Oklo Responses to NRC Request for Additional Information 3: Aurora Step 1 – MCA - Heat Transfer in the Reactor System

October 2020

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1 RAI: AURORA STEP 1 – MCA - 5

NRC staff requests that the FSAR be updated to describe the thermal bonds between (1) the reactor cell can and heat pipe, and (2) the heat pipe and heat exchanger. Specifically, NRC staff requests updates to the following sections of the FSAR:

- FSAR Section 2.1.3.1, "Key dimensions," to clarify the reactor conditions that correspond to the dimensions provided in FSAR Table 2-1 (i.e., hot or cold).
- FSAR Section 2.2.2, "Reactor core system," to describe the thermal bond between the reactor cell can and heat pipe and to provide, as necessary, design commitments and programmatic controls associated with the thermal bond design in order to support DB.RXS.04, "The reactor core system provides a pathway to conduct heat from the fuel to the surrounding systems and ultimately to reject it to the environment."
- FSAR Section 2.6, "Heat exchanger system," to describe the thermal bond between the heat pipe and heat exchanger and to provide, as necessary, design commitments and programmatic controls associated with the thermal bond design in order to support DB.HXS.01, "The heat exchanger system provides a pathway to conduct heat from the heat pipes of the reactor core system to the surrounding systems and ultimately to reject it to the environment."
- FSAR Table 5-7, "Summary of assumptions in safety analysis and reason for conservatism," to include the assumptions imposed on the thermal bonds between (1) the reactor cell cans and heat pipes, and (2) the heat pipes and heat exchanger.

1.1 Oklo response

Oklo recognizes the staff's interest in thermal connections between relevant components in the reactor core system and heat exchanger system. The four sections identified by the staff will be updated as described in the following subsections, with specific markups provided in Section 1.2.

1.1.1 Key dimensions

Section 2.1.3.1 of the FSAR will be updated to clarify that the dimensions provided in Table 2-3 reflect cold (room temperature) conditions.

1.1.2 Reactor core system

The reactor cell can and heat pipe are thermally bonded to enable effective heat transfer between the fuel and the heat pipe. The effectiveness of this thermal bond is necessary to support heat transfer between the fuel and heat pipe; of particular relevance to this RAI is DB.RXS.04, which is replicated below:

Design basis:

DB.RXS.04 The reactor core system provides a pathway to conduct heat from the fuel to the surrounding systems and ultimately to reject it to the environment.

Design evaluation summary:

This section described the layout of the reactor core system, a matrix of hexagonal reactor cells. Decay heat is conducted away from the fuel in both the axial and radial directions both within and among the reactor cells and outward toward surrounding systems. The transient analysis in Chapter 5 shows that, when configured as designed, the reactor core system provides adequate heat conduction to maintain fuel temperatures below their required limits during the decay heat phase of the maximum credible accident (without active cooling). Design commitments are made to ensure proper as-built configuration of the core prior to operation and to demonstrate that the reactor core system can be cooled via conduction. The appropriate programmatic controls are in place to verify them.

Design commitments and programmatic controls:

DC.RXS.04.A The critical components of the reactor core system, as identified in the appropriate procedure, are installed as described in the design documents referenced by the procedure.

SUT.RXS.04.A (see Chapter 14)

DC.RXS.04.B The reactor core system can be cooled by conduction through the surrounding systems (reflector system, shielding system, heat exchanger system, and reactor enclosure system) and subsequent convection from the module shell after shutdown.

SUT.RXS.04.B

As described in Section 1.1.4 and in the response to Aurora Step 1 – MCA - 6 in Section 2, the performance of this thermal bond is defined through relevant metrics of interest to ensure its performance meets the assumptions used in the safety analysis presented in Chapter 5 of the FSAR. The specific metrics of interest are described in Section 1.1.4. While many material choices and design configurations may be sufficient to meet these metrics of interest, it is expected that a stainless-steel mesh will be thermally bonded to both the heat pipe and reactor cell can to provide this thermal coupling. Compatibility with the stainless steel of the heat pipe and reactor cell can results in similar thermal expansion during heatup from cold (room temperature) conditions to hot (operating) conditions.

Section 2.2.2 of the FSAR will be updated to describe the thermal bond between the reactor cell can and heat pipe, and a description of the programmatic controls that ensure efficacy of the thermal bond between the heat pipe and the reactor cell can is provided in the response to Aurora Step 1 – MCA - 6 in Section 2.

1.1.3 Heat exchanger system

Effective thermal coupling between heat pipe and heat exchanger is necessary to enable effective heat transfer between the fuel and the thermal mass of the heat exchanger. Of particular relevance to this RAI is DB.HXS.01, which is replicated below:

Design basis:

DB.HXS.01 The heat exchanger system provides a pathway to conduct heat from the heat pipes of the reactor core system to the surrounding systems and ultimately to reject it to the environment.

Design evaluation summary:

This section describes the design of the heat exchanger system, which is made up of six heat exchanger units. Decay heat is conducted away from the heat pipes of the reactor core system and outward toward surrounding systems through the heat exchanger system. The transient analysis in Chapter 5 shows that, when configured as designed, the heat exchanger system provides adequate heat conduction to maintain fuel temperatures below their required limits during the decay heat phase of the maximum credible accident (without active cooling). A design commitment is made to ensure proper as-built configuration of the heat exchanger system prior to operation and the appropriate programmatic controls are in place to verify it.

Design commitments and programmatic controls:

DC.HXS.01.A The critical components of the heat exchanger system, as identified in the appropriate procedure, are installed as described in the design documents referenced by the procedure.

SUT.HXS.01.A (see Chapter 14)

Section 2.6 of the FSAR will be updated to describe the thermal bond between the heat pipe and heat exchanger, and a description of the programmatic controls that ensure the efficacy of the thermal bond between the heat pipe and heat exchanger is provided in the response to Aurora Step 1 – MCA - 6 in Section 2.

1.1.4 Summary of assumptions

Table 5-7 in the FSAR will be updated to include the assumptions imposed on the thermal bonds between (1) the reactor cell cans and heat pipes, and (2) the heat pipes and heat exchanger, as used in the safety analysis presented in Chapter 5 of the FSAR.

1.2 Associated changes to the COLA

The following portions of the COLA will be revised as described above, and shown in the provided markup below.

Part II, Section 2.1.3.1

The dimensions with first order importance to the core reactivity and thermal characteristics of the system are the key dimensions of the Aurora. The key dimensions are summarized in Table 2-1 and depicted in Figure 2-1. The key dimensions provided in Table 2-1 are dimensions at cold (room temperature) operating conditions. Other dimensions, such as the thicknesses of the surrounding reflector and structural components outside of the active core, do have some effect on the core reactivity and thermal characteristics. However, since these components are at a distance from the fuel and the primary heat transfer pathway of the heat pipes, the neutronic and thermal response of the system is only second- or third-order dependent on these dimensions, making their exact values less relevant than those of the reactor cells. As such, only the reactor cell dimensions presented here are considered key dimensions of the Aurora.

Table 1-1: Key dimensions for the Aurora at cold (room temperature) operating conditions

Part II, Section 2.2.2.3.1

The reactor core system consists entirely of reactor cells, which are integrated structural, nuclear, and thermal units. Each reactor cell is composed of the following components:

- Can
- Lower axial reflector
- Metal fuel
- Upper axial reflector
- Gas plenum
- Axial shielding
- Sodium bond
- Heat pipe

The stainless steel can encloses the fuel, upper and lower axial reflectors, a gas plenum, and axial shielding. The fuel, reflectors, and shielding are annular, and are fully enclosed by the hexagonal outer can wall and the cylindrical inner can wall. Each reactor cell also contains a heat pipe, which is inserted into the cylindrical "socket" formed by the inner can wall, and extends from the base of the can, through the annular components, and into the heat exchanger. The inner cell can and heat pipe are thermally bonded to enable effective heat transfer from the fuel to the heat pipe. Nominal reactor cell dimensions are summarized in Table 2-2, and a reactor cell and its components are shown in Figure 2-2.

Part II, Section 2.6.5.1

During steady state operation the heat exchanger system functions to remove heat from the reactor core system by convectively cooling the heat pipes. The system is optimized to account for the radial power peaking in the core and to remove the appropriate amount of heat from each heat pipe. Thermal bonding between the heat pipe and heat exchanger is necessary to enable sufficient heat transfer from the heat pipe to the working fluid of the heat exchanger system at steady state, and to allow conduction from the heat pipe to the thermal mass of the heat exchanger when the nominal heat sink is unavailable. Theeis steady-state heat removal function relates only to the performance basis of the system, so further details of operation during steady state are not presented.

Part II, Table 5-7

Table 1-2: Summary of assumptions in safety analysis and reason for conservatism

Topic	Assumption	Conservatism
Power	Highest power reactor cell in ring	Maximizes internal heat generation
Heat pipe temperature	All heat pipes set to highest power cell	Overpredicts initial temperatures
Heat transfer from shell	h = 7 W/m^2-K, T = 225 C	Underpredicts passive heat transfer to ultimate heat sink
	No radiative heat transfer	Underpredicts passive heat transfer to ultimate heat sink
Decay heat	Decay heat during timestep assumes initial value	Overpredicts decay heat generation throughout analysis
Reactivity feedback	No negative reactivity feedback effects	Overpredicts rate of power increase during TOP
Overpower heat generation	Power during timestep assumes end value	Overpredicts fission heat generation throughout active phase
Power conversion system	Instantaneous stop of rotating components	Underpredicts heat removal by PCS associated with flow coastdown
Shutdown rod insertion delay	10-second delay from trip setpoint to reactor trip	Overpredicts fission heat generation prior to trip
Fuel thermal conductivity	30% decrement due to burnup	Overpredicts thermal gradients in fuel
Cell-to-cell contact conductance	100 W/m^2-K assumes only radiative heat transfer	Overpredicts thermal gradients in module
Thermal bond between heat pipe and reactor cell can	Solid body with ρ = 1000 kg/m^3, k = 16 W/m-K, c_p = 100 J/kg-K, negligible thermal resistances	Conservative relative to expected thermal bond performance
Thermal bond between heat pipe and heat exchanger	Heat exchanger inner hex as homogeneous body with ρ = 1700 kg/m^3, k = 7 W/m-K, c_p = 945 J/kg-K, contact conductance of 4000 W/m2-K	Conservative relative to expected thermal bond performance

2 RAI: AURORA STEP 1 – MCA - 6

NRC staff requests that Oklo incorporate into the FSAR, either directly or by reference, information to (1) provide evidence of analysis, appropriate test programs, experience, or combination thereof to support the efficacy of the design features used to thermally bond the heat pipes in the Aurora to the reactor cell cans and heat exchanger, and (2) explain how this evidence supports the modeling parameters used in the safety analyses.

2.1 Oklo response

2.1.1 Summary

Oklo recognizes the staff's interest in the efficacy of design features used to bond the heat pipes in the Aurora to the reactor cell cans and heat exchanger. In conjunction with previous RAI responses, namely Aurora Step 1 – MCA - 4, the efficacy of the design features used to thermally bond the heat pipes to the reactor cell cans and heat exchanger are sufficiently ensured by design bases, design commitments, and programmatic controls. The addition of two preoperational tests, one for each of the regions of interest, are proposed as updates to the FSAR to support this response.

Each design commitment is associated with an appropriate pre-operational test (POT), startup test (SUT), or technical specification (TS) to ensure that the system operates as designed. These programmatic controls are fundamental to the Aurora COLA and ensuring that this first-of-a-kind technology will be operated within its design limits. The programmatic controls are performance-based and represent the "appropriate test programs" that will be used to verify the efficacy of the design features used to thermally bond the heat pipes to the reactor cell cans and heat exchanger that are the subjects of this RAI. Simultaneously, these programmatic controls provide the evidence to ensure that the performance of these design features support the modeling parameters used in the safety analyses presented in Chapter 5 of the FSAR.

These programmatic controls are explicitly committed to as license conditions that must be completed prior to startup (POTs must be completed to satisfy an ITAAC), as tests that must be completed during startup (SUTs), and as the operating limits of the reactor (TS) that ensure they continue to be effective during normal operation.

The existing design bases sufficiently describe and capture the efficacy of the thermal bonds, and additional programmatic controls are proposed to ensure that the performance of these design features support the modeling parameters used in the safety analyses.

2.1.2 Detailed response

The heat pipe is thermally bonded to the reactor cell can to enable effective heat transfer between the fuel and the heat pipe, which is ensured by a design basis of the reactor core system (DB.RXS.04). Similarly, the heat pipe is thermally coupled to the heat exchanger to enable effective heat transfer between the heat pipe and the thermal mass of the heat exchanger; this is ensured by a design basis of the heat exchanger system (DB.HXS.01).

Further, a design basis of the instrumentation and control system, namely DB.ICS.01, is written as follows: "The reactor trip system monitors reactor process variables and sends a reactor trip signal when a process variable exceeds a limit setpoint." While not a design basis of the reactor core system, the efficacy of the thermal bond between the reactor cell can and heat pipe is ensured by a specific design commitment for this design basis.

As part of its response to Aurora Step 1 – MCA - 4, Oklo proposed additions to the FSAR to expand the design commitments and programmatic controls associated with the measurement of fuel temperature by thermocouples in the condenser region of the heat pipes. The updated DB.ICS.01 is replicated below, with updates shown in blue and underline (for the purpose of distinguishing updates proposed in a prior RAI response from the updates proposed in this response):

Design basis:

DB.ICS.01 The reactor trip system monitors reactor process variables and sends a reactor trip signal when a process variable exceeds a limit setpoint.

Design evaluation summary:

This section describes the design of the reactor trip system, which provides the ability to detect and respond to multiple trip conditions. The transient analysis in Chapter 5 shows that if reactor trip signals are sent in response to the chosen setpoints, and the shutdown rods insert within the appropriate time interval, then fuel temperatures will be maintained below the required limits. Design commitments are made to ensure that each of the trip conditions will be reliably detected, and will result in a reactor trip signal, and the appropriate programmatic controls are in place to verify it.

Design commitments and programmatic controls:

DC.ICS.01.A The reactor trip system sensors are installed in the correct locations.

POT.ICS.01.A1 and A2 (see Chapter 14)

SUT.ICS.01.A1

[…]

DC.ICS.01.E The reactor trip system correctly infers fuel temperature based on heat pipe temperature.

POT.ICS.01.E1

POT.ICS.01.E2

POT.ICS.01.E3

The proposed additions to the preoperational tests associated with DB.ICS.01 are shown in the table below (updates in blue and underline):

Test identifier	**POT.ICS.01.E1**
Objective	Verify that the output of a thermocouple in the condenser region of a heat pipe is directly correlated to the fuel temperature.
method	Instrument a prototypic reactor cell with thermocouples in the condenser region of the heat pipe and in the surrogate fuel material. Apply varying thermal loads to the surrogate fuel material through non-nuclear heating.
acceptance criteria	The measured temperatures in the surrogate fuel material and the condenser region of the heat pipe sufficiently match the predicted correlation.
Test identifier	**POT.ICS.01.E2**
Objective	Verify that the output of a thermocouple in the condenser region of a heat pipe decreases below the under-temperature limit setpoint following failure of the heat pipe.
method	Instrument a prototypic reactor cell with thermocouples in the condenser region of the heat pipe and in the surrogate fuel material. Apply the nominal thermal load at full power to the surrogate fuel material through non-nuclear heating. Initiate a heat pipe failure.
acceptance criteria	The measured temperature response in the surrogate fuel material and the condenser region of the heat pipe sufficiently match the predicted response.
Test identifier	**POT.ICS.01.E3**
Objective	Verify that the output of a thermocouple in the condenser region of a heat pipe increases above the over-temperature limit setpoint following the loss of heat sink.
method	Instrument a prototypic reactor cell with thermocouples in the condenser region of the heat pipe and in the surrogate fuel material. Apply the nominal thermal load at full power to the surrogate fuel material through non-nuclear heating. Initiate a loss of heat sink.
acceptance criteria	The measured temperature response in the surrogate fuel material and the condenser region of the heat pipe sufficiently match the predicted response.

Specifically, POT.ICS.01.E1 ensures that the thermal coupling between the fuel and the thermocouple in the condenser region of the heat pipe (i.e., in close proximity to the heat exchanger) sufficiently matches the predicted correlation. Included in this evaluation is the consideration of thermal coupling between the (surrogate) fuel and heat pipe and between the heat pipe and the heat exchanger. As such, this preoperational test provides the evidence to ensure that the performance of these design features support the modeling parameters used in the safety analyses presented in Chapter 5 of the FSAR.

In addition to the existing and proposed programmatic controls in the FSAR, Oklo proposes the addition of two programmatic controls to support the efficacy of the design features of interest in this RAI. Namely, Oklo proposes the addition of POT.RXS.04.B and POT.HXS.01.A to the reactor core system and heat exchanger system, respectively. These preoperational tests ensure that the thermal coupling of the heat pipe to the reactor cell can and heat exchanger match or exceed the performance assumed in the safety analysis presented in Chapter 5 of the FSAR.

2.2 Associated changes to the COLA

The following portions of the COLA will be revised as described above and shown in the provided markup below.

Part II, Section 2.2.2.6:

Design basis:

DB.RXS.04 The reactor core system provides a pathway to conduct heat from the fuel to the surrounding systems and ultimately to reject it to the environment.

Design evaluation summary:

This section described the layout of the reactor core system, a matrix of hexagonal reactor cells. Decay heat is conducted away from the fuel in both the axial and radial directions both within and among the reactor cells and outward toward surrounding systems. The transient analysis in Chapter 5 shows that, when configured as designed, the reactor core system provides adequate heat conduction to maintain fuel temperatures below their required limits during the decay heat phase of the maximum credible accident (without active cooling). Design commitments are made to ensure proper as-built configuration of the core prior to operation and to demonstrate that the reactor core system can be cooled via conduction. The appropriate programmatic controls are in place to verify them.

Design commitments and programmatic controls:

DC.RXS.04.A The critical components of the reactor core system, as identified in the appropriate procedure, are installed as described in the design documents referenced by the procedure.

SUT.RXS.04.A (see Chapter 14)

DC.RXS.04.B The reactor core system can be cooled by conduction through the surrounding systems (reflector system, shielding system, heat exchanger system, and reactor enclosure system) and subsequent convection from the module shell after shutdown.

SUT.RXS.04.B

POT.RXS.04.B

Part II, Section 14.9:

Table 14-5: List of reactor system preoperational tests and objectives

Test identifier	Design basis	Objective
POT.RXS.04.B	DB.RXS.04	Verify the performance of the thermal coupling between heat pipe and reactor cell can.
POT.RXS.05.A	DB.RXS.05	Verify the critical components of the as-installed reflector system are installed correctly.
POT.RXS.06.A	DB.RXS.06	Verify the critical components of the as-installed shielding system are installed correctly.

Part II, Section 14.9, add a subsection 14.9.1, "Reactor core system test group":

Frequency	The tests identified as FOAK are performed once for the Aurora design.
Purpose	Completion of this test verifies the tested reactor core system components function correctly.
Prerequisites	None

Test identifier	**POT.RXS.04.B (FOAK)**
objective	Verify the performance of the thermal coupling between heat pipe and reactor cell can.
method	Instrument a prototypic reactor cell with thermocouples in the evaporator region of the heat pipe and in the surrogate fuel material. Apply thermal loads that are representative of steady-state and transient thermal conditions, including conditions experienced during safety analysis, to the surrogate fuel material through non-nuclear heating.
acceptance criteria	The effective thermal conductivity between the reactor cell can and the heat pipe matches or exceeds the performance assumed during safety analysis, including consideration of thermal resistance.

Part II, Section 2.6.6:

Design basis:

DB.HXS.01 The heat exchanger system provides a pathway to conduct heat from the heat pipes of the reactor core system to the surrounding systems and ultimately to reject it to the environment.

Design evaluation summary:

This section describes the design of the heat exchanger system, which is made up of six heat exchanger units. Decay heat is conducted away from the heat pipes of the reactor core system and outward toward surrounding systems through the heat exchanger system. The transient analysis in Chapter 5 shows that, when configured as designed, the heat exchanger system provides adequate heat conduction to maintain fuel temperatures below their required limits during the decay heat phase of the maximum credible accident (without active cooling). A design commitment is made to ensure proper as-built configuration of the heat exchanger system prior to operation and the appropriate programmatic controls are in place to verify it.

Design commitments and programmatic controls:

DC.HXS.01.A The critical components of the heat exchanger system, as identified in the appropriate procedure, are installed as described in the design documents referenced by the procedure.

SUT.HXS.01.A (see Chapter 14)

POT.HXS.01.A

Part II, Section 14.9:

Table 14-10: List of heat exchanger system preoperational tests and objectives

Test identifier	Design basis	Objective
POT.HXS.01.A	DB.HXS.01	Verify the performance of the thermal coupling between heat pipe and heat exchanger.

Part II, Section 14.9, add a subsection 14.9.2, "Heat exchanger system test group":

Frequency	The tests identified as FOAK are performed once for the Aurora design.
Purpose	Completion of this test verifies the tested heat exchanger system components function correctly.
Prerequisites	None

Test identifier	**POT.HXS.01.A (FOAK)**
objective	Verify the performance of the thermal coupling between heat pipe and heat exchanger.
method	Instrument a prototypic reactor cell with thermocouples in the heat exchanger region, in the condenser region of the heat pipe, and in the surrogate fuel material. Apply thermal loads that are representative of steady-state and transient thermal conditions, including conditions experienced during safety analysis, to the surrogate fuel material through non-nuclear heating.
acceptance criteria	The effective thermal conductivity between the heat exchanger and the heat pipe matches or exceeds the performance assumed during safety analysis, including consideration of thermal resistance.