHR) for isotope production. Guidance for submitting a complete, and appropriately formatted, license application and for reviewing non-power reactors would normally be provided in "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors," NUREG-1537, [1] which consists of two parts: 1) standard format and content; and 2) standard review plan. However, the non-power reactors addressed in NUREG-1537 are expected to be fueled as heterogeneous cores with solid fuel; there is no format, content, or staff review plan guidance specific to AHRs. Hence, there is a need to supplement NUREG-1537 with appropriate guidance for an AHR.

This new guidance is being developed by the Office of Nuclear Reactor Regulation (NRR) with additional support from other Offices including the Office of Nuclear Regulatory Research (RES). RES assistance focuses on the reactor and its cooling systems and the accident analysis; areas where the changes from NUREG-1537 are expected to be the most significant. Specifically, Chapter 4, “Reactor Description,” Chapter 5, “Reactor Coolant Systems,” and Chapter 13, “Accident Analysis,” of NUREG-1537 are to be addressed by RES as well as any other sections that might be closely aligned. The isotope production aspects of the plant would not be addressed as part of this effort. The format of the guidance being developed by NRR is as a stand-alone document; formally it will be an Interim Staff Guidance (ISG) document. The Agency intends to incorporate the guidance into a revision to NUREG-1537 at a future date.

In support of ISG development, RES has convened a panel of experts in the various technical disciplines that are needed to understand operation and safety of an AHR. The expert panel is formed to identify key safety issues and the phenomena that may be most dominant in the evaluation of those issues, and then to provide the guidance needed to contribute to an ISG describing format and content and a review plan for licensing submissions for an AHR.

OBJECTIVE

The objective of the panel is to identify and characterize safety issues that should be included as part of staff guidance for review of license applications for AHRs. The safety issues associated with operation of an AHR under all conditions including normal operation, transients, and accident conditions are to be examined. Technical review by the expert panel is to lead to specific guidance that can be used as part of 1) the standard format and content which would be available to a potential licensee and 2) the standard review plan which would primarily be for the benefit of the NRC staff carrying out any license review. The scope of this objective is restricted to Chapters 4, 5 and 13 of NUREG-1537 covering reactor systems, cooling systems, and accident analysis, respectively. Furthermore, the type of AHR to be considered is restricted to one without recirculating fuel.

METHODOLOGY

The panel, consisting of 12 members from the NRC, U.S. National Laboratories, and Japan Atomic Energy Agency, had expertise covering neutronics (including criticality), thermal-hydraulics, chemistry, severe accidents (including source term), reactor systems, reactor safety analysis, and regulatory requirements for non-power reactors. The panel convened three times at NRC Headquarters Complex in Rockville, MD. S. Bajorek and D. Diamond were co-chairs. At the first meeting (September 10, 2010) NRR staff presented the licensing context for the AHR and the needs of NRR. A presentation was made by B&W Technical Services Group on their conceptual design for an AHR for medical isotope production—a system which might be the first to use the AHR ISG being prepared by NRC. The remainder of the meeting was devoted to the panel asking questions of the presenters and then working on the process by which they would satisfy the previously stated objectives.

The panel was broken into four subpanels with assignments to fill in spreadsheets with the change-summary for each section of the three chapters of primary interest as well as for the gas management system which controls the gaseous products of radiolysis and fission product gases. Initially, this latter effort was addressed in NUREG-1537, Section 9.6, "Cover Gas Control in Closed Primary Coolant System." However, this system is an important part of the reactor (see "AHR Features and Implications" below) and, therefore, at the second panel meeting, it was decided to include guidance for dealing with this system within Chapter 4, "Reactor Description."

The spreadsheets each subpanel worked on between the first and second meeting, in addition to having a change-summary, also had columns for technical issues and information gaps relative to the change-summary as well as for estimated level of effort for revision. This information was provided by each subpanel between the first and second meeting, and the resulting spreadsheets were the subject of the second meeting (October 5, 2010). The spreadsheets and the discussion of technical issues at the second meeting were the basis for the draft ISG sections that were written during the period between the second and third meeting.

At the third meeting (October 25, 2010) technical discussion continued, and the entire panel reviewed the draft sections. Following the third meeting, this final report, which contains guidance for AHR licensing in the form of proposed sections for the ISG to replace NUREG-1537, was prepared.

AHR FEATURES AND IMPLICATIONS

The objective of an AHR is to produce ^{99}Mo, a fission product and a precursor for ^{99}Tc, an isotope that is used in thousands of medical diagnostic tests daily; and possibly other isotopes. Although reactors with solid fuel are currently used to obtain ^{99}Mo, the advantage of a solution or homogeneous reactor is that it can operate at much lower power levels, require less uranium, and result in less waste than conventional reactors for the same amount of product. The use of an

aqueous solution provides the neutron moderation. Solutions with uranyl sulphate or uranyl nitrate have been used in the past. An AHR would also have conventional control rods for shutdown and operational control and, if needed, a cooling system.

The history of AHRs goes back to the 1940s and includes over 30 different reactors that were built throughout the world. Although there are none currently operating as isotope production facilities, in recent years there has been considerable interest in this possibility and there are several relatively recent papers which summarize the attributes of such an AHR [2, 3, 4]. In addition, B&W has published some limited material on their concept for an AHR [5, 6].

From a safety point-of-view, an AHR has several advantages and disadvantages. AHRs have negative power coefficients, i.e., negative temperature coefficients. Any bubble formation is also a negative reactivity effect. They have large thermal inertia or heat capacity and low fuel reactivity worth per unit mass or volume. They operate at low temperature and pressure. AHRs in the past have demonstrated damped oscillations under reactivity addition transients. However, on the negative side, there is limited operating experience and the release of fission product gases and radiolytic gases is a unique phenomenon to be addressed. The radiolytic gases include hydrogen and oxygen, and NOx as well if a nitrate solution is used. The gases must be recombined in order to prevent inadvertent release of uncontrolled energy. The generation and escape of gases from the solution is also problematic as it results in oscillations in reactivity and hence, the AHR will not have a perfectly stationary steady state operation. Although some experiments in the past have shown AHRs to have damped oscillations under reactivity insertion, there is evidence that an AHR can become unstable at high power density [2].

The unique features of an AHR require changes to the standard format and content and the standard review plan. There are several impacts of this on Chapter 4, Reactor Description. The primary fission product barrier is now the reactor vessel and associated equipment rather than fuel rod cladding. Hence, the integrity of these components takes on new meaning. The gas management system is more than cover gas control; it has the potential to directly affect reactor behavior and, therefore, it is discussed as a reactor system rather than an auxiliary system. Normal operation is not completely steady because of the generation and release of radiolytic and fission product gases, and operating limits need to account for this behavior. The reactor has the potential to oscillate upon reactivity insertion and it must be assured that these oscillations are damped.

The impact of the unique features on Chapter 13, Accident Analysis is also varied. The accident analysis needs to be based on five limiting phenomena: bulk boiling, fuel precipitation, fission product precipitation, detonation and deflagration of radiolytic gases, and excessively high radiolytic gas release. Each of these may pose a challenge to the primary system boundary. The acceptance criteria for accident analysis are based on the dose limits found in Title 10, Part 20 of the Code of Federal Regulations. However, the accident analysis for an AHR will look quite different from that for a heterogeneous reactor. The maximum hypothetical accident can be one of

several different scenarios where fission products (and fuel in some cases) are released from different parts of the reactor systems. Other event categories also have their unique features.

ORGANIZATION OF REPORT

The results from the panel's deliberations are presented in six appendices: Appendices A and B address Chapter 4, Reactor Description, Part 1, Format and Content and Part 2 Standard Review Plan, respectively; Appendices C and D address Chapter 5, Reactor Coolant Systems, Parts 1 and 2, respectively; and Appendices E and F address Chapter 13, Accident Analysis, Parts 1 and 2, respectively.

REFERENCES

1. "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors," Part 1, Format and Content and Part 2, Standard Review Plan and Acceptance Criteria, NUREG-1537, U.S. Nuclear Regulatory Commission, February 1996.
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APPENDIX A

Chapter 4, Reactor Description, Part 1 Standard Format and Content

4 REACTOR DESCRIPTION

In this chapter of the SAR, the applicant should discuss and describe the principal features, operating characteristics, and parameters of the reactor. The analysis in this chapter should support the conclusion that the reactor is conservatively designed for safe operation and shutdown under all credible operating conditions. Information in this chapter of the SAR should provide the design bases for many systems, subsystems, and functions discussed elsewhere in the SAR and for many technical specifications.

In following the instructions in this chapter for the aqueous homogeneous reactor (AHR), it should be noted that the fuel solution performs the function of the fuel, moderator and the target. In the following subsections, any direct reference to a moderator or target is for designs that might use *solid* moderator or target. It should also be noted that no fuel cladding is used in the AHR design, and consequently, the concept of fission product barrier performed by the cladding is no longer valid. The cladding's role is now performed by the reactor vessel and the boundaries of any penetrations (coolant coils, control rod channels, and fuel solution transfer pipes) in the reactor vessel.

A glossary of terms often used when discussing an AHR is found below:

Boiling: Vapor generation due to phase change that results when a fluid is brought to its saturation temperature.

Fission Product Barrier: That portion of the primary system boundary in contact with fission products only (principally the gas management system boundary).

Fuel Barrier: That portion of the primary system boundary in contact with the fuel solution (principally the vessel, cooling coils, control rod thimbles, piping and valves).

Neutron Moderator: In an AHR, moderation is performed by light elements in the fuel and possibly in a solid moderator. Coolant in the cooling coils also contributes to the moderating capacity.

Primary Cooling Systems: For an AHR the term primary cooling system replaces the term "primary coolant system." The primary cooling systems for an AHR are those components and systems that remove heat from the core.

Primary System Boundary: The primary system boundary consists of all structures that prevent the release of fuel, fission gas or other fission products. For an AHR, this includes the reactor vessel, waste handling tank, and pumps, valves and piping.

Radiolytic Gas Release: The chemical process that generates hydrogen, oxygen, and nitrogen oxides (NOx) from the fuel solution due to dissociation by irradiation.

Reactor Core: The reactor core in an AHR consists of that region of the vessel occupied by the solution containing the fission power producing fissile material. In an AHR, the core geometry may change with time due to changes in density and voiding of the solution. The core does not include that part of the fuel solution that may become entrained into the gas.

Reactor Fuel: The fuel in an AHR refers to the dissolved fissionable material, fission products and solvent they are dissolved in.

Recombiner: Device that recombines hydrogen and oxygen.

Vessel: For an AHR, the vessel is the structure containing the core.

4.1 Summary Description

In this section the applicant should briefly summarize the design and functional characteristics of the reactor. The applicant should present the principal safety considerations in the selection of the reactor type as well as the design principles for the components and systems that address those considerations. This section should contain summary tables of important reactor parameters and sufficient drawings and schematic diagrams to explain and illustrate the main reactor design features.

The applicant should briefly address the following features of the reactor:

- thermal power level
- fuel type and enrichment
- use of gas-tight vessel
- forced and/or natural-convection cooling
- type of coolant, solid moderator (if any), and reflector materials
- principal features for commercial isotope production programs
- pulsing or steady power
- novel concepts requiring substantial new development
- gas management system

4.2 Reactor Core

In this section the applicant should present all design information and analyses necessary to demonstrate that the core can be safely operated. The major core components to be described are fuel, solid neutron moderator (if any), neutron reflector, control elements, neutron startup source, incore cooling components, and any incore experimental facilities. The source or basis of the information presented should be given.

4.2.1 Reactor Fuel

In this section the applicant should describe the reactor fuel system. Included should be the design features selected to ensure that the fuel (including fission products) barrier can withstand all credible environmental and irradiation conditions during their life cycle at the reactor site. The discussions should address the incore fuel operating conditions. Handling, transport, and storage of fuel should be discussed in Chapter 9, "Auxiliary Systems," of the SAR. Drawings and tables of design specifications and operating characteristics of the fuel should be presented.

In AHRs, radiolysis and fission product gases build up within the reactor vessel above the liquid fuel. Hydrogen and oxygen from the radiolysis of water could lead to the development of an explosive gas mixture. In addition, nitrate-based aqueous fuel will generate acidic nitrogen gases (NOx) by radiolysis. Gases generated during fission will also collect in this cover gas space. Therefore, information relevant to the headspace and the gas handling systems should be provided. [1, 2]

All information should be current; supported by referenced tests, measurements, and operating experience; and compared with additional applicant experience where applicable. For AHRs, the information should include the following:

- Chemical composition, enrichment, uranium loading, and fuel chemistry. Information should be provided for fresh and reload fuel composition; solvent type and molarity; uranium loading and enrichment; expected fissile density in solution at operating pressure, temperature, and pH; uranium solubility; buildup of fission products and related decay daughters in solution, precipitates, and sweep gas system.
- Information on radiolytic gas formation and impact on reactor core chemistry, homogeneity, and reactivity. Discuss implications of void formation and condensate return to the core on reactor performance.
- Short term changes in the chemistry of the fuel should be discussed. Changes in the pH, temperature fluctuations, fission gas release and changes in concentration due to radiolytic water and acid destruction would be expected during an operation cycle. The range of these fluctuations and their effects on reactor operation and control should be described.
- Long term changes in the chemistry of the fuel should be discussed. In particular, the buildup of fission products, activation products and corrosion products would be of interest. Any plans and approaches for stabilizing or adjusting the fuel characteristics or composition should be included. Any plans regarding periodic reconstitution or purification of the fuel should also be included. Any scheduled periodic analysis plans for the fuel should also be described. Finally, a description of the fuel at its end of life should be given.

- Description of the volume occupied by the fuel solution including the height and diameter and the portion of the volume occupied by solids. Separate descriptions should be given for the critical and subcritical fuel, i.e., the gas evolved during irradiation should be included in the description of the critical fuel. Special features, such as reflectors, external geometrical designs to enhance cooling capability, and inherent safety or feedback provisions should be discussed.
- Physical properties with significance in regard to safety that are important for the thermal-hydraulic analyses, such as solution density, power density and distribution, temperature, pH, pressure, heat capacity, gas evolution or diffusion (including fission product gas), void formation or collapse, precipitation of fuel or fission product complexes, and sweep gas.
- Material and structural information for the core vessel and coolant coils, such as dimensions, fabrication methods, compatibility of materials, and specifications with tolerances. All types of fuel solution chemical constituents to be used should be described, as well as the fuel preparation method and location.
- Information on material parameters that could affect core vessel and integrity of the coolant coil, control channel and fuel transport pipe, such as melting, softening, or blistering temperatures; corrosion; erosion; and mechanical factors, such as swelling, bending, twisting, compression, and shearing.
- A brief history of the fuel type, with references to the fuel development program, including summaries of performance tests, qualification, and operating history.
- Hydraulic forces, thermal changes and temperature gradients, internal pressures including that from fission products and gas evolution (including removal to gas treatment), pH control, pressure, precipitation, frothing, malfunctions of the gas treatment system, and radiation effects on the solution chemistry.
- Adequate mixing of the fuel solution based on convection and gas evolution should be discussed.

Limits on operating conditions for the fuel should be supported by information and analyses. These limits are specified to ensure that the integrity of the fuel barrier will not be impaired by solution pH, radiolytic gas evolution, solution boiling, power oscillations, precipitation from solution, temperature and pressure extremes or distributions, and materials compatibility. They should form the design bases for this and other chapters of the SAR, for the reactor safety limits, and for other fuel-related technical specifications.

4.2.2 Control Rods

In this section the applicant should give information on the control rods, including all rods or control elements that are designed to change reactivity during reactor operation. The physical,

kinetic, and electromechanical features demonstrating that the rods can fulfill their control and safety functions should be described. Results of computing control rod reactivity worths may be presented in this section, but details of the calculation of reactivity effects should appear in Section 4.5, "Nuclear Design," of the SAR. The information in this section should include the following:

- The number and types of rods (e.g., shim, safety, regulating, transient), their designed locations in the core, and their designed reactivity worths. The considerations and bases for redundancy and diversity should be provided. Limits on core configuration should be discussed.
- The structural and geometric description, including the shape, size, materials, cladding, fabrication methods, and specifications with tolerances for the rods. This should include the type and concentration of neutron absorber, or emitter, if applicable. Also, calculations of changes in reactivity worth due to burnup and assessment of radiation damage, heating effects, and chemical compatibility with the coolant and other core components should be given. If the control rods have followers, the design, composition, and reactivity effects of the follower should be discussed.

  The design of mechanical supports for the active component, the method of indicating and ensuring reproducible positioning in the core, and the drive mechanism of each type of rod. This information should include the source of motive power, usually electrical, and the systems ensuring scram capability.
- The kinetic behavior of the rods, showing either the positive or negative rate of reactivity change, in the normal drive and scram modes of operation. This information should be supplied for all rods, including transient rods in a reactor designed for pulsing.
- The applicant should show that the control rod design conforms to the shutdown margin requirements.
- The scram logic and circuitry, interlocks and inhibits on rod withdrawal, trip release and insertion times, and trip or scram initiation systems should be summarized here and described in detail in Chapter 7, "Instrumentation and Control Systems."
- Special features of the control rods, their core locations, power sources, drive or release mechanisms designed to ensure operability and capability to provide safe reactor operation and shutdown under all conditions during which operation is required in the safety analysis if there is a single failure or malfunction in the control system itself. Such features may include mechanisms to limit the speed of rod movement.
- Technical specification requirements for the control rods and their justification. These are the limiting conditions for operation, surveillance requirements, and design features as discussed in Chapter 14, "Technical Specifications," of this format and content guide.

4.2.3 Neutron Moderator and Reflector

In this section the applicant should discuss any additional materials and systems designed to moderate the neutrons within the fuel region (e.g. solid moderator, if any) and reflect leakage neutrons back into the fuel region. The information should include the materials, geometries, designs for changes or replacement, provisions for cooling, radiation damage considerations, and provisions for experimental facilities or special uses. Multiple-use systems and features such as moderator coolant, fuel moderator, and reflector shield should be described. If solid moderators or reflectors are encapsulated to prevent contact with coolant, the effect of failure of the encapsulation should be analyzed. It should be possible to operate the reactor safely until failed encapsulations are repaired or replaced. If reactor operations cannot be safely continued, the reactor should be placed and maintained in a safe condition until encapsulations are repaired or replaced. Technical specification requirements should be proposed and justified for the moderator and reflector in accordance with the guidance in Chapter 14 of this format and content guide. The nuclear design of the moderator and reflector should be discussed in Section 4.5 of the SAR.

4.2.4 Neutron Startup Source

In this section the applicant should present design information about the neutron startup source and its holder. The applicant should show that the source will produce the necessary neutrons to allow a monitored startup with the reactor instrumentation. The information should include the neutron strength and spectrum, source type and materials, its burnup and decay lifetime, and its regeneration characteristics. Other necessary information includes the material and geometry of the holder, the method of positioning the source in the core, and the core locations in which the source is designed to be used. Utilization information and such limitations as radiation heating or damage and chemical compatibility with coolant and other core components should be discussed. Any technical specification limits on the source should be proposed and justified in this section of the SAR in accordance with the guidance in Chapter 14 of this format and content guide. Examples include the maximum power level the reactor can be operated with the source in place (for plutonium-beryllium sources and other source types that can act as fuel), or surveillance requirements that ensure source integrity.

4.2.5 Reactor Internals Support Structure

In this section the applicant should present design information about the mechanical structures that support and position the core and its components. The information should include the following:

- Since the reactor core is an aqueous solution, the AHR core support structure is the reactor vessel. Therefore this section should discuss the vessel and reflector support structure either top supported or bottom supported as well as the support for the control system and cooling coils and any other material which is in contact with the fuel solution. The positioning function of a core support structure is not applicable to an AHR.

- The materials of construction, including considerations for radiation damage, corrosion, erosion, chemical compatibility with coolant and fuel solution and core components, potential effects on reactivity, induced radioactivities, and maintenance.
- Design features of the support structures that accommodate other systems and components such as radiation shields, reflectors, coolant coils and piping (including accommodation for dynamic loads such as vibration), control rod drive thimbles, coolant plenums or deflectors, gas treatment systems, and nuclear detectors. Piping for fuel transfer to and from the core should be specifically addressed.
- Technical specifications that control important design features, limiting conditions for operation, and surveillances as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

4.3 Reactor Vessel and Pool

The core of the AHR is an aqueous solution within a gas-tight vessel. This vessel may rest in a pool which acts as a shield and removes some small amount of heat from the reactor. In this section the applicant should present all information about vessel and pool necessary to ensure its integrity. The information should include the following:

- Design and considerations to ensure that no hydrodynamic, hydrostatic, mechanical chemical, and radiation forces or stresses could cause failure or loss of integrity of the vessel and pool during its projected lifetime over the range of design characteristics.
- Design and dimensions to ensure sufficient shielding water to protect personnel and components, as well as sufficient depth to ensure necessary coolant flow and pressures. (Also see Sections 4.4 and 4.6 and Chapter 11, "Radiation Protection Program and Waste Management," of this format and content guide.)
- Designs and description of materials, including dimensions, supporting structures, chemical compatibility with the coolant and other reactor system components, radiation fields and any consequences of radiation damage, protection from corrosion in inaccessible regions, and capability to replace components.
- Locations of penetrations and attachment methods for other components and pipes. The relationships of these penetrations to core and water surface elevations should be discussed. Safety-related features that prevent loss of coolant should be discussed and related to Sections 4.4 and 4.6 and to the reduction-in-cooling scenarios analyzed in Chapter 13, "Accident Analyses," as applicable.
- If the inner surface of the vessel is coated to alleviate the impact of contact with the fuel, the effect of failure of the coating should be analyzed.
- Planned methods for assessing radiation damage, chemical damage, erosion, pressure pulses or deterioration during the projected lifetime. In this section the applicant should

assess the possibility of uncontrolled leakage of fuel solution into the coolant or the pool, and should discuss preventive and protective features.

- Technical specifications that control important design features, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

4.4 Biological Shield

In this section the applicant should present information about the principal biological shielding designed for the reactor. The information should include the following:

- The design bases for the radiation shields (e.g., water, concrete, or lead), including the projected reactor power levels and related source terms and the criteria for determining the required protection factors for all applicable nuclear radiation activity. Information about conformance with the regulations for radiation exposure and the facility ALARA (as low as is reasonably achievable) program should appear in Chapter 11. The design basis should include the designed reactor power levels, the associated radiation source terms, and other radiation sources within the pool or tank that require shielding.

- The design details and the methods used to achieve the design bases. The applicant should discuss the protection-of personnel and equipment functions. The information should specify the general size and shape of the shields and the methods used to ensure structural strength, rigidity, and functional integrity. The applicant should discuss the distribution of shielding factors between liquid (e.g., water) and solid (e.g., concrete, lead, etc.) materials. If loss of shield integrity could cause a reduction-in-cooling, the features to prevent the loss of integrity should be described.

- The materials used and their shielding coefficients and factors, including a detailed list of constituents and their nuclear and shielding properties. The applicant should discuss radiation damage and heating or material dissociation during the projected lifetime of the reactor, induced radioactivity in structural components; potential radiation leakage or streaming at penetrations, interfaces, and other voids; shielding at experimental facilities; and shielding for facilities that store fuel and other radioactive materials within the reactor pool or tank.

- The assumptions and methods used to calculate the shielding factors, including references to and justification of the methods. Detailed results of the shielding calculations should give both neutron and gamma-ray dose rates at all locations that could be occupied. The applicant should calculate shield penetrations and voids, such as beam ports, thermal columns, and irradiation rooms or vaults, as well as the shielding of piping and other components that could contain radioactive materials or allow radiation streaming.

- Methods used to prevent neutron irradiation and activation of ground water or soils surrounding the reactor shield that could enter the unrestricted environment. The applicant should estimate the maximum activity should such activation occur and describe remedial actions.
- Technical specifications that control important design features, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

Regulatory Guide 2.1, "Shield Test Program for Evaluation of Installed Biological Shielding in Research and Training Reactors" should be consulted.

4.5 Nuclear Design

In this section the applicant should give information on the nuclear parameters and characteristics of the reactor core and should analyze the behavior of the reactor for steady-state and transient operation throughout its life cycle of allowed cores and burnup as discussed in the safety analysis. The descriptions, analyses, and results should address all safety issues in the design and operation of the reactor and should support the conclusion that the reactor can be built and operated without unacceptable risk to the health and safety of the public. A detailed description of the analytical methods used in the nuclear design should be given. Computer codes that are used should be described in detail as to the name and type of code, the way it is used, and its validity on the basis of experiments or confirmed predictions of similar operating non-power reactors. Code descriptions should include methods of obtaining parameters such as cross sections. Estimates of the accuracy of the analytical methods should be included. Tables and figures should be used as necessary to present information clearly.

4.5.1 Normal Operating Conditions

In this section the applicant should present information on the core geometry and configurations. The limiting core configuration for a reactor is the core that would yield the highest power density using the fuel specified for the reactor. All other core configurations should be demonstrated to be encompassed by the safety analysis of the limiting core configuration. Further information on power density limitations should be given in Sections 4.5.3 and 4.6. The information in the SAR should include the following:

- Discussion and analyses to reflect the impact on nuclear design of the gas management system and gas hold up tanks contained within the fission product barrier including hold up times and subsequent release of fission product gases and NOx. Sweep gas operation and discharge limits, recombiner operations and reactivity impacts associated with these operations will need to be included in this section and in Section 4.7.

- Discussions and analyses of the reactor operating characteristics. The applicant should describe in detail the effects of changes in configuration and fuel chemistry, including effects related to pH, pressure, temperature, radiolytic gas recombination capacity, reactivity and power oscillation, and the control philosophy and methodology for each parameter. If applicable, the applicant should analyze safety-related considerations for all requested operating modes.
- Changes in core reactivity with fuel burnup, plutonium buildup, and poisons, both fission products and those added by design. The reactivity impacts of radiolytic gas and void formation, fission product gas removal, fuel solution and acid addition, and condensate return to the core should also be discussed.
- Analyses of the reactor kinetic behavior and the design requirements and dynamic features of the control rods that allow controlled operation for all possible reactor conditions. This includes effects of radiolytic gas production on expected, self-damping power oscillations, effects of malfunctions in the recombiner and the possible resulting pressure pulses, fuel solution density changes, and temperature changes or distributions in the solution.
- Analyses of the basic reactor criticality physics, including the interacting effects of fuel, solid neutron moderators (if any) and neutron reflectors, control rods, and incore or in-reflector components such as used for medical isotope production. This also includes discussion of the subcritical storage and handling of the full core mass outside the reactor vessel and during transport from and to the core; the reactivity swing of the processed core material after selected fission product removal; and any compensatory measures (such as fissile addition or dilution) to achieve or maintain criticality after reinsertion into the reactor vessel.
- Discussion of the safety considerations for different core configurations, including a limiting core configuration that would yield the highest power densities and fuel temperatures achievable with the planned fuel. This includes the power stability effects of uneven, stochastic surface frothing, as well as void formation and collapse.
- The calculated core reactivities for all core configurations, including the limiting configuration that would yield the highest possible power density.
- Discussion of the administrative and physical constraints to prevent inadvertent addition of positive reactivity.
- Technical specifications that control important design features, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

4.5.2 Reactor Core Physics Parameters

In this section the applicant should discuss the core physics parameters and show the methods and analyses used to determine them. The information should include the following:

- Analysis methods and values for neutron lifetime and effective delayed neutron fraction. The applicant should describe the effects of reactor operating characteristics and fuel burnup, along with a method for calculating and verifying burnup.
- Analysis methods, values, and signs for coefficients of reactivity (e.g., fuel temperature, solid moderator temperature, void, and power). The applicant should describe the effects of reactor operating characteristics and fuel burnup. This analysis, along with the analysis in Chapter 13, should show that reactivity coefficients are sufficiently negative to prevent or mitigate damaging reactor transients.
- The axial and radial distributions of neutron flux densities, justifications for the methods used, and comparisons with applicable measurements. The applicant should describe changes in flux densities with power level, fuel burnup, core configurations, and control rod positions. The information on neutron flux density should include peak-to-average values for thermal-hydraulic analyses. The applicant should validate these calculations by comparing them with experimental measurements and other validated calculations.
- The analysis methods used to address the dynamic behavior of the formation of voids and the collapse of voids due to radiolytic gas formation, and the agglomeration and transport of bubbles to the fuel solution surface. The neutronic impacts of these phenomena should be discussed to demonstrate no adverse effect on safe reactor operations.
- Technical specifications that control important design features, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

4.5.3 Operating Limits

The applicant should present the following information on reactor operating limits:

- Reactivity conditions, excess reactivity, and negative reactivity for combinations of control rods inserted that are analyzed for the limiting core and operating cores during the life of the reactor. The applicant should discuss operational and safety considerations for excess reactivity.
- The excess reactivity based on reactor temperature coefficients, poisons, and worths associated with the radiolytic gas formation and collapse. The applicant should justify the upper limit on excess reactivity to ensure safe reactor operation and shutdown.

- The amount of negative reactivity that must be available by control rod action to ensure that the reactor can be shut down safely from any operating condition and maintained in a safe shutdown state. The analyses should assume that the most reactive control rod is fully withdrawn (one stuck rod), non-scrammable control rods are at their most reactive position, and normal electrical power is unavailable to the reactor. The applicant should discuss how shutdown margin will be verified. The analyses should include all relevant uncertainties and error limits.
- The limiting core configuration that is possible with the planned fuel in this reactor. The limit should be imposed by the maximum neutron flux density and thermal power density compatible with coolant availability. (For the AHR, the limiting power density has been associated with the propensity for the core to become unstable. Consequently, the operating power density must be quantified and substantiated, including any margins specified.) The safety limits and limiting safety system settings for the reactor should be derived from this core configuration. The detailed analyses should be included in Section 4.6. Normal operating conditions and credible events, such as a stuck control rod, should be considered.
- A transient analysis assuming that an instrumentation malfunction drives the most reactive control rod out in a continuous ramp mode in its most reactive region. It should show that the reactor is not damaged and fuel integrity is not lost.
- The redundancy and diversity of control rods necessary to ensure reactor control for the considerations noted above.
- Technical specifications for safety limits, limiting safety system settings, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of this format and content guide. The applicant should justify these technical specifications in this section of the SAR.

4.6 Thermal-Hydraulic Design

In this section the applicant should present the information and analyses necessary to show that sufficient cooling capacity exists to prevent fuel overheating and loss of fuel barrier for all anticipated reactor operating conditions, including pulsing, if applicable. The applicant should address the coolant flow conditions for which the reactor is designed and licensed, forced or natural-convection flow, or both. A detailed description of the analytical methods used in the thermal-hydraulic design should be provided. Computer codes that are used should be described in detail as to the name and type of code, the way it is used, and its validity on the basis of experiments or confirmed predictions of operating similar non-power reactors. Estimates of the accuracy of the analytical methods should be included. The information should include the following:

- The various heat removal systems/approaches from the core should be identified (e.g., cooling coils, pool heat removal, and gas management (heat removal) system including recombiner and reflux chiller condenser. The expected fraction of heat removed by each approach should be discussed. The ability of the combined systems/approaches to accommodate the varying power, from gas formation and collapse and transport, during normal and transient operation should also be discussed.
- The coolant hydraulic characteristics of the core, including cooling coil number and arrangement, and coupling between coils; individual coil and total system flow rates; fuel solution and coolant pressures; pressure changes at channel exits and entrances; material compatibility and heat transfer between fuel solution and coolant coils, to include plating or precipitation of material on the surface of the coil; natural circulation within the fuel solution; temperature profile along a coil from entrance to exit; and frictional and buoyant forces. The applicant should address individual coils as well as the core as a whole for all flow conditions in the primary coolant system, including temperature variations and wave propagation due to vibration, and chemistry changes due to breached coils. The transition from forced to natural-convection flow in the cooling coils should be calculated, and the applicant should prepare calculations for an event during which normal electrical power is lost and the core decay heat must be removed. The discussion should also describe the above core gas removal and overall pool cooling systems and the effect of the loss of these systems on core coolability and decay heat removal.
- The thermal power density distribution in the fuel and heat fluxes into the coolant of each coil and along the coil, derived from the fuel loading and neutron flux characteristics discussed above.
- Calculations and the thermal-hydraulic methodology for the transfer of heat to the coolant. The applicant should take into account uncertainties in thermal-hydraulic and nuclear parameters and such engineering factors as coil thickness and the buildup of any layers both in the coil and on the outside of the coil. The calculations should be based on fuel measurements and procurement specifications, as well as operating history and conditions. The calculational methodology should be applicable to the thermal-hydraulic operating conditions, and the applicant should justify its use.
- The calculations and experimental measurements to determine the coolant conditions ensuring that fuel solution boiling does not occur. The applicant should calculate at least the limiting core configuration. The discussion should also examine the positive reactivity feedback characteristics of overcooling. Operating conditions should include steady fission power, shutdown decay heat, planned pulses, and transients analyzed in Chapter 13. The applicant should take into account operational and fuel characteristics from the beginning to the end of fuel life.

- For the core geometry and the coolant thermal-hydraulic characteristics, a discussion to establish the fuel conditions that ensure vessel integrity and prevent solution boiling, such as fuel pressure, temperature, pH, solubility of fuel and fission products, radiolytic gas recombiner capacity, and temperature distributions. The discussion should show correlations among these factors and justify their use in deriving safety limits and limiting safety system settings for the technical specifications.
- The design bases for the primary coolant system, emergency core cooling system, gas treatment system cooling and pool cooling and other systems designed to maintain vessel and primary fuel barrier integrity and prevent solution boiling, which should also be discussed in Chapter 5, "Reactor Coolant Systems." The analyses here and in Chapter 13 should describe reduction-in-cooling scenarios for forced-flow reactors. Natural-convection cooling that removes decay heat to ensure thermal stability should also be discussed. Flow blockages should be analyzed in Chapter 13.
- In the case of the AHR, the coolant flows through coils immersed in the fuel solution; thus, the breach of a coolant coil should be analyzed in Chapter 13 as should the effects of localized moderation in the vicinity of the coil.

4.7 Gas Management System

In this section, the applicant should describe the design of the system for removing radiolysis and fission product gases from the core and cover gas of the AHR. The Gas Management System may also provide some reactor cooling; this aspect of its function should be described in Section 4.6 and Chapter 5 of the SAR. The applicant should describe the major components of the Gas Management System, which may include:

- particulate trap
- radiolytic gas recombiner
- recombiner cooling system
- reflux condenser
- gas chiller/condenser
- condensate return
- chemical makeup
- compressor
- gas storage tanks
- pressure relief valves

The essential functions of a Gas Management System are to remove the radiolytic hydrogen and oxygen, and subsequently recombine them, to prevent a hydrogen deflagration or detonation hazard, contain hazardous chemicals (e.g., radiolytic NOx gases) and volatile fission products (e.g., Kr, Xe, I) until ultimate discharge, and provide venting of any pressure transients that could result in damage to the reactor vessel or primary cooling system and result in loss of containment

of the reactor fuel. The applicant should describe the Gas Management System features that perform these duties in sufficient detail to demonstrate that the reactor core can be operated safely and in accordance with applicable environmental release criteria. This information should include the geometric dimensions of the major components and piping (including whether it is favorable geometry), the materials of construction (including chemical compatibility with evolved gases), the composition of any trap media/filters, the pressure the equipment is designed to withstand, surge capacity for fission products storage, and any additional passive or active devices, such as alarms and pressure relief devices, needed to perform the system's intended function.

The recombiner may need its own cooling system because the catalyzed recombination of hydrogen and oxygen is an exothermic reaction. This is not part of the primary cooling system of the reactor, but rather an auxiliary system as discussed in Chapter 9.

Technical Rationale: The specific components in the Gas Management System may vary from one applicant to another; this is designed to be general in nature. A component for recombining hydrogen and oxygen will be an essential part of this. A system for condensing water and acid and allowing it (and hopefully entrained uranium) back into the reactor core is desirable and would probably be part of any such design. A system for trapping entrained uranium and holding fission products until they can be safely disposed of (the exact means of doing this are unclear) is essential. There would be essentially five classes of hazards that must be protected against: an inadvertent criticality outside the reactor core, a radiolytic gas deflagration or detonation, a NOx release, a release of gaseous fission products, and an increase in the pressure in the headspace over the core. The means of preventing these events must be described. Two of these hazards (deflagration/detonation and pressure increase) could potentially increase the density of the core and affect the power density. These potential events should be discussed in terms of reactor control.

4.8 References

1. Homogeneous Aqueous Solution Reactors for the Production of Mo-99 and Other Short Lived Radioisotopes. IAEA –TECDOC-1601, International Atomic Energy Agency, September 2008.

2. Fluid Fueled Reactors "Part 1 Aqueous Homogeneous Reactors", James A. Lane, editor, AddisonWesley,1958. http://moltensalt.org/references/static/downloads/pdf/

APPENDIX B

Chapter 4, Reactor Description, Part 2 Standard Review Plan

4 REACTOR DESCRIPTION

This chapter gives guidance for evaluating the description in the SAR of the reactor and how it functions as well as the design features for ensuring that the reactor can be safely operated and shut down from any operating condition or accident assumed in the safety analysis. Information in this chapter of the SAR should provide the design bases for many systems and functions discussed in other chapters of the SAR and for many technical specifications. The systems that should be discussed in this chapter of the SAR include the reactor core, reactor vessel, gas management system, and biological shield. The nuclear design of the reactor and the way systems work together are also addressed. In this chapter the applicant should explain how the design and proper operation of an AHR make accidents extremely unlikely. This chapter of the SAR along with the analysis in Chapter 13, "Accident Analyses." should demonstrate that even the consequences of the design-basis accident would not cause unacceptable risk to the health and safety of the public.

A glossary of terms often used when discussing an AHR is found below:

Boiling: Vapor generation due to phase change that results when a fluid is brought to its saturation temperature.

Fission Product Barrier: That portion of the primary system boundary in contact with fission products only (principally the gas management system boundary)

Fuel Barrier: That portion of the primary system boundary in contact with the fuel solution (principally the vessel, cooling coils, control rod thimbles, piping and valves)

Neutron Moderator: In an AHR, moderation is performed by light elements in the fuel. Coolant in the cooling coils also contributes to the moderating capacity.

Primary Cooling Systems: For an AHR the term primary cooling system replaces the term "primary coolant system". The primary cooling systems for an AHR are those components and systems that remove heat from the core

Primary System Boundary: The primary system boundary consists of all structures that prevent the release of fuel, fission gas or other fission products. For an AHR, this includes the reactor vessel, waste handling tank, and pumps, valves and piping.

Radiolytic Gas Release: The chemical process that generates hydrogen, oxygen, and nitrogen oxides (NOx) from the fuel solution due to dissociation by irradiation

Reactor Core: The reactor core in an AHR consists of that region of the vessel occupied by the solution containing the fission power producing fissile material. In an AHR, the core geometry may change with time due to changes in density and voiding of the solution. The core does not include that part of the fuel solution that may become entrained into the gas.

Reactor Fuel: The fuel in an AHR refers to the dissolved fissionable material, fission products and solvent they are dissolved in.

Recombiner: Device that recombines hydrogen and oxygen

Vessel: For an AHR, the vessel is the structure containing the core.

4.1 Summary Description

This section of the SAR should contain a general overview of the reactor design and important characteristics of operation. The reviewer need not make any specific review findings for this section. The detailed discussions, evaluations, and analyses should appear in the following sections of the SAR.

This section should contain a brief discussion of the principal safety considerations in the way the facility design principles achieve the principal safety considerations. Included should be summaries for the items requested in this section of the format and content guide and descriptive text, summary tables, drawings, and schematic diagrams.

4.2 Reactor Core

This section of the SAR should contain the design information on all components of the reactor core. The information should be presented in diagrams, drawings, tables of specifications, and text and analysis sufficient to give a clear understanding of the core components and how they constitute a functional AHR that could be operated and shut down safely.

By reviewing this section, the reviewer gains an overview of the reactor core design and assurance that the SAR describes a complete operable AHR core. Subsequent sections should contain a description and analysis of the specifications, operating characteristics, and safety features of the reactor components. Although cooling systems should be discussed in Chapters 5, "Reactor Coolant Systems," of the SAR, relevant information should also be presented or referenced in this chapter. The information in the following sections should address these systems and components:

- reactor fuel, including use of reactor vessel as fuel and fission product barrier
- control rods
- solid neutron moderator (if any) and neutron reflector
- neutron startup source

- core support structures
- gas treatment system

The information in the SAR for each core component and system should include the following:

- design bases
- system or component description, including drawings, schematics, and specifications of principal components, including materials
- operational analyses and safety considerations
- instrumentation and control features not fully described in Chapter 7, "Instrumentation and Control Systems," of the SAR and reference to Chapter 7
- technical specifications requirements and their bases, including testing and surveillance, or a reference to Chapter 14, "Technical Specifications"

4.2.1 Reactor Fuel

Areas of Review

The information in the SAR should include a reference to the fuel development program and the operational and limiting characteristics of the specific fuel used in the reactor.

The design basis for an AHR should be the maintenance of primary system boundary integrity under any conditions assumed in the safety analysis. Loss of integrity is defined as the escape of any fuel and fission products from the primary system boundary. Since the fuel in an AHR is an aqueous solution without cladding or encapsulation, the primary barrier is the interface surface between the fuel solution, including fission products, and any egress point. During operation, this interface includes the reactor vessel, the gas management system, the cooling coils, the control rod thimbles, and any pipes used for transferring fuel from and to the core. Therefore, the fuel solution must be shown to be compatible with the materials of construction for the fuel barrier (including fission products) for any normal or upset condition. The reviewer should be able to conclude that the applicant has included all information necessary to establish the limiting characteristics beyond which fuel barrier integrity could be lost.

Within the context of the factors listed in Section 4.2 of this review plan, the information on and analyses of fuel should include the information requested in this section of the format and content guide. Sufficient information and analyses should support the limits for operational conditions. These limits should be selected to ensure the integrity of the fuel barrier. Analyses in this section of the SAR should address mechanical forces and stresses; corrosion and erosion of the fuel barrier, or collection of fission products, decay daughters, or fuel precipitates on the fuel barrier, whether due to changes in solution chemistry (such as pH, density, pressure, and temperature) or from normal operation; hydraulic forces, including natural convection in the fuel solution; thermal changes and temperature gradients; and internal and external pressures from fission products and the production of fission gas. The analyses should also address radiation effects,

including the maximum fission densities and fission rates that the fuel is designed to accommodate. Results from these analyses should form part of the design bases for other sections of the SAR, for the reactor safety limits, and for other fuel related technical specifications. [1, 2]

Acceptance Criteria

The acceptance criteria for the information on reactor fuel include the following: [2, 3]

- The design bases for the fuel should be clearly presented, and the design considerations and functional description should ensure that fuel conforms to the bases. Maintaining fuel barrier integrity should be the most important design objective.
- The chemical and physical characteristics of the fuel constituents, including the solvent and any stabilizing additives, should be chosen for compatibility with each other and the anticipated environment, including interaction with the fuel barrier. Consideration should be given to fission product buildup in or precipitation from the homogeneous fuel solution.
- Fuel enrichment should be consistent with the requirements of 10 CFR 50.64.
- The fuel operating parameters should take into account characteristics that could limit fuel barrier integrity, such as heat capacity and conductivity, melting, softening, and blistering temperatures of the vessel and cooling coil materials; corrosion and erosion caused by coolant or fuel solution; chemical compatibility of the fuel solution with the fuel barrier; physical stresses from mechanical or hydraulic forces (internal pressures, vibration, and Bernoulli forces); fuel burnup; radiation damage to the fuel barrier; and retention of fission products.
- The fuel design should include the nuclear features of the reactor core, such as structural materials with small neutron absorption cross-sections and minimum impurities, neutron reflectors, and burnable poisons, if used.
- The various phenomena that result in changes to the initial fuel composition and properties. The submittal should include information on radiolytic gas formation, the transport and collapse and removal of gas, the return of condensate following recombination and condensation of gas/bubbles outside the core vessel, associated pH changes, potential fuel and fission product precipitation, and the addition of fuel and acid, along with the reactivity implications of these items.
- The discussion of the fuel should include a summary of the fuel development, qualification, and production program.
- The applicant should propose technical specifications as discussed in Chapter 14 of the format and content guide to ensure that the fuel meets the safety-related design require-

ments. The applicant should justify the proposed technical specifications in this section of the SAR.

Technical Rationale

The parameters included in the technical review have been identified as important based on experience with previous operating AHRs as discussed in References 2 and 3.

Review Procedures

The reviewer should confirm that the information on the reactor fuel includes a description of the required characteristics. The safety-related parameters should become design bases for the reactor operating characteristics in other sections of this chapter, especially Section 4.6 on the thermal-hydraulic design of the core.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The applicant has described in detail the fuel solution to be used in the reactor. The discussion includes the design limits (chemical and physical) and clearly gives the technological and safety-related bases for these limits.
- The applicant has discussed the constituents, materials, components, and preparation specifications for the fuel. Compliance with these specifications for all fuel used in the reactor will ensure uniform characteristics and compliance with design bases and safety-related requirements.
- The applicant has referred to the fuel development program under which all fuel characteristics and parameters that are important to the safe operation of the reactor were investigated. The design limits are clearly identified for use in design bases to support technical specifications.
- Information on the design and development program for this fuel offers reasonable assurance that the fuel can function safely in the reactor without adversely affecting the health and safety of the public.

4.2.2 Control Rods

Areas of Review

The control rods in an AHR are designed to change reactivity by changing the amount of neutron absorber (or fuel) in or near the reactor core. Depending on their function, control rods can be designated as regulating, safety, shim, or transient rods. To trip the reactor, the negative reactivity of the control rods is usually added passively and quickly when the rods drop into the core, although gravity can be assisted by spring action. Because the control rods serve a dual function (control and safety), control and safety systems for non-power reactors are usually not completely separable. In non-power reactors, a reactor trip does not challenge the safety of the reactor or cause any undue strain on any systems or components associated with the reactor.

The areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on control rods include the following:

- The control rods, blades, followers (if used), and support systems should be designed conservatively to withstand all anticipated stresses and challenges from mechanical, hydraulic, and thermal forces and the effects of their chemical and radiation environment.
- The control rods should be sufficient in number and reactivity worth to comply with the "single stuck rod" criterion; that is, it should be possible to shut down the reactor and comply with the requirement of minimum shutdown margin with the highest worth scrammable control rod stuck out of the core. The control rods should also be sufficient to control the reactor in all designed operating modes and to shut down the reactor safely from any operational condition. The design bases for redundancy and diversity should ensure these functions.
- The control rods should be designed for rapid, fail-safe shutdown of the reactor from any operating condition. The discussion should address conditions under which normal electrical power is lost.
- The control rods should be designed so that tripping them does not challenge their integrity or operation or the integrity or operation of other reactor systems.
- The control rod design should ensure that positioning is reproducible and that a readout of positions is available for all reactor operating conditions.
- The drive and control systems for each control rod should be independent from other rods to prevent a malfunction in one from affecting insertion or withdrawal of any other.

- The drive speeds and scram times of the control rods should be consistent with reactor kinetics requirements considering mechanical friction, hydraulic resistance, and the electrical or magnetic system.
- The control rods should allow replacement and inspection, as required by operational requirements and the technical specifications.
- The action of the control rod (manual of automatic) should be such that it does not affect the stability of the core, which has been known to show significant variations in the power level but a return to a stable state following small perturbations (including physical ones from radiolytic gas formation and collapse), if the core is designed within an acceptable power density limit.
- Technical specifications should be proposed according to the guidance in Chapter 14 of the format and content guide, which describes important design aspects and proposes limiting conditions for operations and surveillance requirements, and should be justified in this section of the SAR.

Review Procedures

The reviewer should confirm that the design bases for the control rods define all essential characteristics and that the applicant has addressed them completely.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The applicant has described the control and safety rod systems for the reactor and included a discussion of the design bases, which are derived from the planned operational characteristics of the reactor. All functional and safety-related design bases can be achieved by the control rod designs.
- The applicant has included information on the materials, components, and fabrication specifications of the control rod systems. These descriptions offer reasonable assurance that the control rods conform with the design bases and can control and shut down the reactor safely from any operating condition.
- Information on scram design for the control rods has been compared with designs at other non-power reactors having similar operating characteristics. Reasonable assurance exists that the reactor trip features designed for this reactor will perform as necessary to ensure fuel barrier integrity and to protect the health and safety of the public.

- The control rod design includes reactivity worths that can control the excess reactivity planned for the reactor, including ensuring an acceptable shutdown reactivity and margin, as defined and specified in the technical specifications.
- Changes in reactivity caused by control rod dynamic characteristics are acceptable. The staff evaluations included maximum scram times and maximum rates of insertion of positive reactivity for normal and ramp insertions caused by system malfunctions.
- The applicant has justified appropriate design limits, limiting conditions for operation and surveillance requirements for the control rods and included them in the technical specifications.

4.2.3 Solid Neutron Moderator and Neutron Reflector

Areas of Review

In this section of the SAR, the applicant should describe moderators and reflectors and their special features. The fuel solution of the AHR is self-moderating. The information pertinent to this section is therefore that for any *solid* moderator that might be additionally used in the AHR design. The core of the aqueous homogeneous reactor is an aqueous fuel solution that self-moderates, surrounded by either a liquid or solid neutron reflector. The primary coolant is kept separate from the fuel material in cooling coils; these provide heterogeneous moderation within the homogeneous core solution. The solid reflectors are chosen primarily for favorable nuclear properties and physical characteristics. Section 4.2.1 of the SAR should contain a description of the relationship of all moderators to the core. Buildup of contaminating radioactive material in the moderator or coolant and reflector during reactor operation should be discussed in Chapter I1, "Radiation Protection Program and Waste Management," of the SAR.

Areas of review should include the following:

- geometry
- materials
- compatibility with the operational environment
- structural designs
- response to radiation heating and damage
- capability to be moved and replaced, if necessary.

Nuclear characteristics should be discussed in Section 4.5 of the SAR.

Acceptance Criteria

The acceptance criteria for the information on neutron moderators and reflectors include the following:

- The non-nuclear design bases such as reflector encapsulations should be clearly presented, and the nuclear bases should be briefly summarized. Non-nuclear design considerations should ensure that the moderator and reflector can provide the necessary nuclear functions.
- The design should ensure that the moderator and reflector are compatible with their chemical, thermal, mechanical, and radiation environments. The design specifications should include cooling coil and core vessel material and construction methods to ensure primary barrier integrity. If the barrier should fail, the applicant should show that the reactor can continue to be operated safely until the barrier is repaired or replaced or should shut the reactor down until the barrier is repaired or replaced.
- The design should allow for dimensional changes from radiation damage and thermal expansion to avoid malfunctions of the moderator or reflector.
- The design should provide for removal and/or replacement of solid moderator or reflector components and systems, if required by operational considerations.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which describes important design aspects, and proposes limiting conditions for operations and surveillance requirements. The proposed technical specifications should be justified in this section of the SAR.

Review Procedures

The reviewer should confirm that the information on the neutron moderator and reflector completely describes the required systems. The bases for the nuclear characteristics should appear in Section 4.5 of the SAR.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff’s safety evaluation report:

- The moderator and reflector are integral constituents of a reactor core; the staff's evaluation of the nuclear features appears in Section 4 5. The designs take into account interactions between the moderator or reflector and the reactor environment. Reasonable assurance exists that degradation rates of the moderator or reflector will not affect safe reactor operation, prevent safe reactor shutdown, or cause uncontrolled release of radioactive material to the unrestricted environment.

- Graphite moderators or reflectors are clad in (state cladding material) if they are located in an environment where coolant or fuel solution infiltration could cause changes in neutron scattering and absorption, thereby changing core reactivity. Reasonable assurance exists that leakage will not occur. In the unlikely event coolant or fuel solution infiltra-

tion occurs, the applicant has shown that this infiltration will not interfere with safe reactor operation or prevent safe reactor shutdown.

- The moderator or reflector is composed of materials incorporated into a sound structure that can retain size and shape and support all projected physical forces and weights. Therefore, no unplanned changes to the moderator or reflector would occur that would interfere with safe reactor operation or prevent safe reactor shutdown.
- The applicant has justified appropriate design limits, limiting conditions for operation, and surveillance requirements for the moderator and reflector and included them in the technical specifications.

4.2.4 Neutron Startup Source

Areas of Review

Each nuclear reactor should contain a neutron startup source that ensures the presence of neutrons during all changes in reactivity. This is especially important when starting the reactor from a shutdown condition. Therefore, the reviewer should evaluate the function and reliability of the source system.

Areas of review should include the following:

- type of nuclear reaction
- energy spectra of neutrons
- source strength
- interaction of the source and holder, while in use, with the chemical, thermal, and radiation environment
- design features that ensure the function, integrity, and availability of the source
- technical specifications

Acceptance Criteria

Acceptance criteria for the information on the neutron startup source include the following:

- The source and source holder should be constructed of materials that will withstand the environment in the reactor core and during storage, if applicable, with no significant degradation.
- The type of neutron-emitting reaction in the source should be comparable to that at other licensed reactors, or test data should be presented in this section of the SAR to justify use of the source.
- The natural radioactive decay rate of the source should be slow enough to prevent a significant decay over 24 hours or between reactor operations.

- The design should allow easy replacement of the source and its holder and a source check or calibration.
- Neutron and gamma radiations from the reactor during normal operation should not cause heating, fissioning, or radiation damage to the source materials or the holder.
- If the source is regenerated by reactor operation, the design and analyses should demonstrate its capability to function as a reliable neutron startup source in the reactor environment.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements, and should be justified in this section of the SAR.

Review Procedures

The reviewer should confirm that the information on the neutron startup source and its holder includes a complete description of the components and functions. In conjunction with Chapter 7 of the SAR, the information should demonstrate the minimum source characteristics that will produce the required output signals on the startup instrumentation.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The design of the neutron startup source is of a type (i.e., neutron-emitting reaction) that has been used reliably in similar reactors licensed by NRC (or the design has been fully described and analyzed). The staff concludes this type of source is acceptable for this reactor.
- The source will not degrade in the radiation environment during reactor operation. Either the levels of external radiation are not significant or the source will be retracted while the reactor is at high power to limit the exposure.
- Because of the source holder design and fabrication, reactor neutron absorption is low and radiation damage is negligible in the environment of use. When radiation heating occurs, the holder temperature does not increase significantly above the ambient water temperature.
- The source strength produces an acceptable count rate on the reactor startup instrumentation and allows for a monitored startup of the reactor under all operating conditions.

- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for the source and included them in the technical specifications.
- The source and holder design operate safely and reliably.

4.2.5 Reactor Internals Support Structures

Areas of Review

An aqueous homogeneous reactor fuel core is composed of the homogeneous fuel solution and off gas inside a reactor vessel; the core does not require a support structure beyond the reactor vessel. However, all other reactor core components must be secured firmly and accurately because the capability to maintain a controlled chain reaction depends on the relative positions of the components. Controlling reactor operations safely and reliably depends on the capability to locate components and reproduce responses of instrument and control systems, including nuclear detectors and control rods. Predictable fuel barrier integrity depends on stable and reproducible control rod action and coolant flow patterns. Generally, the control rods of non-power reactors are suspended from a superstructure, which allows gravity to rapidly change core reactivity to shut down the reactor.

Areas of review include the design of the support structure for the core components and reactor vessel, including a demonstration that the design loads and forces are conservative compared with all expected loads and hydraulic forces and that relative positions of components can be maintained within tolerances.

Additional areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

Acceptance criteria for the information on the core support structure include the following:

- The design should show that the support structure will conservatively hold the weight of all core-related components with and without the buoyant forces of the water in the tank or pool.
- The design should show that the support structure will conservatively withstand all hydraulic forces from anticipated coolant flow with negligible deflection or motion.
- The methods by which core components (reflector pieces, control rods, and coolant systems, and the fuel transport pipe) are attached to the core support structure should be considered in the design. The information should include tolerances for motion and reproducible positioning. These tolerances should ensure that variations will not cause reactivity design bases, coolant design bases, safety limits, or limiting conditions for operation in the technical specifications to be exceeded.

- The effect of the local environment on the material of the support structure should be considered in the design. The impact of radiation damage, mechanical stresses, chemical compatibility with the coolant and core components, and reactivity effects should not degrade the performance of the supports sufficiently to impede safe reactor operation for the design life of the reactor.
- The design should show that stresses or forces from reactor components other than the core could not cause malfunctions, interfere with safe reactor operation or shutdown, or cause other core-related components to malfunction.
- The core of an AHR used for medical isotope production could vary in dimension due to the purpose of the facility. Fuel can be transferred to and from the core during planned operations; consequently there are devices to ensure that such operations do not occur inadvertently. The design for a changing core configuration should contain features that ensure safe and reliable operation. This includes position tolerances to ensure safe and reliable reactor operation within all design limits including reactivity and cooling capability. The description should include the interlocks that keep the reactor core configuration from changing while the reactor is critical or while forced cooling is required, if applicable. The design should show how the reactor is shut down if unwanted action occurs.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements, and should be justified in this section of the SAR.

Review Procedures

The reviewer should confirm that the design bases define a complete support system.

Evaluation findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- The applicant has described the support system for the reactor core, including the design bases, which are derived from the planned operational characteristics of the reactor and the core design. All functional and safety related design bases can be achieved by the design
- The support structure includes acceptable guides and supports for other essential core components, such as control rods, nuclear detectors, and neutron reflectors.
- The support structure provides sufficient coolant flow to conform with the design criteria and to prevent loss of fuel barrier integrity from overheating.

- The support structure is composed of materials shown to be resistant to radiation damage, coolant or fuel solution erosion and corrosion, thermal softening or yielding, and excessive neutron absorption.
- The core support structure is designed to ensure a stable and reproducible core configuration for all anticipated conditions (e.g., reactor trips, coolant flow change, and core motion) through the reactor life cycle.
- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for the core support structure and included them in the technical specifications.

4.3 Reactor Vessel

Areas of Review

The vessel of the AHR is an essential part of the primary fuel system, and is the primary fuel barrier (including fission products). The vessel may also provide some support for components and systems mounted to the core supports.

The areas of review are the design bases of the vessel and the design details needed to achieve those bases. The information that the applicant should submit for review is discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the reactor vessel include the following:

- The vessel dimensions should include thickness and structural supports, and fabrication methods should be discussed. The vessel should be conservatively designed to withstand all mechanical and hydraulic forces and stresses to which it could be subjected during its lifetime.
- The construction materials and vessel treatment should resist chemical interaction with the fuel solution and be chemically compatible with other reactor components in the primary system. The compatibility between the vessel material and fuel solution should be addressed to prevent fuel solution leakage.
- The dimensions of the vessel and the materials used to fabricate it should assure that radiation damage to the vessel is minimized so that the vessel will remain intact for its projected lifetime.
- The construction materials and vessel treatment should be appropriate for preventing corrosion of the vessel interior due to fuel solution, and exterior due to pool water.
- A plan should be in place to assess irradiation of and chemical damage to the vessel materials. Remedies for damage or a replacement plan should be discussed.

- All penetrations and attachments to the vessel below the fuel solution level should be designed to avoid malfunction and loss of fuel solution.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements, and should be justified in this section of the SAR.

Technical Rationale

Fuel chemistry has been shown to affect corrosion resulting in possible loss of vessel integrity based on the experience from operation of previous reactors as described in References 2 and 3.

Review Procedures

The reviewer should confirm that the design bases describe the requirements for the vessel and that the detailed design is consistent with the design bases and acceptance criteria for the vessel.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- Information on gas composition (hydrogen, oxygen, nitrogen (NOx) and fission gases) from radiolytic decomposition of fuel solution, and gas handling and condensate return has been provided.
- The vessel system can withstand all anticipated mechanical and hydraulic forces and stresses to prevent loss of integrity, which could lead to a loss of fuel solution or other malfunction that could interfere with safe reactor operation or shutdown.
- The penetrations and attachments to the vessel are designed to ensure safe reactor operation. Safety and design considerations of any penetrations below the fuel solution level include analyses of potential malfunction and loss of fuel solution. The applicant discusses credible fuel spill and leak scenarios in Chapter 13, "Accident Analyses," Section 13.1.4.
- The construction materials, treatment, and methods of attaching penetrations and components are designed to prevent chemical interactions among the vessel and the fuel solution, pool water, and other components.
- The outer and inner surfaces of the vessel are designed and treated to avoid corrosion in locations that are inaccessible for the life of the vessel. Vessel surfaces will be inspected in accessible locations.
- The applicant has considered the possibility that fuel solution may leak into unrestricted areas, including ground water, and has included precautions to avoid the uncontrolled release of radioactive material.

- The design considerations include the shape and dimensions of the vessel to ensure sufficient radiation shielding to protect personnel and components. Exposures have been analyzed, and acceptable shielding factors are included in the vessel design.
- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for the vessel and included them in the technical specifications.
- The design features of the vessel offer reasonable assurance of its reliability and integrity for its anticipated life. The design of the vessel is acceptable to avoid undue risk to the health and safety of the public.

4.4 Biological Shield

Areas of Review

The radiation shields around non-power reactors are called biological shields and are designed to protect personnel and reduce radiation exposures to reactor components and other equipment. The principal design and safety objective is to protect the staff and public. The second design objective is to make the shield as thin as possible, consistent with acceptable protection factors. The medical isotope production AHR uses the neutron flux for fissioning and direct production of Mo-99. Access to this radioactive Mo-99 within a few days to a week is necessary because of the relatively short half-life of the material. This necessitates the transfer of the fuel solution to the separations facility at the plant site and this should be addressed in the shield design. Traditional methods of improving protection factors without increasing shield thickness are to use materials with higher density, higher atomic numbers for gamma rays, and higher hydrogen concentration for neutrons. The optimum shield design should consider all these.

Areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the biological shields include the following:

- The principal objective of the shield design should be to ensure that the projected radiation dose rates and accumulated doses in occupied areas do not exceed the limits of 10 CFR Part 20 and the guidelines of the facility ALARA (as low as is reasonably achievable) program discussed in Chapter 11 of the SAR.
- The shield design should address potential damage from radiation heating and induced radioactivity in reactor components and shields. The design should limit heating and induced radioactivity to levels that could not cause significant risk of failure.
- The pool design and the solid shielding materials should be apportioned to ensure protection from all applicable radiation and all conditions of operation.

- Shielding materials should be based on demonstrated effectiveness at other non-power reactors with similar operating characteristics, and the calculational models and assumptions should be justified by similar comparisons. New shielding materials should be justified by calculations, development testing, and the biological shield test program during facility startup.
- The analyses should include specific investigation of the possibilities of radiation streaming or leaking from shield penetrations, inserts, and other places where materials of different density and atomic number meet. Any such streaming or leakage should not exceed the stated limits.
- Supports and structures should ensure shield integrity, and quality control methods should ensure that fabrication and construction of the shield exceed the requirements for similar industrial structures.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements. The applicant should justify the proposed technical specifications in this section of the SAR.

Review Procedures

The reviewer should confirm that the objectives of the shield design bases are sufficient to protect the health and safety of the public and the facility staff; and that the design achieves the design bases. The reviewer should compare design features, materials, and calculational models with those of similar non-power reactors that have operated acceptably.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The analysis in the SAR offers reasonable assurance that the shield designs will limit exposures from the reactor and reactor-related sources of radiations so as not to exceed the limits of 10 CFR Part 20 and the guidelines of the facility ALARA program.
- The design offers reasonable assurance that the shield can be successfully installed with no radiation streaming or other leakage that would exceed the limits of 10 CFR Part 20 and the guidelines of the facility ALARA program.
- Reactor components are sufficiently shielded to avoid significant radiation related degradation or malfunction.
- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for the shield and included them in the technical specifications.

4.5 Nuclear Design

In this section of the SAR, the applicant should show how the systems described in this chapter function together to form a nuclear reactor that can be operated and shut down safely from any operating condition. The analyses should address all possible operating conditions throughout the reactor's anticipated life cycle. Because the information in this section describes the characteristics necessary to ensure safe and reliable operation, it will determine the design bases for most other chapters of the SAR and the technical specifications. The text, drawings, and tables should completely describe the reactor operating characteristics and safety features.

4.5.1 Normal Operating Conditions

Areas of Review

In this section of the SAR, the applicant should discuss the configuration for a functional reactor that can be operated safely.

The areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on normal operating conditions include the following:

- The information should show a complete, operable reactor core. Control rods should be sufficiently redundant and diverse to control all proposed excess reactivity safely and to safely shut down the reactor and maintain it in a shutdown condition. The analyses of reactivities should include individual and total control rod effects.
- The information should describe anticipated power oscillations and their effects on safety-related equipment and systems. These oscillations should be shown to be self-damping and controllable.
- Anticipated core evolution should account for uranium burnup; actinide and fission product buildup; changes in fuel solution chemical stability due to radiolysis including changes in pH, temperature, pressure, density, and specific heat capacity; and poisons, both from fission products and those added by design, for the life of the reactor. This should also analyze the total fuel solution volume as a function of total burnup.
- The analyses should show initial and changing reactivity conditions, control rod reactivity worths, and reactivity worths of reflector units, and incore components for all anticipated configurations. There should be a discussion of administrative and physical constraints that would prevent inadvertent movement that could suddenly introduce more than one dollar of positive reactivity or an analyzed safe amount, whichever was larger. These analyses should address movement, flooding, and voiding of core components, including fission gas generation and failure of the gas recombiners.

- The reactor kinetic parameters and behavior should be shown, along with the dynamic reactivity parameters of the instrumentation and control systems. Analyses should prove that the control systems will prevent nuclear transients from causing loss of fuel barrier integrity or uncontrolled addition of reactivity.
- The information should include calculated core reactivities for the possible and planned configurations of the control rods. The reactivity impacts of radiolytic gas and void formation, fission product gas removal, fuel solution and acid addition, and condensate return to the core should be provided. If only one core configuration will be used over the life of the reactor, the applicant should clearly indicate this. The limiting core configuration during reactor life should be indicated. This information should be used for the analyses in Section 4.6 of the SAR. The information should also include reactivities for fuel solution storage and handling outside the reactor, fuel transport to and from the core, as well as the effects of core recycling after isotope removal processing.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements, and should be justified in this section of the SAR.

Technical Rationale

Power oscillations in AHRs are expected and usually are self-limiting due to the large negative reactivity feedback coefficients. It is necessary to assure that oscillations are bounded for proper operation of the reactor based on operation of previous AHRs found in References 2 and 3.

Review Procedures

The reviewer should confirm that a complete, operable core has been analyzed.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- The applicant has described the proposed initial core configuration and analyzed all reactivity conditions. These analyses also include other possible core configurations planned during the life of the reactor. The assumptions and methods used have been justified and validated.
- The analyses include reactivity and geometry changes resulting from burnup, plutonium buildup, the buildup and removal of fission products, both in solution and in the gas management system, fuel solution condensate return to the core, fuel solution and acid addition, and the use of poisons, as applicable.

- The reactivity analyses include the reactivity values for the incore components, such as control rods or cooling coils, and the excore components, such as the reflector and pool. The assumptions and methods used have been justified.
- The analyses address the steady power operation and kinetic behavior of the reactor and show that the dynamic response of the control rods and instrumentation is designed to prevent uncontrolled reactor transients.
- The analyses show that any incore components that could be flooded or voided could not cause reactor transients beyond the capabilities of the instrumentation and control systems to prevent fuel damage or other reactor damage. This also should include failure of radiolytic recombiners and subsequent pressure pulses resulting from deflagration or explosions of radiolytic gas.
- The analyses address a limiting core that is the minimum size possible with the planned fuel. Since this core configuration has the highest power density, the applicant uses it in Section 4.6 of the SAR to determine the limiting thermal-hydraulic characteristics for the reactor.
- The analyses and information in this section describe a reactor core system that could be designed, built, and operated without unacceptable risk to the health and safety of the public.
- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for minimal operating conditions and included them in the technical specifications. The applicant has also justified the proposed technical specifications.

4.5.2 Reactor Core Physics Parameters

Areas of Review

In this section of the SAR, the applicant should present information on core physics parameters that determine reactor operating characteristics and are influenced by the reactor design. The principal objective of an AHR is to produce isotopes for use, and not pose an unacceptable risk to the health and safety of the public. By proper design (sufficiently low power density), the reactor will operate at steady power; however power oscillation in AHRs is expected, and the reactor systems will be able to terminate or mitigate transients without reactor damage. The areas of review should include the design features of the reactor core that determine the operating characteristics and the analytical methods for important contributing parameters. The results presented in this section of the SAR should be used in other sections of this chapter.

The areas of review are discussed further in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on reactor core physics parameters include the following:

- The calculational assumptions and methods should be justified and traceable to their development and validation, and the results should be compared with calculations of other similar facilities and previous experimental measurements. The ranges of validity and accuracy should be stated and justified.
- Uncertainties in the analyses should be provided and justified
- Methods used to analyze neutron lifetime, effective delayed neutron fraction, and reactor periods should be presented, and the results should be justified. Comparisons should be made with similar reactor facilities. The results should agree within the estimates of accuracy for the methods.
- Coefficients of reactivity (temperature, void, and power) should all be negative over the significant portion of the operating ranges of the reactor. The results should include estimates of accuracy. If any parameter is not negative within the error limits over the credible range of reactor operation, the combination of the reactivity coefficients should be analyzed and shown to be sufficient to prevent reactor damage and risk to the public from reactor transients as discussed in Chapter 13 of the SAR.
- Changes in feedback coefficients with core configurations, power level, and fuel burnup should not change the conclusions about reactor protection and safety, nor should they void the validity of the analyses of normal reactor operations.
- The methods and assumptions for calculating the various neutron flux densities should be validated by comparisons with results for similar reactors. Uncertainties and ranges of accuracy should be given for other analyses requiring neutron flux densities, such as fuel burnup, thermal power densities, radiolytic gas production, control rod reactivity worths, and reactivity coefficients. This should also include a description of the method of calculating and verifying the burnup and the fuel composition after isotope removal. This also should include methods to analyze gas evolution and the generation of void spaces and predict their reactivity effects.
- Technical specifications, if required, should be proposed according to the guidance in Chapter 14 of the format and content guide, which proposes limiting conditions for operation and surveillance requirements, and should be justified in this section of the SAR.

Review Procedures

The reviewer should confirm that generally accepted and validated methods have been used for the calculations, evaluate the dependence of the calculational results on reactor design features

and parameters, review the agreement of the methods and results of the analyses with the acceptance criteria, and review the derivation and adequacy of uncertainties and errors.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- The analyses of neutron lifetime, effective delayed neutron fraction, and coefficients of reactivity have been completed, using methods validated at similar reactors and experimental measurements.
- The effects of fuel burnup and reactor operating characteristics for the life of the reactor are considered in the analyses of the reactor core physics parameters.
- The numerical values for the reactor core physics parameters depend on features of the reactor design, and the information given is acceptable for use in the analyses of reactor operation.
- The applicant has justified appropriate limiting conditions for operation and surveillance requirements for the reactor core physics parameters and included them in the technical specifications. The applicant has also justified the technical specifications.

4.5.3 Operating Limits

Areas of Review

In this section of the SAR, the applicant should present the nuclear design features necessary to ensure safe operation of the reactor core and safe shutdown from any operating condition. The information should demonstrate a balance between fuel loading, control rod worths, and number of control rods. The applicant should discuss and analyze potential accident scenarios, as distinct from normal operation, in Chapter 13 of the SAR.

The areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on operating limits include the following:

- All operational requirements for excess reactivity should be stated, analyzed, and discussed. These could pertain to at least the following:
    - temperature coefficients of reactivity
    - fuel burnup between reloads or shutdowns
    - void coefficients
    - xenon and samarium override

- overall power coefficient of reactivity if not accounted for in the items listed above
- fuel processing, handling, and recycling, and implications to reactor safety

- Credible inadvertent insertion of excess reactivity should not damage the reactor or fuel barrier; this event should be analyzed in Sections 4.5 and 4.6 and Chapter 13 of the SAR.
- The minimum amount of total control rod reactivity worth to ensure reactor subcriticality should be stated.
- A transient analysis assuming that an instrumentation malfunction drives the most reactive control rod out in a continuous ramp mode in its most reactive region should be performed. The analysis should show that the reactor would not be damaged and fuel barrier integrity would not be lost. Reactivity additions under accident conditions should be analyzed in Chapter 13 of the SAR.
- An analysis should be performed that examines reactivity assuming that the reactor is operating at its maximum licensed conditions, normal electrical power is lost, and the control rod of maximum reactivity worth and any non-scrammable control rods remain fully withdrawn. The analysis should show how much negative reactivity must be available in the remaining scrammable control rods so that, without operator intervention, the reactor can be shut down safely and remain subcritical without risk of fuel damage even after temperature equilibrium is attained, and all transient poisons such as xenon are reduced, with consideration for the most reactive core loading.
- On the basis of analysis, the applicant should justify a minimum negative reactivity (shutdown margin) that will ensure the safe shutdown of the reactor. This discussion should address the methods and the accuracy with which this negative reactivity can be determined to ensure its availability.
- The core configuration with the highest power density possible for the planned fuel should be analyzed as a basis for safety limits and limiting safety system settings in the thermal-hydraulic analyses. The core configuration should be compared with other configurations to ensure that a limiting configuration is established for steady power.
- The effects of surface frothing as an intermittent reflector/moderator should be considered.
- The applicant should propose and justify technical specifications for safety limits, limiting safety stem settings, limiting conditions for operation, and surveillance requirements as discussed in Chapter 14 of the format and content guide.

Review Procedures

The reviewer should confirm that the methods and assumptions used in this section of the SAR have been justified and are consistent with those in other sections of this chapter.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- The applicant has discussed and justified all excess reactivity factors needed to ensure a readily operable reactor. The applicant has also considered the design features of the control systems that ensure that this amount of excess reactivity is fully controlled under normal operating conditions.
- The discussion of limits on excess reactivity shows that a credible rapid withdrawal of the most reactive control rod or other credible failure that would add reactivity to the reactor would not lead to loss of fuel barrier integrity. Therefore, the information demonstrates that the proposed amount of reactivity is available for normal operations, but would not cause unacceptable risk to the public from a transient.
- The definition of the shutdown margin is negative reactivity obtainable by control rods to ensure reactor shutdown from any reactor condition, including a loss of normal electrical power. With the assumption that the most reactive control rod is inadvertently stuck in its fully withdrawn position, and non-scrammable control rods are in the position of maximum reactivity addition, the analysis derives the minimum negative reactivity necessary to ensure safe reactor shutdown. The applicant conservatively proposes a shutdown margin of xx in the technical specifications. The applicant has justified this value; it is readily measurable and is acceptable.
- The SAR contains calculations of the peak thermal power density achievable with any core configuration. This value is used in the calculations in the thermal-hydraulic section of the SAR to derive reactor safety limits and limiting safety system settings, which are acceptable.

4.6 Thermal-Hydraulic Design

Areas of Review

The information in this section should enable the reviewer to determine the limits on cooling conditions necessary to ensure that fuel barrier integrity will not be lost under any reactor conditions, including accidents. In the case of a low power aqueous homogeneous reactor there is no concern about damaging fuel; however, there is concern about damaging the fuel barrier (and fission product barriers).

Since the fuel solution is free to move in an aqueous form, the temperature within the fuel can more readily equalize; however, the power shape may still cause some hot spots, which may lead to instability and ultimately fuel and fission product precipitation. Because some of the factors in the thermal-hydraulic design are based on experimental measurements and correlations that are a function of coolant conditions, the analyses should confirm that the values of such parameters are applicable to the reactor conditions analyzed.

The AHR design may contain a flow loop that circulates radiolysis gas, fission gases, water vapor, and a cover gas. The reviewer needs to determine the constituents in the bubbly mixture and cover gas. The capacity of recombiners and condensers in the system may limit achievable stable and safe operation. The reviewer needs to determine if the makeup and flow rate of the circulating mixture is within the design limits of any recombiners for radiolysis gases or condensers of water vapor. The reviewer should also ensure that any sources and sinks of energy in the flow loop are within the design capacities of any heat exchangers in the loop

The areas of review are discussed in this section of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on thermal-hydraulic design include the following:

- The applicant should propose criteria and safety limits based on the criteria for acceptable safe operation of the reactor, thus ensuring fuel barrier integrity under all analyzed conditions. The discussion should include the consequences of these conditions and justification for the alternatives selected. It should also include the limiting power density to offset the onset of instability following perturbation to the system (including those from radiolytic gas generation). These criteria could include the following:
    - There should be no coolant flow instability in any cooling coil that could lead to a significant decrease in fuel cooling. This can be ascertained using a suitable onset-of-flow-instability correlation.
    - The departure-from-nucleate-boiling ratio should be no less than 2.0 along any coolant coil.
- Safety limits, as discussed in Chapter 14 of the format and content guide, should be derived from the analyses described above, the analyses in Section 4.5.3 of the SAR, and any other necessary conditions. The safety limits should include conservative consideration of the effects of uncertainties or tolerances and should be included in the technical specifications.
- Limiting safety system settings (LSSSs), as discussed in Chapter 14 of the format and content guide of the SAR, should be derived from the analyses described above, the analyses in Section 4.5.3 of the SAR, and any other necessary conditions. These settings

should be chosen to maintain fuel barrier integrity when safety system protective actions are conservatively initiated at the LSSSs.

- A forced-flow reactor should be capable of switching to natural-convection flow without jeopardizing safe reactor shutdown. Loss of normal electrical power should not change this criterion. These limits should be based on the thermal-hydraulic analyses and appear in the technical specifications.
- For AHRs undercooling may change the pH of the system resulting in fuel or fission product plate-out or precipitation and should be considered in the thermal hydraulic design.
- The gas treatment system including recombiners will contain fission product gas and hazardous chemicals. Since this forms a part of the fuel barrier, cooling systems associated with this system should be considered in this section and shown to be adequate to maintain the function of these systems and maintain fuel barrier integrity under normal and abnormal operation.
- The pool water surrounding the reactor vessel is expected to provide some heat removal during steady state operation. The effects of loss of pool cooling should be analyzed and shown not to affect the fuel barrier (vessel) integrity under normal and abnormal operation.

Technical rationale

Previous experience with AHRs has indicated the importance of the interrelationship of temperature of the fuel solution, chemical pH, and radiolytic gas recombination rates as described in References 2 and 3.

Review Procedures

The reviewer should confirm that the thermal-hydraulic analyses for the reactor are complete and address all issues that affect key parameters (e.g., flow, temperature, pressure, power density, pH and peaking). The basic approach is an audit of the SAR analyses, but the reviewer may also perform independent calculations to confirm SAR results or methods.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will appear in the staff's safety evaluation report:

- The information in the SAR includes the thermal-hydraulic analyses for the reactor. This includes the radiolytic gas generation, void formation and collapse, and fuel solution mixing, which might minimize precipitation with the fuel volume or frothing on fuel solution surface, and subsequent core transient. The applicant has justified the assumptions and methods and validated their results.

- All necessary information on the primary coolant hydraulics and thermal conditions of the fuel solution is specified for this reactor. The analysis has considered the various approaches/systems for heat removal such as the cooling coils, the pool, and the gas management system. The analyses give the limiting conditions of these features that ensure fuel barrier integrity.
- Safety limits and limiting safety system settings are derived from the thermal-hydraulic analyses. The values have been justified and appear in the technical specifications. The thermal-hydraulic analyses on which these parameters are based ensure that overheating or overcooling during any operation or credible event will not cause loss of fuel barrier integrity and unacceptable radiological risk to the health and safety of the public nor cause fuel/fission product plate out or precipitation which could lead to loss of fission product integrity. The analysis includes methods for calculating the induced natural convection within the homogeneous fuel solution.

4.7 Gas Management System

Areas of Review

This section of the SAR should contain the design information on all components of the Gas Management System. The design information should be presented in drawings, diagrams, text, and analysis in sufficient detail for staff to understand the flow of evolved gases and fission products from their generation in the reactor core to their ultimate release. Using this information, the staff should determine whether there is reasonable assurance that the gas management system will be capable of preventing a hydrogen deflagration/detonation hazard, containing hazardous chemicals and volatile fission products until they can be released safely and in accordance with environmental release criteria, and withstanding any pressure transients within the reactor core.

In evaluating the analysis demonstrating these capabilities, the staff should ensure that these criteria can be met for the maximum power density that is considered credible during power oscillations. The applicant should provide justification for the maximum fission product and radiolytic gas generation rates during power oscillations.

The areas of review are discussed in this section of the format and content guide.

Technical Rationale

Areas of review, acceptance criteria, and evaluation findings, are all dictated by five hazards; an inadvertent criticality outside the reactor core, a radiolytic gas deflagration/detonation, an NOx release, a release of gaseous fission products, and an increase in the pressure in the headspace over the core. Although the reactor will operate in a steady state mode, power oscillations may be possible. Therefore, the design must be sufficiently robust to sustain fission product and

NOx generation, heat generation, and pressures that will occur at peak power. The dynamics of criticality accidents show that a sudden spike in power of several orders of magnitude can occur in solution systems. This can occur when there is a rapid reactivity insertion that causes the solution to go prompt critical. The spike is generally terminated by the negative reactivity effect of void formation due to radiolytic gas generation. The actual first spike yield and total fission yield during accidents and planned critical excursions can vary widely, so fairly conservative assumptions should be made concerning the assumed dynamics during a prompt critical excursion.

Acceptance Criteria

The design of the gas management system should be found acceptable if it meets the following acceptance criteria:

- The geometry of all equipment and piping should be favorable geometry (e.g., subcritical when filled with optimally moderated reactor core solution).
- If any portions of the equipment or piping are not favorable geometry, the applicant's analysis should demonstrate that no single failure can result in a criticality outside the core.
- Monitoring should be provided periodically for the long-term accumulation of fissionable material entrained in the system
- The radiolytic gas recombiner must be capable of preventing a hydrogen deflagration/detonation anywhere within the gas confinement boundary, and especially in the reactor vessel
- The cooling system for the recombiner must be sufficient to dissipate the reaction heat.
- The materials of construction must be compatible with the chemical environment (e.g., NOx gases), such that corrosion cannot lead to loss of confinement.
- The maximum pressure resulting from heat and radiolytic gas generation must not exceed the design pressure for the system, unless redundant pressure relief features are described.
- The maximum release of fission gases must not exceed applicable regulatory criteria
- The maximum release of hazardous chemicals must not exceed applicable regulatory criteria. (This should include any potential effect on workers in the production facility.)
- Monitoring should be provided for concentrations of hazardous chemicals and fission products to detect build-up and leaks.

Acceptance criteria for any credited cooling function of the gas management system are found in Chapter 5. Acceptance criteria for the recombiner's cooling system are found in Chapter 9.

Technical Rationale

Most of these are events that can result in release pathways through the loss of confinement (e.g., by deflagration/detonation, corrosion, or over-pressurization. The exception to this is criticality, which will result in the generation of more fission products (though this will be small compared to those generated during normal reactor operations). Criticality should not be allowed outside the reactor vessel, because there are no means to control it or adequately protect personnel outside such an environment. Ideally, all equipment that is connected to the reactor vessel should be favorable geometry, though at some point a connection might need to be made to non-favorable geometry. Maintaining solution and aerosolized fuel within the reactor core (ideally) or favorable geometry part of the gas management system (as an anticipated upset) is crucial. For chemical releases, both the effects of NOx on personnel and on equipment must be considered.

Review Procedures

The reviewer should confirm that the design of the gas management system and the associated analysis is sufficient to provide reasonable assurance of safe operation of the reactor and compliance with all applicable chemical and radiological release criteria.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The applicant has described the system in sufficient detail to prevent criticality outside the reactor vessel, due to the entrainment of uranium in the gas, slow accumulation over time, or backflow of solution from the reactor vessel.
- The applicant has described the system in sufficient detail to prevent occurrence of a radiolytic hydrogen deflagration/detonation that could breach confinement and result in exceeding the applicable regulatory limits on hazardous chemical or fission product releases.
- The applicant has designed the system so as to withstand the maximum pressure that could occur during credible power oscillations, so as to avoid breaching confinement and exceeding applicable regulatory limits.
- The applicant has designed the system to allow for control of the reactor during possible explosions or increases in pressure.

- The applicant has designed the system to be compatible in the chemical environment to which it will be exposed, avoiding corrosion that could result in a release of hazardous chemicals or fission products exceeding applicable regulatory limits.
- The applicant has designed sufficient surge capacity to contain hazardous chemicals and allow for the decay of fission products until they can be released in accordance with applicable regulatory limits.

Technical Rationale

These conclusions are driven by the consideration of hazards discussed previously.

4.8 References

1. "Homogeneous Aqueous Solution Reactors for the Production of Mo-99 and Other Short Lived Radioisotopes," IAEA –TECDOC-1601, International Atomic Energy Agency, September 2008.

2. Fluid Fueled Reactors "Part 1 Aqueous Homogeneous Reactors," James A. Lane, editor, Addison Wesley, 1958. http://moltensalt.org/references/static/downloads/pdf/

3. C. Cappiello, T. Grove, and R. Malenfant, "Lessons Learned from 65 Years of Experience with Aqueous Homogenous Reactors," LA-UR-10-02947, Los Alamos National Laboratory, May 2010.

APPENDIX C

Chapter 5, Reactor Coolant Systems, Part 1, Standard Format and Content

5 REACTOR COOLANT SYSTEMS

In this chapter of the SAR, the applicant should give the design bases, descriptions, and functional analyses of the AHR coolant systems. The principal purpose of the coolant systems is to safely remove the fission and decay heat from the fuel and dissipate it to the environment. The discussions should include all significant heat sources in the reactor and should show how the heat is safely removed and transferred to the environment.

The reactor core in an AHR consists of that region of the vessel occupied by the solution containing the fission power producing fissile material. In an AHR, the core geometry may change with time due to changes in density and voiding of the solution. The core does not include that part of the fuel solution that may become entrained into the gas. It is expected that during normal operation most if not all of the heat generation will occur in the core. Decay heat, however, can be produced by two separate sources within the reactor vessel: by soluble and insoluble decay products that remain in the core, and by gaseous decay products and any other decay products entrained by those gases into the gas space above the core. It may be necessary to provide separate systems to remove the decay heat from each of these regions.

For an AHR the term primary cooling system replaces the term "primary coolant system." The primary cooling systems for an AHR are those components and systems that remove heat from the core. Heat from an AHR core is expected to be removed through one or more cooling coils immersed in the core and this system is expected to remove the majority of heat produced in the core. This guidance does not pertain to cooling systems in which the fuel solution is transported outside the vessel in an external loop. Supplemental cooling systems may be necessary to remove heat from the fission gases above the core and heat produced in the recombiners. If the AHR is designed to operate at such low power levels that no significant temperature increases will occur during normal operation, an engineered primary cooling system is not required For such a design, the applicant should, in Chapter 4, "Reactor Description," of the SAR, discuss the disposition of the heat produced, estimate potential temperature increases during operation, and justify why an engineered primary cooling system for heat removal is not required. In this chapter the applicant should summarize those considerations and conclusions.

The applicant should also describe and discuss in this chapter systems to remove and dispose of the waste heat. The design bases of the reactor cooling systems for the full range of normal operation should be based on ensuring acceptable reactor conditions established in Chapter 4 of the SAR. The design bases of any features of the core cooling system designed to respond to poten-

tial accidents or to mitigate the consequences of potential accidents should be derived from the analyses in Chapter 13, "Accident Analyses." These features should be summarized in this chapter and discussed in detail in Chapter 6, "Engineered Safety Features." In this chapter the applicant should discuss and reference the technical specifications where analyses are used as the basis for a requirement.

The "secondary cooling systems" for an AHR are those systems and components that transfer heat from the primary cooling systems to the environment or heat sink(s). These secondary cooling systems may involve additional heat exchangers and pumps to circulate the coolant.

In this chapter, the applicant should identify and discuss reactor cooling systems including auxiliary and reactor core subsystems that remove heat from the reactor. The description will thus include for example, information on core cooling coils which are the primary cooling system, and the partition of heat removal by additional reactor cooling systems that remove heat directly such as the gas management system or passively through the reactor vessel walls. These additional reactor cooling systems should be summarized in Section 5.1 and discussed in detail in Chapter 4 "Reactor Description" if reactor core systems are involved such as a gas management system. Details of auxiliary systems using coolant other than the primary cooling system such as passive core cooling by the pool surrounding the vessel should be discussed in Chapter 9, "Auxiliary Systems."

In this chapter the applicant should describe all auxiliary and subsystems that use and contribute to the heat load of either the primary or secondary cooling systems. Any auxiliary systems using coolant from other sources should be discussed in Chapter 9, "Auxiliary Systems."

5.1 Summary Description

In this section the applicant should provide a brief description of the primary cooling systems and supplementary core heat removal pathways, summarizing the principal features. Information should include the following:

- type of coolant: liquid, gas, or solid (conduction to surrounding structures)
- type of cooling system:
- type of coolant flow in the primary cooling system: forced-convection, natural-convection, or both
- type(s) of secondary cooling system(s), if present, and the method of heat disposal to the environment
- capability to provide sufficient heat removal to support continuous operation at full licensed power

- special or facility-unique features

For an AHR, in this section the applicant should provide the following additional information on the reactor cooling systems unique to the principal features of AHRs. This information should include the following:

- Supplementary core heat removal pathways: if the primary coolant system is not the sole means of heat removal and the core heat removal is partitioned between supplementing pathways these additional pathways should be mentioned. The energy partitioning should be given. These other means of heat transport from the core should be summarized, including the corresponding amount of heat transported from the core and fraction of total core heat removed.

5.2 Primary Cooling System

The basic requirements and design bases of the primary cooling system are to maintain reactor facility conditions within the range of design conditions and accident analyses assumptions derived from other chapters of the SAR, especially Chapters 4 and 13. The applicant should show the interrelationships among all SAR chapters and the way the designed primary cooling system provides all necessary functions. The following information should be included:

- Design bases and functional requirements of the primary cooling system.
- Schematic and flow diagrams of the system, showing such essential components as the heat source (reactor core), heat sink (heat exchanger), pumps, piping, valves, control and safety instrumentation, interlocks, and other related subsystems.
- Tables of allowable ranges of important design and operating parameters and specifications for the primary cooling system and its components, including
  - coolant material
  - coolant flow rates
  - inlet and outlet temperatures and pressure throughout the system
  - elevation of components and water levels relative to the reactor core
  - construction materials of components
  - fabrication specifications of safety-related components
  - coolant quality requirements for operation and shutdown conditions, including pH and conductivity at a minimum
- Discussions and analyses keyed to drawings showing how the system provides the necessary cooling for all heat loads and all potential reactor conditions analyzed in the thermal-hydraulics section of Chapters 4 and 13, including the following:

- Removal of heat from the fuel and waste gases by all modes of heat transfer that apply. Discussion and analyses of the effect of the size, shape, and structural features of the primary vessel or surrounding pool on cooling characteristics; the function of the pool as a heat reservoir, and the effect of water depth on natural thermal convection cooling.

- Transfer of heat from the primary coolant to a secondary coolant system for all reactor conditions. This discussion should include any heat exchanger design and operating conditions. Some AHRs may have only a primary cooling system that functions as a heat reservoir. For such systems, the analyses should include any factors that limit continuous operation, such as pool water temperature, and the proposed technical specifications that ensure operation within the analyzed limits.

- Safe reactor shutdown, including passive removal of decay heat from the fuel. This discussion should include the loss of offsite electrical power.

- Locations, designs, and functions of essential components such as primary cooling coils. These components ensure that the primary cooling system is operable and that uncontrolled loss or discharge of fuel solution from the fuel core tank into the primary cooling system does not occur. In addition, locations, designs, and functions of such essential components as drains, siphon-breaks, pumps, isolation valves, and check valves. Radiological effects of potential coolant releases should primarily be analyzed in Chapter 11, "Radiological Protection Program and Waste Management."

- Discussion of the control and safety instrumentation, including location and functions of sensors and readout devices. The scram or interlock functions that prevent safety limits from being exceeded should be shown and discussed, including the related technical specifications.
- Description and function of any special features of the primary cooling system.
- Brief description and functions of special features or components of the primary coolant system that affect or limit personnel radiation exposures from such radionuclides as nitrogen-16 and argon-41 and from radioactive contaminants.
- Description of radiation monitors or detectors incorporated into the primary cooling system and discussion of their functions.
- Brief discussion and references to detailed discussions in later sections of auxiliary systems using primary cooling, such as coolant cleanup, makeup water, emergency core cooling, and biological shield cooling. The direct effect of these auxiliary systems on the design and functioning of the primary cooling system should be discussed.
- Discussion of leak detection and allowable leakage limits, if any.

- Discussion of normal primary coolant radiation concentration limits, including sampling frequency, isotopes of interest, and actions to be taken if limits are exceeded.
- For reactors that have closed systems, a discussion of allowable hydrogen limits in air spaces that are in contact with the primary coolant.
- Discussion of technical specification requirements for parameters of the primary cooling system, including the bases and surveillance requirements.

5.3 Secondary Coolant System

In this section the applicant should give information about those AHRs that include a secondary coolant system. For the others, the applicant should state that a secondary coolant system is not needed and should justify that conclusion. The following information should be provided:

- The design bases and functional requirements of the secondary coolant system, including whether the system is designed for continuous full-power reactor operation and whether it is shared with other reactors within the facility.
- Schematic and flow diagrams of the secondary coolant system, showing such essentials as how the heat exchanger connects the primary cooling system (the heat source) to the secondary coolant system, pumps, piping, valves, control and safety instrumentation, interlocks, and interface with the environment for ultimate release of the heat.
- Tables of the range of important design and operating parameters and specifications of the secondary coolant system, including the following:
    - coolant material and its source
    - coolant flow rates
    - type of heat dissipation system, such as cooling tower, refrigerator radiator, or body of water
    - location of heat dissipation system in relation to the reactor and the heat exchanger
    - construction materials and fabrication specifications of components
    - heat dissipation specifications related to environmental factors (e.g., temperature and humidity)
    - specifications and limitations on coolant quality and corrosion of the secondary coolant system components including the environmental effects of the use of secondary coolant chemicals
- Discussion and functional analyses keyed to the drawings showing how the system provides the necessary cooling for all potential reactor conditions. These discussions should address the following:

- Inlet and outlet temperatures and pressures throughout the system, including the pressure differential between the primary and secondary coolant systems in the heat exchanger. (The applicant should discuss how the pressure in the secondary coolant system is maintained above that in the primary coolant system for all operating conditions, or analyze the radiological effect of leakage of contaminated primary cooling into the secondary coolant system. Isolation of the heat exchanger during shutdown periods is an acceptable method to control potential primary-to-secondary system leakage if secondary coolant system pressure is lower than primary cooling system pressure only during periods of system shutdown. The applicant does not need to perform an analysis of primary-to-secondary-system leakage if secondary coolant system pressure is lower than primary cooling system pressure for only short periods for system testing or repair. If the transfer of primary coolant into the secondary coolant system is caused by an abrupt event, such as a tube rupture in the heat exchanger, the analysis should be given in Chapter 13 and summarized here.)

- Control of heat removal from the secondary coolant system necessary to maintain temperatures in the core and primary cooling system within the limits derived in the thermal-hydraulics analyses in Chapters 4 and 13 of the SAR.

- Removal of heat from the heat exchanger. and release to the environment when the primary cooling system operates in all anticipated and licensed modes, as applicable.

- Safe reactor shutdown and removal and dissipation of decay heat.

- Response of the secondary coolant system to the loss of primary coolant.

- Locations, designs, and functions of such essential components as drains, sumps, pumps, makeup water, and check valves that ensure contaminated primary coolant is not inadvertently transferred to the secondary coolant system and released to the environment.

- Discussion of control and safety instrumentation, including locations and functions of sensors and readout devices and interlocks or safety capabilities.
- Descriptions of functions of any radiation monitors or detectors incorporated into the secondary coolant system. Discussion of surveillance to measure secondary coolant activity including frequency, action levels, and action to be taken.

- Brief comments and reference to detailed discussion in other sections of auxiliary cooling systems that transfer heat to the secondary coolant system.
- Discussion of technical specification requirements, as appropriate, for the secondary coolant system, including the bases and surveillance requirements.

5.4 Primary Coolant Cleanup System

In the AHR, the primary coolant is separated from the fuel solution by a material barrier, such as a cooling tube wall, which isolates the mobile fission products from the coolant system components. For an AHR, the inner wall radius of an immersed cooling coil (e.g. tube) is the primary coolant boundary; analogous to defining the outer radius of fuel cladding surrounding solid fuel as a primary coolant boundary. Experience has shown that integrity of cladding, and presumably other metal boundaries is improved if corrosion is reduced by maintaining high chemical purity of the coolant. Thus, purity of the primary coolant should be maintained as high as reasonably possible for the following reasons:

- to limit the chemical corrosion of primary coolant barrier, control and safety rod cladding, reactor vessel or pool, and other essential components in the primary cooling system
- to limit the concentrations of particulate and dissolved contaminants that could be made radioactive by neutron irradiation

The applicant should give the following information:

- The design bases and functional requirements of the primary coolant cleanup system. Experience at non-power reactors has shown that with a well-planned water cleanup system and good housekeeping practices, primary coolant quality can be maintained within the following ranges:
  - electrical conductivity <5 µmho/cm
  - pH between 5.5 and 7.5

  The design bases should be consistent with the discussions in Chapter 4 of the SAR.
- Schematic drawings and flow diagrams of the primary coolant cleanup loop.
- Table of specifications for the cleanup system demonstrating that it is designed for the volume and throughput of the primary cooling system.
- Locations and functions of control and monitoring instrumentation, including sensors, recorders, and meters. The discussion of monitors should include methods for continuously assessing coolant quality and effectiveness of the cleanup system.
- Locations and functional designs of cleanup system components such as branch points, pumps, valves, filters, and demineralizers.

- Discussion of schedules and methods for replacing or regenerating resins and filters and disposing of resultant radioactivity to ensure that radiation exposures do not exceed the limits discussed in Chapter 11 of the SAR.
- Summary of methods for predicting, monitoring, and shielding radioactivity deposited in filters and demineralizers from routine operations. The detailed discussion should be in Chapter 11.
- Summary of methods for predicting and limiting exposures of personnel in the event of inadvertent release of excess radioactivity in the primary cooling system and deposition in filters and demineralizers. The detailed discussion should be in Chapter 13.
- Provisions in the design and operation of the cleanup system to avoid malfunctions that could lead to significant loss of primary coolant or release of contaminated coolant, which could cause radiological exposure of personnel or release to the unrestricted environment to exceed the requirements in 10 CFR Part 20 and the facility ALARA (as low as is reasonably achievable) program guidelines.
- Discussion of technical specification requirements for the primary coolant cleanup system, including the bases and surveillance requirements.

5.5 Primary Coolant Makeup Water System

During operations at non-power reactors with a water-based primary cooling system, primary coolant must be replaced or replenished. Coolant may be lost as a result of radiolysis, designed leakage as from pump seals, or other operational activities. The AHR should include a system or a procedure that meets the projected needs for coolant. The makeup water system need not be designed to provide a rapid, total replacement of the primary coolant inventory, but should be able to maintain the minimum acceptable water quantity and quality for reactor operation.

The applicant should provide the following information:

- The design bases for the primary coolant makeup water system that account for all activities that could cause a decrease in the primary coolant. A large loss-of-coolant event should be analyzed in Chapter 13 of the SAR. Although a required emergency core cooling system need not be a part of the makeup water system, it should be discussed in Chapter 6 if it exists.
- Schematic diagrams and functional discussions that show the source of water, the methods of addition to the primary cooling system, and the requirements for pretreatment before addition.
- Locations and functions of control instrumentation, including sensors, readout displays, and interlocks. Methods should be discussed for tracking additions of makeup water to

detect significant changes that might indicate leaks or other malfunction of the primary cooling system.

- Discussion of safety systems and administrative controls to ensure that the system or procedures for adding makeup water will not lead to significant loss of primary coolant and will prevent leakage of contaminated coolant into the potable water supply.
- Discussion of technical specification requirements for the primary coolant makeup water system, including the bases and surveillance requirements.

5.6 Nitrogen-16 Control System

When ordinary oxygen is irradiated with neutrons of sufficient energy, nitrogen-16, a high-energy beta and gamma emitter with a 7-second half-life, is formed. In water-cooled reactors operated above a few hundred kilowatts, the radioactivity of this nuclide may require specific systems or procedures for limiting personnel exposure.

In reactors with forced- convection cooling, the coolant carrying the nitrogen-16 out of the core may be passed through a system such as a large shielded and baffled tank. This delay allows the radioactivity to decay significantly before the coolant emerges from the shielding. Another method of radiation control is to shield the entire primary cooling system.

The applicant should analyze the potential for personnel exposure to nitrogen-16 and propose control systems or procedures that include the following:

- Design bases and functional design of the nitrogen-16 control system or procedures. The design bases should be derived from analyses in Chapter 11 of the SAR.
- Schematic drawings and system and component specifications for the nitrogen-16 control system.
- The method used by the nitrogen-16 control system to reduce exposure rates and potential doses in occupied areas. Potential doses with and without the nitrogen-16 controls should be analyzed in Chapter 11 and summarized in this section of the SAR.
- The effect of the nitrogen-16 control system on overall reactor safety and operation.
- Other reactor design features affected by the nitrogen-16 control system. For example, a large shielded decay tank may affect coolant flow parameters, pump sizes, access for surveillance or inservice testing, or other factors for the primary cooling system.
- An assessment that the nitrogen-16 control system would not lead to an uncontrolled loss of primary coolant or the release of contaminated primary coolant that exceeds

the requirements in 10 CFR Part 20 and the facility ALARA program guidelines. Methods for analyzing radiation exposures as a result of coolant release should be consistent with the analyses in Chapter 11.

- Discussion of any technical specification requirements for the nitrogen-16 control system, including the bases and surveillance requirements.

5.7 Auxiliary Systems Using Primary Coolant

In addition to the systems discussed above that are associated with the primary cooling system, other auxiliary cooling systems may require the use of primary coolant and may affect the operation or safety of the reactor. If the reactor design includes an emergency core cooling system, it should be described and discussed in Chapter 6.

The applicant should provide the following information about these systems in this section:

- Design bases and functional requirements of the auxiliary systems based on discussions elsewhere in the SAR
- Schematic drawings and flow diagrams that show the source of water, locations of sensors and instruments, and locations of the components cooled .
- Tables of the range of important parameters of the systems and specifications of materials and components
- Discussion of components to be cooled, the source of heat, the source of the coolant water, heat transfer to the coolant, and coolant heat dissipation
- Discussion of the provisions in the auxiliary system designs to prevent interference with safe reactor shutdown
- Discussion of the provisions in the auxiliary system design to prevent the uncontrolled release of primary coolant or radiation exposures that would exceed the requirements in 10 CFR Part 20 and the facility ALARA program guidelines.
- Requirements for minimum water quality
- Discussion of any technical specification requirements for the auxiliary cooling systems, including the bases and surveillance requirements

APPENDIX D

Chapter 5, Reactor Cooling Systems, Part 2, Standard Review Plan

5 REACTOR COOLING SYSTEMS

This chapter gives guidance for evaluating the design bases, descriptions, and functional analyses of the AHR coolant systems. The principal purpose of the coolant system is to safely remove the fission and decay heat from the fuel and dissipate it to the environment. In an AHR, the primary cooling systems are those components and systems that remove heat from the core, where the core consists of that region of the vessel occupied by the solution containing the fission power producing fissile material. In an AHR, the core geometry may change with time due to changes in density and voiding of the solution. The core does not include that part of the fuel solution that may become entrained into the gas.

For an AHR, the applicant should describe and discuss in this chapter all systems that remove and dispose of the heat from the reactor. The design bases of the core cooling systems for the full range of normal operation should be derived in Chapter 4 of the SAR.

For an AHR, the primary cooling system removes heat from the core by being in direct contact with the fuel solution through a structural barrier or by the heat removal accompanying the fluid mass transport out of and into the fuel solution and is the cooling system which removes the largest fraction of the core heat.

The AHR may include other cooling systems that remove a significant fraction of the total heat produced by the core and fission products however. Cooling systems may include core heat removal by radiolysis gas management systems or passive heat removal through the reactor vessel to a surrounding pool.

In addition, the “Secondary Coolant Systems” for an AHR are defined to be those systems and components that transfer heat from the primary cooling systems to the environment or intermediate heat sink(s). Secondary cooling systems may consist of additional heat exchangers and pumps to circulate the coolant. The secondary coolant system is the secondary cooling system which removes the heat from the primary cooling system to the environment.

In this Chapter, the applicant should identify and discuss reactor cooling systems including auxiliary and reactor core subsystems that remove heat from the reactor core, and major components. The description should include for example, information on core cooling coils which might be the primary cooling system, and the partition of heat removal by additional reactor cooling systems that remove core heat directly such as the radiolysis gas management system or passively through the reactor vessel. These additional reactor cooling systems should be summarized in Section 5.1 and discussed in detail in Chapter 4 “Reactor Description” if reactor core

systems are involved such as gas management systems. Details of auxiliary systems using coolant other than the primary cooling system such as passive core cooling by the pool surrounding the vessel should be discussed in Chapter 9, "Auxiliary Systems."

All auxiliary systems and subsystems that use and contribute to the heat load of either the primary or secondary coolant system should also be described and discussed in this chapter. Any auxiliary systems using coolant from other sources, such as building service water, should be discussed in Chapter 9, "Auxiliary Systems." The design bases of any features of the core cooling system designed to respond to potential accidents or to mitigate the consequences of potential accidents should be derived from the analyses in Chapter 13, "Accident Analyses." These features should be summarized in this chapter and discussed in detail in Chapter 6, "Engineered Safety Features," of the SAR. In this chapter the applicant should discuss and reference the technical specifications that are needed to ensure operability consistent with SAR analyses assumptions.

This chapter gives the review plan and acceptance criteria for information on the heat removal systems. The information suggested for this section of the SAR is outlined in Chapter 5 of the format and content guide.

5.1 Summary Description

In this section, the applicant should give a brief description of reactor cooling systems including the supplementary core heat removal pathways, summarizing the principal features. Information should include the following:

- type of coolant: liquid, gas, or solid (conduction to surrounding structures)
- type of cooling system: open or closed to the atmosphere
- type of coolant flow in the primary cooling systemtype of secondary cooling system, and the method of heat disposal to the environment
- capability to provide sufficient heat removal to support continuous operation at full licensed power
- special or facility-unique feature

The applicant should summarize the principal features of the reactor cooling systems unique to the AHR, including the following:

- In addition to the primary cooling system, other means of heat transport from the core should be described, including the corresponding amount of heat transported from the core and fraction of total core heat removed. These are the supplementary core heat removal pathways.

5.2 Primary Cooling System

Areas of Review

For an AHR the term primary cooling systems replaces the term "primary coolant system". The primary cooling systems for an AHR are those components and systems that remove heat from the core.

The primary cooling system is a key component in the overall design and should have the capability to

- remove the fission and decay heat from the core during normal reactor operation and decay heat during reactor shutdown
- transfer the heat to a secondary coolant system for controlled dissipation to the environment
- maintain high water quality to limit corrosion of cooling coils, control and safety rods, reactor vessel or pool, and other essential components
- prevent uncontrolled leakage or discharge of contaminated coolant to the unrestricted environment

The basic requirements for these functions are generally derived and analyzed in other chapters of the SAR. In this chapter the applicant should describe how the cooling system provides these functions. Specific areas of review for this section are discussed in Section 5.2 of the format and content guide.

The liquid fuel solution in an AHR is expected to be highly corrosive and contain mobile radioactive fission product species. In addition, no fuel cladding barrier exists for the fuel solution as is characteristic of solid fuel elements in conventional non-power reactors. Therefore, it may be appropriate to consider solid material barriers that isolate the primary coolant from the fuel (such as cooling tube walls) as analogous to fuel cladding. Because this could affect the design of AHR cooling systems, consideration should be given to:

- Construction materials of components and fabrication specifications of safety-related components as they relate to corrosion resistance to the fuel solution.
- Coolant quality requirements for operation and shutdown conditions given the presence of liquid fuel solution on the core side of components.
- Locations, designs, and functions of essential components such as cooling coils located in the reactor vessel. These components ensure that the primary cooling system is operable and that, uncontrolled loss or discharge of fuel solution from the fuel core tank into the primary cooling system does not occur.

Specific areas of review for this section are discussed in Section 5.2 of the format and content

guide. For an AHR, in this section the applicant should provide information on the reactor coolant systems unique to these principal features of AHRs.

Acceptance Criteria

The acceptance criteria for the information on the primary coolant system include the following:

- Chapter 4 of the SAR should contain analyses of the reactor core including coolant parameters necessary to ensure removal of heat from the core. Safety limits (SLs) and limiting safety system settings (LSSSs) should be derived from those analyses and included in the technical specifications. Examples of cooling system variables on which LSSSs may be established are maximum thermal power level for operation, minimum and maximum coolant temperatures, minimum and maximum coolant flow rates, and coolant pressure range. The analyses in this section should show that the components and the functional design of the primary cooling system will ensure that no LSSS will be exceeded through the normal range of reactor operation. The analyses should address forced flow or natural-convection flow in the primary cooling system as applicable.
- The functional design should show that safe reactor shutdown and decay heat removal are sufficient to ensure fuel boundary integrity for all possible reactor conditions, including potential accident scenarios. Scenarios that postulate loss of flow or loss of coolant should be analyzed in Chapter 13 and the results summarized in this section of the SAR.
- The descriptions and discussions should show that sufficient instrumentation, coolant parameter sensors, and control systems are provided to monitor and ensure stable coolant flow, respond to changes in reactor power levels, and provide for a rapid reactor shutdown in the event of loss of cooling. There also should be instrumentation for monitoring the radiation of the primary coolant because elevated radiation levels could indicate a loss of primary coolant barrier integrity. There should be routine sampling for gross radioactivity in the coolant and less frequent radioactive spectrum analysis to identify the isotopes and concentrations found in the coolant. This spectrum analysis may also detect primary cooling system integrity failure at its earliest stages.
- The primary coolant should provide a chemical environment that limits corrosion of primary coolant barrier, control and safety rod surfaces, reactor vessels or pools, and other essential components. Other requirements for water purity should be analyzed in the SAR, and proposed values of conductivity and pH should be justified. Experience in non-power reactors has shown that the primary water conditions, electrical conductivity $\leq$ 5 µmho/cm and pH between 5.5 and 7.5 can usually be attained with good housekeeping and a good filter and demineralizer system. Chemical conditions should be maintained, as discussed in Section 5.4 of this standard review plan.
- Radioactive species including nitrogen-16 and argon-41 may be produced in the primary coolant. Additional radioactivity may occur as a result of neutron activation of coolant

contaminants and fission product leakage from the fuel. Provisions for limiting personnel radiological hazards should maintain potential exposures from coolant radioactivity below the requirements of 10 CFR Part 20 and should be consistent with the facility ALARA program. To ensure that facilities or components for controlling, shielding, or isolating nitrogen-16 are acceptable, potential exposures should not exceed the requirements of 10 CFR Part 20 and should be consistent with the facility ALARA program. The nitrogen-16 control system is discussed in Section 5.6 of this standard review plan.

- Argon-41 is another radionuclide that can be produced in the primary cooling system. Because this radionuclide may be an important release to the environment during a reduction-in-cooling event, special analyses and discussion of its production and consequences should be given in Chapter 11 of the SAR. If any special design or operational features of the primary cooling system modify or limit exposures from argon-41, they should be discussed in this section of the SAR. This discussion should demonstrate that any facilities or components added to the primary cooling system to modify argon-4l releases can limit potential personnel exposures to the values found acceptable in Chapter 11.
- Closed systems also may experience a buildup of hydrogen in air spaces in contact with the coolant. The discussion should show that it is not possible to have hydrogen build up to concentrations that are combustible. This may require gas sweep systems and hydrogen concentration monitoring. These systems should be discussed in Chapter 9.
- Because the primary cooling system may provide essential heat removal from the core, the system design should avoid uncontrolled release or loss of coolant. Some design features to limit losses include locating components of the primary cooling system above the core level, avoiding drains or valves below core level in the pool or tank, providing siphon breaks in piping that enters the primary vessel or pool, and providing check valves to preclude backflow. The designs and locations of such features should provide reasonable assurance that primary system boundary failure is very unlikely. A potential accident of rapid loss of coolant should be analyzed in Chapter 13 and summarized in this section of the SAR.
- If contaminated coolant were lost from the primary cooling system, the design and analyses should ensure that potential personnel exposures and uncontrolled releases to the unrestricted environment do not exceed acceptable radiological dose consequence limits derived from the accident analyses. The radiological consequences from the contaminated coolant should be discussed in Chapter 11 and summarized in this section of the SAR. Necessary surveillance provisions should be included in the technical specifications.

- The primary coolant should provide a chemical environment that limits corrosion of primary coolant barrier material and components of the primary cooling system given the presence of liquid fuel solution on the core side of the primary coolant barrier material. The barrier should prevent the fuel solution from contaminating the primary coolant and the primary coolant from diluting the fuel solution with accompanying reactivity and chemistry effects.
- The design of the primary cooling system components ensure that the primary cooling system is operable and that uncontrolled loss or discharge of fuel solution from the fuel core tank into the primary system does not occur. The system design should avoid uncontrolled release of fuel solution to the primary coolant. If contaminated coolant were lost from the primary cooling system, the design and analyses should ensure that potential personnel exposures and uncontrolled releases to the unrestricted environment do not exceed acceptable radiological dose consequence limits derived from the accident analyses. The designs and locations of such essential components as fuel tank core cooling coils should provide this reasonable assurance. The applicant discussion should demonstrate that the design of the primary cooling system can limit potential personnel exposures to the values found acceptable in Chapter 11.
- Acceptance criteria for fuel integrity and fuel cladding integrity limits are to be limits unique to the AHR liquid fuel solution core as defined in Chapter 4. These criteria provide the acceptable margin to the breach of the fuel solution boundary integrity.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should compare the functional design and the operating characteristics of the primary cooling system with the bases for the design presented in this and other relevant chapters of the SAR. The system design should meet the appropriate acceptance criteria presented above considering the specific facility design under review.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The primary cooling system is designed in accordance with the design bases derived from all relevant analyses in the SAR
- Design features of the primary cooling system and components give reasonable assurance of primary system boundary integrity under all possible reactor conditions. The system should be designed to remove sufficient fission heat from the core to allow all licensed

operations without exceeding the established limiting safety system settings that are included in the technical specifications.

- Designs and locations of primary cooling system components have been specifically selected to avoid coolant loss that could lead to primary system boundary failure, or uncontrolled release of excessive radioactivity.
- The primary cooling system is designed to convert in a passive or fail-safe method, to natural-convection flow sufficient to avoid loss of fuel integrity. *(This feature is evaluated in conjunction with the reviews of the reactor description and accidents. It is applicable to AHRs to be licensed to operate with forced-convection coolant flow.)*
- The chemical quality of the primary coolant will limit corrosion of the primary barrier to release of fission products, the control and safety rod cladding, the inside of the reactor vessel (or pool), and other essential components in the primary cooling system for the duration of the license and for the projected utilization time of the fuel.
- Systems are present that will prevent hydrogen concentrations from reaching combustible limits.
- Primary cooling system instrumentation and controls are designed to provide all necessary functions and to transmit information on the operating status to the control room.
- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary primary cooling system operability for reactor operations as analyzed in the SAR.
- The design bases of the primary cooling system provide reasonable assurance that the environment and the health and safety of the public will be protected.

5.3 Secondary Coolant System

Areas of Review

The secondary coolant system of an AHR should be designed to transfer reactor heat from the primary and possibly other cooling systems to the environment. The secondary cooling system should be designed for continuous operation at licensed power level. Therefore, the secondary coolant system in these reactors must be designed to dissipate heat continuously. In this section of the SAR, the applicant should justify how any necessary heat dissipation is accomplished. Specific areas of review for this section are discussed in Section 5.3 of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the secondary coolant system include the following:

- The analyses and discussions of Section 5.3 should demonstrate that the secondary coolant system is designed to allow the primary cooling system to transfer the heat as necessary to ensure fuel integrity. The analyses should address primary cooling systems operating with forced flow, natural-convection flow, or both for reactors licensed for both modes. The design should show that the secondary coolant system is capable of dissipating all necessary fission and decay heat for all potential reactor conditions as analyzed in the SAR.
- The primary coolant will usually contain radioactive contamination. The design of the total coolant system should ensure that release of such radioactivity through the secondary coolant system to the unrestricted environment would not lead to potential exposures of the public in excess of the requirements of 10 CFR Part 20 and the ALARA program guidelines. Designs should ensure that the primary cooling system pressure is lower than the secondary coolant system pressure across the heat exchanger under all anticipated conditions, the secondary coolant system is closed, or radiation monitoring and effective remedial capability are provided. The secondary coolant system should prevent or acceptably mitigate uncontrolled release of radioactivity to the unrestricted environment. Periodic samples of secondary coolant should be analyzed for radiation. Action levels and required actions should be discussed.
- The secondary coolant system should accommodate any heat load required of it in the event of a potential engineered safety feature operation or accident conditions as analyzed in Chapters 6 and 13 of the SAR.
- The secondary coolant system design should provide for any necessary chemical control to limit corrosion or other degradation of the heat exchanger and prevent chemical contamination of the environment.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should verify that all reactor conditions, including postulated accidents, requiring transfer of heat from the primary coolant system to the secondary coolant system have been discussed. The reviewer should verify that the secondary coolant system is capable of removing and dissipating the amount of heat and the thermal power necessary to preclude accidents. The reviewer should also confirm the analyses of secondary coolant system malfunctions including the effects on reactor safety, fuel integrity, and the health and safety of the public.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- Design features of the secondary coolant system and components will allow the transfer of the necessary reactor heat from the primary cooling system under all possible reactor conditions.
- Locations and design specifications for secondary coolant system components ensure that malfunctions in the system will not lead to reactor damage, fuel failure, or uncontrolled release of radioactivity to the environment.
- Secondary coolant system instrumentation and controls are designed to provide all necessary functions and to transmit information on the operating status to the control room.
- The secondary coolant system is designed to respond as necessary to such postulated events as a reduction in cooling due to either a loss of primary coolant or primary coolant flow.
- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary secondary coolant system operability for normal reactor operations.

5.4 Primary Coolant Cleanup System

Areas of Review

Experience has shown that potable water supplies are usually not sufficiently pure for use as a reactor primary coolant without additional cleanup. The AHR concepts considered here consist of a configuration with a primary cooling system immersed in fuel solution. The primary coolant is separated from the fuel solution by a material barrier which isolates the mobile fission products from the coolant system components. This is the primary coolant barrier such as the primary cooling coil material. The purity of the primary coolant should be maintained as high as reasonably possible for the following reasons:

- to limit the chemical corrosion of primary coolant coils, control and safety rod cladding, reactor vessel or pool, and other essential components in the primary cooling system
- to limit the concentrations of particulate and dissolved contaminants that might become radioactive by neutron irradiation

Specific areas of review for this section are discussed in Section 5.4 of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the primary coolant cleanup system include the following:

- The primary coolant quality should be maintained in the ranges established as acceptable in Chapters 4 and 11 of the SAR. Experience has shown that quality water conditions, electrical conductivity ≤5 μmho/cm and pH between 5.5 and 7.5, can usually be achieved by good housekeeping and a cleanup loop with particulate filters and demineralizers. Such a system is acceptable unless the SAR analyses establish other purity conditions as acceptable.
- Radioactively contaminated resins and filters should be disposed of or regenerated in accordance with radiological waste management plans discussed in Chapter 11, and potential exposures and releases to the unrestricted environment shall not exceed the requirements of 10 CFR Part 20 and should be consistent with the facility ALARA program.
- Location, shielding, and radiation monitoring of the water cleanup system for routine operations and potential accidental events should be such that the occupational staff and the public are protected from radiation exposures exceeding the requirements of 10 CFR Part 20 and acceptable radiological consequence dose limits for accidents.
- Location and functional design of the components of the water cleanup system should ensure the following:
  - malfunctions or leaks in the system do not cause uncontrolled loss or release of primary coolant.
  - personnel exposure and release of radioactivity do not exceed the requirements of 10 CFR Part 20 and are consistent with the facility ALARA program.
  - safe reactor shutdown is not prevented.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should compare the design bases for the primary coolant water quality with the design bases by which the primary coolant cleanup system will achieve the requirements. The comparison should include performance specifications, schematic diagrams, and discussion of the functional characteristics of the cleanup system. The reviewer should evaluate (1) design features to ensure that leaks or other malfunctions would not cause inadvertent damage to the reactor or exposure of personnel and (2) the plan for control and disposal of radioactive filters and demineralizer resins.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The design bases and functional descriptions of the primary water cleanup system give reasonable assurance that the required water quality can be achieved. The design ensures that corrosion and oxide buildup of coolant coils and other essential components in the primary cooling system will not exceed the acceptable limits.
- The primary coolant cleanup system and its components have been designed and selected so that malfunctions are unlikely. Any malfunctions or leaks will not lead to radiation exposure to personnel or releases to the environment that exceed the requirements of 10 CFR Part 20 and the facility ALARA program guidelines.
- The plans for controlling and disposing of radioactivity accumulated in components of the primary water cleanup system, which results from normal operations and potential accident scenarios, conform with applicable regulations, including 10 CFR Part 20, and acceptable radiological consequence dose limits for accidents.
- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary primary water cleanup system operability for normal reactor operations.

5.5 Primary Coolant Makeup Water System

Areas of Review

During operations, it may be necessary to replace or replenish the primary coolant. Coolant may be lost through radiolysis, leaks from the system, and other operational activities. It might also be plausible that primary coolant is bled off to storage or holding tanks where evaporation would reduce makeup inventory. Although each reactor should have a makeup water system or procedure to meet projected operational needs, the system need not be designed to provide a rapid, total replacement of the primary coolant inventory. Specific areas of review for this section are discussed in Section *5.5* of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the primary coolant makeup water system include the following:

- The projected loss of primary cooling water inventory for anticipated reactor operations should be discussed. The design or plan for supplying makeup water should ensure that those operational requirements are satisfied.

- If storage of treated makeup water is required by the design bases of the primary cooling system, the makeup water system or plan should ensure that such water is provided.
- Not all AHRs must provide makeup water through hardware systems directly connecting the reactor to the facility potable water supply. However, for those that do, the makeup water system or plan should include components or administrative controls that prevent potentially contaminated primary coolant from entering the potable water system.
- The makeup water system or plan should include features to prevent loss or release of coolant from the primary coolant system.
- The makeup water system or plan should include provisions for recording the use of makeup water to detect changes that indicate leakage or other malfunction of the primary cooling system.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should compare the design bases and functional requirements for replenishing primary coolant including the quantity and quality of water, the activities or functions that remove primary coolant, and the systems or procedures to accomplish water makeup with the acceptance criteria. The review should focus, as applicable, on safety precautions to preclude overfilling of the reactor coolant system, loss of primary coolant through the nonradioactive service drain system, and the release of primary coolant back through the makeup system into potable water supplies.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The design bases, functional descriptions, and procedures for the primary coolant makeup water system give reasonable assurance that the quantity and quality of water required will be provided.
- The system design or procedures will prevent overfilling of the primary cooling system or malfunction of the makeup water system and will prevent the loss or release of contaminated primary coolant that would exceed the requirements of 10 CFR Part 20 and the facility ALARA program guidelines.
- The system design or procedures will prevent contaminated primary coolant from entering the potable water system through the makeup water system.

- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary makeup water system operability for normal reactor operations.

5.6 Nitrogen-16 Control System

Areas of Review

Nitrogen-16, a high-energy beta and gamma ray emitter with a half-life of approximately seven seconds, is a potential source of high radiation exposure at water-cooled reactors. It tends to remain dissolved in the coolant water as it leaves the core. The quantity and concentration of nitrogen-16 should be considered and provisions made to control personnel exposure. Because of the relatively short half-life potential doses can be decreased by delaying the coolant within shielded regions. If the reactor makes use of natural-convection cooling to a large open pool, stirring or diffusing the convection flow to the surface can produce a delay. For forced-flow cooling, passing the coolant through a large shielded and baffled tank can produce the delay. Specific areas of review for this section are discussed in Section 5.6 of the format and content guide.

Acceptance Criteria

The acceptance criteria for the information on the nitrogen-16 control system include the following:

- The reduction in personnel exposure to nitrogen-16 should be consistent with the nitrogen-16 analyses in Chapter 11 of the SAR. Total dose shall but not exceed the requirements of 10 CFR Part 20 and should be consistent with the facility ALARA program.
- System design should not decrease cooling efficiency so that any limiting safety system setting would be exceeded; or lead to uncontrolled release or loss of coolant if a malfunction were to occur; or prevent safe reactor shutdown and removal of decay heat sufficient to avoid fuel damage.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should evaluate the design bases and functional requirements of the system designed to control personnel exposures to nitrogen-16 by:

- confirming the amount of nitrogen-16 predicted by the SAR analysis at the proposed power level and the potential personnel exposure rates, including exposures from direct radiation and airborne nitrogen-16
- reviewing the type of system and the decrease in exposure rates

- reviewing the effect of the proposed system on the full range of normal reactor operations
- reviewing the possible effects of malfunctions of the nitrogen-16 control system on reactor safety, safe reactor shutdown, and release of contaminated primary coolant.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- Design bases and design features give reasonable assurance that the nitrogen-16 control system can function as proposed and reduce potential doses to personnel so that doses do not exceed the requirements of 10 CFR Part 20 and are consistent with the facility ALARA program.
- Design and functional operation of the nitrogen-16 control system give reasonable assurance that the system will not interfere with reactor cooling under anticipated reactor operating conditions and will not reduce cooling below the acceptable thermal-hydraulic performance discussed in Chapter 4 of the SAR.
- Design features give reasonable assurance that malfunction of the nitrogen-16 control system will not cause uncontrolled loss or release of primary coolant and will not prevent safe reactor shutdown.
- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary nitrogen-16 control system operability for normal reactor operations.

5.7 Auxiliary Systems Using Primary Coolant

Areas of Review

The primary coolant may serve functions other than cooling the reactor core. Some of these auxiliary functions could involve cooling other heated components, which may affect the heat load of the primary cooling system. Auxiliary uses of the primary coolant could affect its availability as a fuel coolant, which is its principal use. Although the principal discussions of these auxiliary systems should be located in other sections of the SAR, their effects on the coolant systems should be summarized in this section.

Acceptance Criteria

The acceptance criteria for the information on the auxiliary systems using primary coolant include the following:

- The system should remove sufficient projected heat to avoid damage to the cooled device.

- The system should not interfere with the required operation of the primary core cooling system.
- Any postulated malfunction of an auxiliary system should not cause uncontrolled loss of primary coolant or prevent a safe reactor shutdown.
- The shielding system using primary coolant should provide sufficient protection factors to prevent personnel exposures that exceed the requirements of 10 CFR Part 20 and the facility ALARA program guidelines.
- The system should not cause radiation exposures or release of radioactivity to the environment that exceeds the requirements of 10 CFR Part 20 and the facility ALARA program guidelines.
- The applicant should identify operational limits, design parameters, and surveillances to be included in the technical specifications.

Review Procedures

The reviewer should verify that auxiliary cooling or shielding using primary coolant is described in this section of the SAR for any component (other than the core) in which potentially damaging temperature increases or excessive radiation exposures are predicted. If the potential exists for radiation heating of components near the reactor core, the reviewer should verify that the heat source, temperature increases, heat transfer mechanisms, and heat disposal have been discussed and analyzed. The reviewer should verify that the potential personnel radiation exposures from sources shielded by primary coolant have been analyzed and the protection factors provided by the coolant have been discussed.

Evaluation Findings

This section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff's safety evaluation report:

- The applicant has described and analyzed auxiliary systems that use primary coolant for functions other than core cooling, has derived the design bases from other chapters of the SAR, has analyzed any reactor components located in high radiation areas near the core for potential heating that could cause damage to the reactor core or failure of the component, and has planned acceptable methods to remove sufficient heat to ensure the integrity of the components The coolant for these systems is obtained from the purified primary coolant system without decreasing the capability of the system below its acceptable performance criteria for core cooling.
- The applicant has analyzed any reactor components or auxiliary systems for which primary coolant helps shield personnel from excessive radiation exposures. The use of the coolant for these purposes is acceptable, and the estimated protection factors limit the

exposures to the requirements of 10 CFR Part 20 and the facility ALARA program guidelines. There is reasonable assurance that credible and postulated malfunctions of the auxiliary cooling systems will not lead to uncontrolled loss of primary coolant, radiation exposures, or release of radioactivity to the unrestricted environment that exceeds the requirements of 10 CFR Part 20 and the facility ALARA program guidelines.

- The technical specifications, including testing and surveillance, provide reasonable assurance of necessary auxiliary cooling system operability for normal reactor operations.

APPENDIX E

Chapter 13, Accident Analysis, Part 1 Standard Format and Content

13 Accident Analysis

Introductory material

In the other chapters of the SAR, the applicant should discuss and analyze the safety considerations and functional requirements at an AHR facility for the design bases that ensure safe reactor operation and shutdown and acceptable protection for the public, the operations and user staff, and the environment. In those chapters, the applicant should not only discuss potential equipment malfunctions, deviations of process variables from normal values, and potential effects of external phenomena on the facility, but should also describe how equipment will work when needed in accident situations. In Chapter 13 of the SAR, the applicant should submit information and analyses that show that the health and safety of the public and workers are protected and that the applicant has considered potential radiological consequences in the event of malfunctions, and the capability of the facility to accommodate such disturbances. The major purpose of this chapter is for the applicant to demonstrate that the facility design features, safety limits, limiting safety system settings, and limiting conditions for operation have been selected to ensure that no credible accident could lead to unacceptable radiological consequences to people or the environment.

Unlike in solid-fuel reactors, in an AHR the fuel is in a liquid solution and the resulting fission products, both liquid and gaseous, must be contained within the facility rather than within cladding. The primary boundary consists of all structures that prevent the release of fuel, fission gases and other fission products that remain in the liquid solution. For an AHR, the primary boundary includes the reactor vessel (and associated penetrations such as control rod guide tubes), the primary cooling system (e.g., cooling coils), the gas management system (including waste gas storage), and associated pumps, heat exchangers, valves and piping.

The accidents analyzed should range from such anticipated events as a loss of normal electrical power to a postulated fission product release with radiological consequences that exceed those of any accident considered to be credible. This limiting accident is named the maximum hypothetical accident (MHA) for non-power reactors; the details are reactor specific. Because the MHA is not expected to occur, the scenario need not be entirely credible. The initiating event and the scenario details need not be analyzed, but the potential consequences should be analyzed and evaluated.

The information on the credible postulated accidents should achieve the following objectives:

- Ensure that enough events have been considered to include any accident with significant radiological consequences. Rejection of a potential event should be justified.
- Categorize the initiating events and scenarios by type and likelihood of occurrence so that only the limiting cases in each group must be quantitatively analyzed.
- Develop and apply consistent, specific acceptance criteria for the consequences of each postulated event.

The selection of accident scenarios to be analyzed should be based on the consideration of phenomena unique to an AHR that may limit safe operation. Limiting phenomena refer to those physical phenomena that may occur during the course of a transient or accident that significantly affect the subsequent likelihood of failure of the primary boundary. Identification and understanding of these limiting phenomena is useful in classifying the consequences of potential transients and accidents as well as in the determination of appropriate operating limits. For AHRs, the five limiting phenomena are: bulk boiling, fuel precipitation, fission product precipitation, detonation and deflagration of radiolytic gases, and excessively high radiolytic gas release. Definitions for these phenomena are:

- Bulk boiling of fuel solution (i.e. change of phase occurs as liquid evaporates into gas)

  Bulk boiling refers to the formation of vapor in the AHR due to phase change of the solution. Bulk boiling may lead to several adverse effects for the AHR, for example, increased fission product release from the core and potentially increased reactivity [1]. Bulk boiling may result in the transport of aerosols from the reactor core and lead to hot-spots elsewhere in the plant system. While AHRs are generally characterized by strong negative void/temperature reactivity feedback; the potential consequences in terms of reactor dynamic power level as well as the redistribution of fuel and fission products may challenge primary boundary integrity.

- Precipitation of fission products / precipitation of fuel (uranium)

  Precipitation refers to the formation of solids in the AHR fuel solution. Precipitation of the fuel or fission products should be avoided in AHRs [1, 2]. Precipitation of the fuel or fission products will result in the collection of these precipitates in the bottom of the reactor, leading to core heterogeneity. Collection of radioactive fission products or fuel in concentrated areas near the reactor core primary boundary may lead to excessive local heating and high temperatures on the reactor vessel or cooling coils. Subsequent chemical and thermal-mechanical effects may then challenge primary boundary integrity.

- Detonation or deflagration of combustible gas mixtures

  The formation of radiolytic gases (namely hydrogen and oxygen) is characteristic of AHRs (which have historically been referred to as water boilers for this very reason) [3]. The hydrogen and oxygen produced by these reactors may ignite causing a detonation or deflagration within the primary boundary. Such an event may compromise the integrity of the primary boundary.

- Excessively high radiolytic gas release

  Excessively high radiolytic gas release refers to a specific condition where instantaneous radiolytic gas generation rates exceed the capacity of the plant systems to recombine the gases. Under these circumstances, it is possible for the formation of the gases to result in vessel pressurization. Given that AHRs typically have a strong negative void reactivity feedback, it is possible for excessively high radiolytic gas generation rates to initiate a positive feedback in the AHR system whereby power continues to increase and the system pressure continues to increase [4]. High pressure or rapid increases in pressure may challenge the primary boundary integrity.

  Additionally, excessive radiolytic gas release above the capacity to recombine necessarily implies the presence of hydrogen and oxygen gases in the associated gas management system. The explosion of these gases may pose a challenge to the primary boundary integrity away from the core region.

Accordingly, for an AHR with non-circulating fuel, the following postulated event categories should be evaluated:

- Maximum hypothetical accident

- Insertion of excess reactivity

- Reduction in cooling

  Technical Rationale

  Events previously categorized as loss of coolant and loss of coolant flow have been re-defined for the AHR more generically as "reduction in cooling" events. The purpose for re-defining these events is to address unique aspects of the heat removal from an AHR. The AHR fuel is liquid, and therefore, the cooling system(s) may differ significantly from those for more conventional solid fuel reactors. Additionally, since the fuel is liquid and lacks a cladding, gaseous fission products escape from the core region and are transported to other areas of the plant. A reduction in cooling event is characterized by a reduced capacity to remove fission or decay heat from the fission products.

- Mishandling or malfunction of fuel

  Technical Rationale

  Fuel malfunction has historically referred to events where there is fuel damage or failure of the cladding to retain fission products. For AHRs, the fuel is in liquid form. The function of the primary barrier is served by the primary system boundary instead of a cladding. Therefore, fuel malfunction in the context of the AHR has to be re-defined to address aspects of the fuel that could result in a failure of the primary boundary. The fuel is therefore considered to "malfunction" or have been "mishandled" if the physical state of the fuel solution is subjected to any of the identified limiting phenomena of bulk boiling, fuel precipitation or fission product precipitation; or if the corrosion rates becomes excessively high.

- Loss of normal electric power

- External events (include natural hazards and man-made events)

- Mishandling or malfunction of equipment

- Large and undamped power oscillations

  Technical Rationale

  Historical experience with AHR operation has indicated very strong fuel temperature/void reactivity feedback [1, 3, 4, 5]. While in most cases the experience has shown AHRs to be inherently stable, the nature of power oscillations at high power density is not well characterized [3]. It is expected that normal operation of an AHR will include irregular power oscillations owing to the dynamics of radiolytic gas formation and reactivity feedback. These conditions will not pose a challenge to the primary barrier provided these power oscillations do not grow (which is indicative of an unstable condition).

  Reactivity feedback coupled with plant response may yield conditions which are not inherently stable. An example may include positive feedback due to radiolytic gas formation and vessel pressurization under conditions where the recombiner capacity of an AHR is exceeded. Such conditions where positive feedback is possible must be examined to determine if the reactor remains stable; or, if the reactor becomes unstable such that the power oscillations are large and undamped, that these unstable power oscillations can be acceptably detected and suppressed.

- Detonation and deflagration

  Technical Rationale

  For AHRs, formation of radiolytic gases introduces the possibility of detonation or deflagration by chemical reaction between hydrogen and oxygen gases. Explosion within the primary boundary presents two potentially challenging consequences: (1) the explosion will send a pressure wave throughout the system, which may result in a reactivity insertion, and (2) the explosion itself may compromise primary boundary integrity and at the same time result in the energetic dispersal of the contents of vessels holding fuel and fission products

- Unintended exothermic chemical reactions other than explosion

  Technical Rationale

  Depending on the fuel solution, the formation of radiolytic gases other than oxygen and hydrogen introduce the possibility of other exothermic chemical reactions other than the recombination of hydrogen and oxygen. For example, the oxidation of NOx gases is exothermic.

- Facility system interaction events

  Technical Rationale

  For medical isotope production AHRs, the reactor (or reactors for a multi-unit facility) supply feed products to chemical processing facilities. Therefore, it is possible that events occurring within the processing facility would have an influence on the reactor. Additionally, for multi-reactor facilities, shared systems may initiate transient or accident events that affect more than a single reactor. Facility system interaction events, generally, classify the influence of shared systems and coupled systems to the reactor or reactors. An example of such an event may be the common mode failure of external chemical processing systems that challenge (simultaneously) the primary boundary integrity for multiple reactor units. Within this category, event propagation to other units should also be considered. For example, an event initiated in one reactor unit may influence an adjoining unit through a phenomenon such as pipe rupture due to explosion; whereby the ruptured pipe may physically interact with another system or the shockwave may affect other systems.

Events in each of the above categories should be evaluated systematically to identify the limiting event selected for detailed quantitative analysis. Limiting events in each category should have

potential consequences that exceed all others in that group. The MHA selected should bound all credible potential accidents at that facility, yet should be an event that is not likely to occur during the life of the facility.

13.1 Accident Initiating Events and Scenarios

In this section of the SAR, the applicant should describe potential accident initiating events and scenarios. For documents on general accident scenarios and analysis, radiological consequences, and fuel types, see Section 13.4, References. The following sections contain suggestions for selecting and categorizing postulated accidents:

13.1.1 Maximum Hypothetical Accident

Breach of the primary boundary of the various vessels to allow for unrestricted dispersal of the radioactive material that is already in a highly mobile form could form the basis for selection of the MHA. Possible MHAs for an AHR could be one or a combination of the following events:

- Energetic dispersal of the contents of the primary boundary with bypass of any scrubbing capacity (e.g. by a pool surrounding the fuel vessel)
- Detonation of hydrogen in the recombiner resulting in waste gas tank failure and release of some or all of the fuel and fission product contents in aerosolized form
- Complete loss of fuel inventory (e.g. vessel break)

For multi-reactor AHR facilities, the MHA could be a facility wide event that may simultaneously release a radioactive inventory from within the facility that exceeds that of a single reactor. For multi-reactor AHR facilities, consideration should be given to hypothetical events that could release radioactivity from multiple vessels, holdup tanks, and processing systems holding both liquids and fission gases.

Possible MHAs for a multi-reactor AHR facility could be one or a combination of the following events:

- a man-made external event that breaches the primary boundary of more than one unit
- a facility wide external event that breaches various systems containing radioactive fluids

13.1.2 Insertion of Excess Reactivity

For AHRs, the insertion of excess reactivity can become an initiating event that leads to a challenge to the integrity of the primary fission product boundary.

For AHRs, the following events leading to insertion of excess reactivity should be considered:

- Pressurization of the fuel fluid

Technical Rationale

Pressurization of the fuel fluid should be considered for an AHR given the large, negative void reactivity coefficient characteristic of this reactor type

- Excessive cooldown via cooling system malfunction

  Technical Rationale

  Excessive cooldown via cooling system malfunction should be considered for an AHR given the large, negative temperature reactivity coefficient characteristic of this reactor type

- Moderator addition due to cooling system malfunction (e.g. cooling tube rupture)

  Technical Rationale

  AHRs are expected to have internal cooling heat exchangers (e.g. coils) submerged in the liquid reactor fuel. A breach of this heat exchanger piping could introduce additional moderator to the fuel and may potentially increase reactivity. Moderator (water) addition can also occur if the reactor core vessel itself is breached and if the pool water intrudes into the vessel.

  The normal operating condition of an AHR may be over-moderated. However, positive reactivity will be inserted directly if the water makes a layer which works as reflector in the vessel.

  Indirectly, there may be several possible reactivity insertion scenarios. For example, a hypothetical event whereby water is injected in the middle of the vessel may confer negative reactivity (depending on the under- or over- moderation) and power may decrease. Radiolytic gas formation will also be reduced and such a reduction in void may add reactivity. Such reactivity effects will be dependent on the core geometry, plant system configurations, and solution characteristics.

- Fuel injection

  Technical Rationale

  Liquid-fueled reactors are expected to have systems for de-fueling and re-fueling the primary boundary vessel. Therefore, failures in plant systems or control systems may add liquid fuel to a critical reactor, thus increasing reactivity.

- Realistic, adverse geometry changes

  Technical Rationale

For liquid-fueled AHRs, the core geometry is variable. Therefore, a phenomenon such as sloshing of the reactor fuel due to vibration or other mechanisms may reduce neutron leakage and increase reactivity.

- Reactivity insertion due to moderator lumping effects

  Technical Rationale

  AHRs are expected to have internal cooling heat exchanges (e.g. coils) submerged in the liquid reactor fuel. Void formation within the heat exchanger changes the moderation profile within the reactor. Since the moderating effect of the cooling system is separate from the fuel solution, there is the potential for such changes to introduce negative or positive reactivity depending on the design-specific geometry and neutron spectrum. The reactivity effect of lumped moderator changes within the primary cooling system must be considered.

- Inadvertent introduction of other material into the fuel solution

  Technical Rationale

  AHRs are expected to have systems for adding additional materials into the reactor core. Nitrate based systems will generally require the addition of nitric acid to compensate for the radiolytic formation and loss of NOx. Malfunction of such make-up systems may introduce other material into the reactor.

These AHR-specific reactivity insertion events must be considered along-side more traditional reactivity insertion events, such as control rod withdrawal or control rod ejection.

13.1.3 Reduction in Cooling

The effect of reduction in cooling should be considered for all AHRs. The cooling systems include all systems and components that remove heat from the reactor vessel and the fission gases as identified in Section 5.1. They consist of the cooling coils inside the vessel, the pool that provides external cooling of the vessel, and cooling systems in the off-gas handling system for removing heat from the gases generated in the fission process. The reduction in cooling due to an initiating event such as loss of electric power, failure of an active component in the heat removal system, a cooling coil or heat exchanger tube rupture, flow obstruction in a heat exchanger, etc., may lead to a high temperature or subsequent adverse chemical effects, excessive thermal stress, or induce a reactivity insertion that could ultimately challenge the integrity of the primary boundary.

As an example, a reduction of cooling to the recombiner may result in a local hot spot in the primary boundary and a subsequent failure of the primary boundary due to thermal stress. This

event sequence is analogous to pump seal failure induced loss-of-coolant accidents in pressurized water reactors.

13.1.4 Mishandling or Malfunction of Fuel

Since the fuel in the AHR is liquid, fuel mishandling events may be characterized as fuel spills or leaks where some amount of this fuel may gather or migrate to locations it is not intended to be in. One immediate concern for the outcome of such a spill or leak is the accumulation of a sufficient mass of fuel in a geometry leading to an unintended criticality in an area where its consequences may pose a threat to facility staff. This kind of event is frequently analyzed and guarded against in fuel processing facilities. The applicant should address these events and the consequences of fuel spills and leaks.

Fuel leakage or excessive fuel leakage should be considered within the context of this class of accidents.

Fuel malfunction events for an AHR may be thought of as those events where the physical or chemical form of the fuel or solvent undergoes a change resulting in adverse chemical effects such as fuel precipitation or excessive corrosion. The following initiators need to be considered in this event category:

- Failure to control pH of the fuel solution, for example, by failing to add proper chemicals at prescribed times to the fuel solution
- Failure to control solution temperature, for example, excessive cooling of the fuel during off-normal operation, resulting in fuel crystallization or precipitation
- Failure to control solution pressure, for example, exposing the primary vessel to a vacuum thereby initiating fuel boiling

13.1.5 Loss of Normal Electrical Power

This accident initiator can result from an onsite or offsite power failure. Emergency power is assumed to operate. Failure of emergency power coincident with loss of normal power can create a ‘station blackout’ condition. It is assumed that control rods will operate under gravity to make the reactor sub-critical. However, the consequent loss of all active heat removal capability and its impact on removing decay heat from the primary vessel, the off-gas system, and the waste gas storage tank should be analyzed.

13.1.6 External Events

These events include natural phenomena, such as extreme winds, tornados, floods, or seismic events as well as man-made events such as explosions or toxic releases in the vicinity of the reactor building. The impact of seismically induced changes in the geometry of the fuel solution should be considered.

13.1.7 Mishandling or Malfunction of Equipment

The applicant should consider the consequences of mishandling or malfunction of equipment that may result in the spillage or leakage of contaminated fluids. Additionally, since fission gases are not retained in the fuel for the AHR, the applicant should consider the leakage or release of fission gases.

As an example, a stuck open relief valve or inadvertent opening of a valve in the waste gas storage system(s) or holdup tanks is an equipment malfunction that may allow radioactive gases to leak out of the primary boundary at an excessive rate. Such an equipment malfunction would constitute a loss of integrity of the boundary of the waste gas holding tank that allows escape of fission gas and radiolysis gas into the building confinement.

13.1.8 Large Undamped Power Oscillations

The AHR design is expected to experience a strong temperature and density feedback. The SAR should include a discussion of those conditions that could lead to positive feedback and result in growing power oscillations that are large and undamped. Such large, undamped power oscillations may challenge the integrity of the primary barrier.

The applicant should evaluate plant system behavior in its determination of reactor stability. For instance, pressurization due to excessive radiolytic gas formation may result in a positive feedback mechanism.

13.1.9 Detonation and Deflagration

The formation of radiolytic gas and release from the fuel solution introduces the potential for deflagration or combustion of these gases within the primary boundary. The applicant should identify and evaluate the consequences of postulated deflagration and detonation events.

13.1.10 Unintended Exothermic Chemical Reactions Other Than Detonation

This class of accidents is characterized by the unintended reaction of gases other than the hydrogen/oxygen reaction that may pose a challenge to the integrity of the primary boundary. An example of an event in this category is the exothermic reaction of NOx with oxygen. It may be postulated that that a large quantity of NOx has evolved in a hypothetical AHR waste gas system. The rapid oxidation of these gases may increase system pressure and temperature; which may in turn, breach the waste gas system primary boundary.

13.1.11 Facility System Interaction Events

This class of accident initiators is characterized by the dynamic interactions of connected or co-located plant systems. For the AHR Isotope Production Facility, in particular, attention should be given to potential system interactions that may occur between the reactor side and the isotope

separation side of the facility. This includes malfunctions or accidents in isotope processing operational facilities such as hot cells, etc. that could impact the reactor.

Since the facility will consist of multiple reactors and processing units, that potential share systems, structures, and components. Interactions between these systems could exacerbate consequences relative to a single reactor facility. Initiators in this class include:

- common mode failures affecting multiple units
- propagation of a failure to then impact another unit (e.g. pipe-whip)

13.2 Accident Analysis and Determination of Consequences

In this section of the SAR, the applicant should discuss each event giving information consistently and systematically for gaining a clear understanding of the specific reactor and making comparisons with similar reactors. Many of the steps used to select the limiting event in each category may be semi-quantitative. However, the analyses and determination of consequences of the limiting events should be as quantitative as possible. The following steps are suggested:

1. State the initial conditions of the reactor and equipment. Discuss relevant conditions depending on fuel burnup, experiments installed, core configurations, or other variables. Use the most limiting conditions in the analyses.

2. Identify the causes that initiate the event; the causes may include equipment malfunction, operator error, or a natural phenomenon or one caused by humans. Base the scenario on a single initiating malfunction, rather than on multiple causes.

3. List the sequence of events, assumed equipment operation and malfunction, and operator actions until a final stabilized condition is reached. Discuss functions and actions assumed to occur that change the course of the accident or mitigate the consequences, such as reactor scrams or initiation of such engineered safety features as emergency core cooling. If credit is taken for mitigation of the accident consequences, discuss the bases used to determine that the systems are operable and discuss the system functions.

4. Classify damage that might occur to components during the accident until the situation is stabilized. Discuss all components and barriers that could affect the transfer of radiation and radioactivity from the reactor to the public and that ensure continued stability of conditions after the accident.

5. Prepare realistic analyses to demonstrate a detailed, quantitative evaluation of the accident evolution, including the performance of all barriers and the transport of radioactive materials to the unrestricted area. Include the assumptions, approximations, methodology, uncertainties, degree of conservatism, margins of safety, and both intermediate transient and ultimate radiological conditions. Justify the methods used. Further, ensure the information is sufficiently complete to allow the results to be independently reproduced or confirmed. Demonstrate the validation of the computational models, codes, assumptions, and approximations by comparison with measurements and experiments when possible. Describe in detail computer codes that are used as to the name and type of code, the way it is used, and its validity on the

basis of experiments or confirmed predictions of similar operating non-power reactors. Include estimates of the accuracy of the analytical methods. In Chapter 11, “Radiation Protection Program and Waste Management," of the SAR, the methods and assumptions used to analyze the release and dispersion of radioactive materials from normal operations are discussed. Adapt those methods as appropriate for accident analyses.

6. Define and derive the radiation source terms, if any are involved. Include in the source terms the quantity and type of radionuclides that could be released, their physical and chemical forms, and the duration of potential releases. Describe potential radiation sources that could cause direct or scattered radiation exposure to the facility staff and the public.

7. Evaluate the potential radiological consequences using realistic methods. Discuss the degree of conservatism in the evaluation. For example, include a discussion of the degree of conservatism introduced by the use of postulated release fractions or assumption of an infinite hemispherical cloud.

   Include environmental and meteorological conditions specific for the facility site to illustrate consequences. Exposure conditions should account for the facility staff until the situation is stabilized (including staff evacuation and reentry), the most exposed member of the public in the unrestricted environment until the accident conditions are terminated or the person is moved, and the integrated exposure at the facility boundary and the nearest permanent residence. The radiological consequences should include external and internal exposures. Address contamination of land and water where applicable; include exposure control measures to be initiated.

13.3 Summary and Conclusions

In this section of the SAR, the applicant should summarize the important conclusions about the postulated accidents and the potential consequences. The applicant should compare the projected radiological consequences with the acceptance criteria discussed previously in this chapter. The information should demonstrate that all reasonable measures have been incorporated into the facility design bases to prevent undue radiation exposures and contamination of the unrestricted environment. The discussions should show that engineered safety-features have been incorporated where necessary to limit consequences to acceptable levels.

13.4 References

1. IAEA-TECDOC-1601, “Homogeneous Aqueous Solution Nuclear Reactors for the Production of Mo-99 and Other Short Lived Radioisotopes,” International Atomic Energy Agency, September 2008.

2. Fluid Fuel Reactors, Addison-Wesley, 1958; Part I: Aqueous Homogenous Reactors, ed. Lane, Chapter 1

3. LA-UR-10-02947, “Lessons Learned from 65 Years of Experience with Aqueous Homogeneous Reactors,” Los Alamos National Laboratory, May 2010.

4. Fluid Fuel Reactors, Addison-Wesley, 1958; Part I: Aqueous Homogenous Reactors, ed. Lane, Chapter 2

5. LA-UR-10-04318, “Stability Analysis of the SUPO Reactor,” Los Alamos National Laboratory, June 2010.

APPENDIX F

Chapter 13, Accident Analysis, Part 2 Standard Review Plan

13 ACCIDENT ANALYSIS

13.1 Introductory Material

Other chapters of the SAR should contain discussions and analyses of the AHR facility as designed for normal operation. The discussions should include the considerations necessary to ensure safe operation and shutdown of the reactor to avoid undue risk to the health and safety of the public, the workers, and the environment. The analyses should include limits for operating ranges and reactor parameters within which safety could be ensured. The bases for the technical specifications should be developed in those chapters.

In this chapter the applicant should present a methodology for reviewing the systems and operating characteristics of the reactor facility that could affect its safe operation or shutdown. The methodology should be used to identify limiting accidents, analyze the evolution of the scenarios, and evaluate the consequences. The analyses should start with the assumed initiating event. The effects on designed barriers, protective systems, operator responses, and mitigating features should be examined. The endpoint should be a stable reactor. The potential radiological consequences to the public, the facility staff, and the environment should be analyzed. The information and analyses should show that facility system designs, safety limits, limiting safety system settings, and limiting conditions for operation were selected to ensure that the consequences of analyzed accidents do not exceed acceptable limits.

The applicant should also discuss and analyze postulated accident scenario whose potential consequences are shown to exceed and bound all credible accidents. For non-power reactors (including AHRs), this accident is called the maximum hypothetical accident (MHA). Because the accident of greatest consequence at a non-power reactor would probably include the release of fission products, the MHA, in most cases, would be expected to contain such a scenario involving fuel and/or fission products outside the core and need not be entirely credible. The review and evaluation should concentrate on the evolution of the scenario and analyses of the consequences, rather than on the details of the assumed initiating event.

Because the consequences of the postulated MHA should exceed those of any credible accident at the facility, the accident is not likely to occur during the life of the facility. The MHA is used to demonstrate that the maximum consequences of operating the reactor at a specific site are within acceptable limits. The applicant may choose to perform sensitivity analysis of the assumptions of the MHA. For example, reactor operating time before accident initiation may be examined to determine the change in MHA outcome if a more realistic assumption is made. As-

sumptions made in the accident analysis may form the basis for technical specification limits on the operation of the facility For example, if the accident analysis assumes that the reactor operates for five hours a day, five days a week, this may become a limiting condition for operation.

The information in this chapter should achieve the objectives stated in this chapter of the format and content guide by demonstrating that all potential accidents at the reactor facility have been considered and their consequences adequately evaluated. Each postulated accident should be assigned to one of the following categories, or grouped consistently according to the type and characteristics of the particular reactor. For AHRs, the following categories are applicable:

- maximum hypothetical accident
- insertion of excess reactivity
- reduction in cooling
- mishandling or malfunction of fuel
- loss of normal electric power
- external events (include natural hazards and man-made events)
- mishandling or malfunction of equipment
- large and undamped power oscillations
- detonation or deflagration of flammable gas mixtures
- unintended exothermic chemical reactions other than explosion
- facility system interaction events

The applicant should systematically analyze and evaluate events in each group to identify the limiting event selected for detailed quantitative analysis. The limiting event in each category should have consequences that exceed all others in that group. The discussions may address the likelihood of occurrence, but quantitative analysis of probability is not expected or required. As noted above, the MHA analyzed should bound all credible potential accidents at the facility. The applicant should demonstrate knowledge of the literature available for AHR accident analysis.

13.2 Areas of Review

Area of review should include systematic analysis and discussion of credible accidents for determining the limiting event in each category. The applicant may have to analyze several events in a particular accident category to determine the limiting event. This limiting event should be analyzed quantitatively. The steps suggested for the applicant to follow once the limiting event is determined for a category of accidents are given in Chapter 13 of the format and content guide.

13.3 Acceptance Criteria

The dose limits in 10 CFR 20 can be referenced as the acceptance criteria for AHRs. For MHAs, acceptable consequences may exceed 10 CFR 20 limits. The reviewer will evaluate this on a case-by-case basis. The applicant should discuss why the MHA is not likely to occur during the operating life of the facility.

13.4 Review Procedures

Information in the SAR should allow the reviewer to follow the sequence of events in the accident scenario from initiation to a stabilized condition. The reviewer should confirm the following:

- The credible accidents were categorized, and the most limiting accident in each group was chosen for detailed analyses.
- The reactor was assumed to be operating normally under applicable technical specifications before the initiating event. However, the reactor may be in the most limiting technical specification condition at the initiation of the event.
- Instruments, controls, and automatic protective systems were assumed to be operating normally or to be operable before the initiating event. Maximum acceptable non-conservative instrument error may be assumed to exist at accident initiation.
- The single malfunction that initiates the event was identified.
- Credit was taken during the scenario for normally operating reactor systems and protective actions and the initiation of engineered safety features.
- The sequence of events and the components and systems damaged during the accident scenario were clearly discussed.
- The mathematical models and analytical methods employed, including assumptions, approximations, validation, and uncertainties, were clearly stated.
- The radiation source terms were presented or referenced.
- The potential radiation consequences to the facility staff and the public were presented and compared with acceptable limits.

The reviewer should confirm that the integrity of the primary boundary will be maintained under all credible accidents that have been analyzed. The primary boundary consists of all structures that prevent the release of fuel and fission products in solution and the fission gases generated during operation; they include the vessel containing the fuel, the off-gas systems and the waste gas holding system(s), the cooling coils in the vessel, and the associated pumps, valves, heat exchangers, and piping.

The reviewer should determine if the applicant has categorized and analyzed all credible accidents in terms of the limiting phenomena identified below that may pose a challenge to the integrity of the primary boundary in different locations in the facility. The reviewer should also determine if the applicant has identified the limiting sources and amounts of radionuclides that may be released within the facility or to the outside environment, thereby exposing the facility staff or the general public to radiation. The limiting phenomena for AHRs are expected to be as follows:

- bulk boiling of fuel solution (i.e. change of phase occurs as liquid evaporates into gas)
- precipitation of fission products
- precipitation of fuel (uranium)
- detonation or deflagration of combustible gas mixtures
- excessively high radiolytic gas release

Technical Rationale

The limiting phenomena are analogous to phenomena for light water reactors (LWRs) that set operational and safety limits. For example, departure from nucleate boiling has been identified as a phenomenon that greatly increases the likelihood of cladding failure in LWRs and is useful in deriving quantitative operating and safety limits. Additionally, regulatory limits such as cladding oxidation are tied to the phenomenon of loss of cladding ductility. While the specific safety limits will depend upon the reactor design, the reviewer should confirm that the applicant has addressed these limiting phenomena in their definitions of operating and safety limits as well as accident analyses.

Reactivity limits and the functional designs of control and safety-related systems should prevent loss of primary boundary integrity during credible accidents involving insertion of some fraction of excess reactivity. Applicable reactivity feedback coefficients and automatic protective actions, if applicable, should be included in the analyses

The reviewer should confirm that the applicant has analyzed potential power instabilities including unstable (growing) power oscillations that are large and undamped. These large, undamped power oscillations may result from positive feedback. The reviewer should confirm that the reactor will return to a stable state such that the integrity of the primary boundary is not challenged.

The reviewer should confirm that loss of normal electrical power and consequent reduction in cooling will not lead to a challenge to the primary boundary. Safe reactor shutdown should not be compromised by loss of normal electric power.

13.5 Evaluation Findings

It is essential that all credible accidents at an AHR be considered and evaluated during the design stage. Experience has indicated that such facilities can be designed and operated so that the environment and the health and safety of the staff and the public can be protected. Because AHRs are designed to operate with primary coolant temperatures and pressures close to ambient, the margins for safety are usually large, and few, if any, credible accidents can be sufficiently damaging to release radioactive materials to the unrestricted area. For potential accidents and the MHA that could cause a release, the acceptance criteria and review procedures discussed above are sufficiently comprehensive and will not be repeated for each postulated accident. However, the potential consequences, detailed analyses, evaluations, and conclusions are facility specific

and accident specific. The findings for the nine major accident categories are presented below. These findings are examples only. The actual wording should be modified for the situation under review.

This section of the SAR should contain sufficient information to support the types of conclusions given below. Those conclusions will be included in the staff's safety evaluation report. The appropriate number for the reactor under evaluation should replace the notation “xx”. The reviewer should modify these conclusions to conform to the reactor design under consideration.

13.5.1 MHA

The applicant has considered the consequences to the public of all credible accidents at the reactor facility. A maximum hypothetical accident (MHA), an accident that would release fission products from fuel would have consequences greater than any credible accident, has been analyzed. The MHA, however, is not credible for a non-power reactor. (The MHA is specific to the reactor design and power. The reviewer may have to evaluate an MHA that differs from the suggested list of MHAs below.)

Possible MHAs for an AHR could be one or a combination of the following events:

- Energetic dispersal of the contents of the primary boundary with bypass of any scrubbing capacity (e.g. a pool surrounding the fuel vessel)

- Detonation of hydrogen in the recombiner resulting in waste gas tank failure and release of some or all of the fuel and fission product contents in aerosolized form

- Complete loss of fuel inventory (e.g. vessel break)

Possible MHAs for a multi-reactor AHR facility could be one or a combination of the following events:

- a man-made external event that breaches the primary boundary of more than one unit
- a facility wide external event that breaches various systems containing radioactive fluids

The reviewer should modify the following paragraphs, as appropriate:

The air handling and filtering systems (i.e., confinement or containment) are assumed to function as designed, and radioactive material is held up temporarily in the reactor room and then released from the building. Realistic methods are used to compute external radiation doses and dose commitments resulting from inhalation by the facility staff. Realistic but conservative methods are used to compute potential doses and dose commitments to the public in the unrestricted area. Methods of calculating doses from inhalation or ingestion (or both) and direct shine of gamma rays from dispersing plumes of airborne radioactive material are applicable and no less conserva-

tive than those developed in Chapter 11 of the SAR. The exposure time for the reactor staff is "xx" and for the public it is "yy".

The calculated maximum effective doses for the MHA scenario are the following:

external - (xx mrem) staff, (yy mrem) public

internal- (xx mrem) staff, (yy mrem) public

These doses and dose commitments are within the acceptable limits (state the limits). Because the assumptions of the scenario are conservative, the postulated accident would not be likely to occur during the life of the facility. The applicant has examined more realistic assumptions about operating time and release fractions that decreased the source term by xx percent of the one calculated, lowering the maximum doses by that factor (if applicable). Thus, even for the MHA, whose consequences bound all credible accidents possible at the facility, the health and safety of the facility staff and the public are protected

13.5.2 Insertion of Excess Reactivity

The review should determine if the following finding is applicable.

The applicant has considered the following initiators that could insert excess reactivity in AHRs:

- pressurization of the fuel fluid
- excessive cooldown via heat sink malfunction
- moderator injection due to cooling system malfunction, e.g. cooling tube rupture
- fuel injection
- realistic, adverse geometry changes, e.g. due to 'sloshing' of the fuel solution in the vessel
- reactivity insertion due to moderator lumping effects, e.g. voiding in the cooling coil
- inadvertent introduction of other material into the fuel solution, e.g. excessive acid addition
- control rod removal or ejection or system malfunction

The reviewer should determine that the limiting reactivity insertion event has been identified and analyzed and the consequences of this event are within the dose acceptance limits and bounded by the MHA. Radiation doses to the public and staff are thus within acceptable limits and the safety and health of the staff and public are adequately protected. The reviewer should also confirm that the reactor attains a stable condition following the limiting event.

13.5.3 Reduction in Cooling

The applicant has considered postulated events that lead to reduction or loss of cooling. The following initiators have been analyzed:

- Loss of electrical power
- Failure of active components in the normal heat removal system(s)
- Cooling coil or heat exchanger tube rupture
- Flow obstruction in heat exchangers
- Loss of forced circulation
- Recombiner burnout

The reviewer should confirm that the consequences of reduction in cooling events have been analyzed and shown to be bounded by the MHA. Radiation doses to the public and staff are thus within acceptable limits and the safety and health of the staff and public are adequately protected.

13.5.4 Mishandling or Malfunction of Fuel

The reviewer should determine that the applicant considered the consequences of fuel solution mishandling events such as excessive leakage or spillage that could potentially initiate an unintended criticality event in an area or location where it could pose a threat to facility staff. The reviewer should confirm that the accidental dose consequences of such postulated events are bounded by the MHA. Therefore, doses to the staff and the public are within acceptable limits and the health and safety of the staff and public are adequately protected.

The reviewer should determine that the applicant considered the consequences of fuel malfunction events for an AHR. These events include failure to control pH, temperature, or pressure of the fuel solution, which can impact the physical or chemical form of the fuel or solvent resulting in adverse chemical effects such as fuel precipitation or excessive corrosion. The reviewer should confirm that the accidental dose consequences of such postulated events are bounded by the MHA. Therefore, doses to the staff and the public are within acceptable limits and the health and safety of the staff and public are adequately protected.

13.5.5 Loss of Electrical Power

The reviewer should determine that the applicant evaluated the consequences of a loss of electrical power. The review should determine if the following finding is applicable.

The applicant's analysis considered the effects of radiolytic decomposition of the fuel solution and the formation of fission gases, addressed the system response to gas formation and evaluated the potential for the decomposed gases to react explosively. The applicant's analyses were carried out for a sufficient duration to demonstrate that the reactor reaches a stable state. The accidental dose consequences of such postulated events are bounded by the MHA. Therefore, doses to the staff and the public are within acceptable limits and the health and safety of the staff and public are adequately protected.

13.5.6 External Events

The reviewer should determine that the applicant evaluated the consequences of external events including events that have a potential for changing the geometry of the fuel solution in the reactor vessel. The review should determine if the following finding is applicable.

The design to withstand external events and the potential associated accidents is discussed in Chapters 2 and 3 of the SAR. The reactor facility is designed to accommodate these events by shutting down, which would not pose undue risk to the health and safety of the public. For events that cause facility damage, the damage is within the bounds discussed for other accidents in this chapter. Therefore, exposure to the staff and the public is within acceptable limits and external events do not pose an unacceptable risk to the health and safety of the public.

13.5.7 Mishandling or Malfunction of Equipment

Initiating events under this heading would require a case-by-case, reactor-specific discussion. If the SAR discusses additional events that fall outside the other categories, the potential consequences should be compared with similar events already analyzed or with the MHA, as applicable.

13.5.8 Large Undamped Power Oscillations

The reviewer should determine if the applicant has evaluated potential unstable (growing), large undamped power oscillations and demonstrated that such oscillations are either not possible, or, if they develop, can be readily detected and suppressed so that the reactor reaches a stable state. The reviewer should consider the potential for positive feedback to arise due to system interaction. Reactivity feedback coupled with plant response may yield conditions which are not inherently stable. An example may include positive feedback due to radiolytic gas formation and vessel pressurization under conditions where the recombiner capacity of an AHR is exceeded. Such conditions where positive feedback is possible must be examined to determine if the reactor remains stable; or, if the reactor becomes unstable such that the power oscillations grow over time, that these unstable power oscillations can be acceptably detected and suppressed. The review should determine if the following finding is applicable.

Power oscillations should be stable or can be readily detected and suppressed such that the consequences are bounded by the MHA. Therefore, doses to the staff and the public are within acceptable limits and the health and safety of the staff and public are adequately protected.

13.5.9 Detonation and Deflagration

The reviewer should determine if the applicant has evaluated the consequences of potential deflagration or detonation of combustible gases within the primary boundary. The reviewer should evaluate the assumptions regarding the impact of potential explosions on primary boundary integrity. This review should consider both the mechanical impact of the explosion in terms of pri-

mary barrier integrity, but also the core response in terms of dynamic fuel response and reactivity response to any impinging pressure waves. The reviewer should also evaluate the applicant's assumptions regarding aerosolization of the fuel. The reviewer should confirm that the limiting event has been identified and that the consequences are bounded by the MHA. The review should determine if the following finding is applicable.

The consequences of the limiting credible detonation within the primary boundary are bounded by the MHA. Therefore, doses to the staff and public are within acceptable limits and the health and safety of the staff and public are adequately protected.

13.5.10 Unintended Exothermic Chemical Reactions Other Than Explosion

The reviewer should determine if the applicant has evaluated the consequences of potential unintended exothermic chemical reactions (other than explosion) that may occur within the primary boundary. As a precursor to this event an excess of gases may accumulate in the primary boundary and subsequently react with oxygen to release heat. The heat may increase pressure within the primary boundary or induce thermal stress on the primary boundary. The reviewer should confirm that the types of possible exothermic reactions have been identified and the relative consequences assessed by the applicant. The reviewer should further determine if the following finding is applicable.

The consequences of the limiting unintended exothermic chemical reaction (other than detonations as discussed in Section 13.5.9) within the primary boundary are bounded by the MHA. Therefore, doses to the staff and public are within acceptable limits and the health and safety of the staff and public are adequately protected.

13.5.11 Facility System Interaction Events

Initiating events under this heading would require a case-by-case, reactor-specific discussion. If the SAR discusses additional events that fall outside the other categories, the potential consequences should be compared with similar events already analyzed or with the MHA, as applicable.

For medical isotope production facilities, the reviewer should determine if the following finding is applicable. The applicant's analysis has considered potential system interactions between the reactor and the isotope production facility. The accidental dose consequences of such postulated events are bounded by the MHA. Therefore, doses to the staff and the public are within acceptable limits and the health and safety of the staff and public are adequately protected.