February 26, 2021

TP-LIC-LET-0004
Project Number 99902087

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington DC 20555-0001

Subject: TerraPower®, LLC – Advanced SFR Type 1 Fuel Pin Qualification Plan

References: 1. Letter – TerraPower LLC to Document Control Desk, "*Regulatory Guidance Development Report*," July 16, 2020 (ML20209A155)

TerraPower, LLC received a Regulatory Assistance Grant from the DOE to develop an Advanced Fuel Qualification Methodology Report. The Report will provide regulatory guidance, describe methodologies, and identify regulatory and qualification criteria for Sodium Fast Reactors (SFR) metallic fuel. The final report will include a Regulatory Guidance Development Report, an Advanced SFR Fuel Assembly Qualification Plan, a Type 1Fuel Pin Qualification Plan, and a Type 1B Fuel Pin Qualification Plan. TerraPower LLC submitted the Regulatory Guidance Development Report to the NRC for review and feedback on July 16, 2020, (see Ref. 1).

The Type 1 Fuel Pin Qualification Plan is the third submittal of the Advanced Fuel Qualification Methodology Report. There are two primary objectives of this Plan 1) adequately review and identify fuel-related needs required for license application to support development of a high-level schedule and budget for those activities; and 2) provide enough detail on the planned activities so that independent reviews can be performed to verify the adequacy of the plans to address technical risks and regulatory needs. Although the focus of this Plan is on individual fuel pins, applicable interfaces required to support fuel pin design criteria are identified.

Portions of the Type 1 Fuel Pin Qualification Plan are considered proprietary, and TerraPower requests it be withheld from public disclosure in accordance with the provisions of 10 CFR 2.390. Additionally, the information indicated as proprietary has also been determined to contain Export Controlled Information. This information must be protected from disclosure pursuant to the requirements of 10 CFR 810. Enclosures 1 and 2 to this report provide the approved proprietary and non-proprietary versions of this report, designated as AFQMG-ENG-PLAN-0001 and AFQMG-ENG-PLAN-0001R, respectively. An affidavit supporting the withholding request is provided in Enclosure 3. TerraPower authorizes the NRC to reproduce and distribute the submitted non-proprietary content, as necessary, to support the conduct of their regulatory responsibilities.

This submittal is a White Paper. TerraPower is requesting the NRC review and evaluate the Type 1 Fuel Pin Qualification Plan and provide preliminary feedback on the approach. TerraPower understands the NRC will perform a preliminary assessment to understand the scope and content. After the preliminary assessment, NRC may provide a bulletized series of questions and comments to address the observations.

If you have any questions, please contact me at 423-208-2188 or at pgaillard@terrapower.com. This letter makes no regulatory commitments and no revisions to any existing regulatory commitments.

Sincerely,

Peter C. Gaillard

Peter C. Gaillard, PE
Director, Regulatory Affairs
TerraPower, LLC

Enclosures:
1) AFQMG-ENG-PLAN-0001, Type 1 Fuel Pin Qualification Plan, Revision 0 (Proprietary)
2) AFQMG-ENG-PLAN-0001R Type 1 Fuel Pin Qualification Plan, Revision 0 (Non-Proprietary)
3) Affidavit Supporting Request for Withholding from Public Disclosure (10 CFR 2.390)

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ENCLOSURE 2

Type 1 Fuel Pin Qualification Plan, Revision 0
(Non-Proprietary)

TerraPower™

TYPE 1 FUEL PIN QUALIFICATION PLAN

Non-Proprietary

February 2021

15800 Northup Way
Bellevue, WA 98008

REVISION HISTORY

Revision No.	Effective Date	Affected Section(s)	Description of Change(s)
0	2/24/2021	All	Initial Issue

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1 PURPOSE

This document provides an assessment of the fuel-related activities required to support licensing of a plant starting up with a sodium-bonded metallic fuel form consistent with the HT9-clad fuel used successfully in both the Experimental Breeder Reactor II (EBR-II) and the Fast Flux Test Facility (FFTF). This fuel will be generically referred to as Type 1 Fuel throughout the remainder of the document. There are two primary objectives of this plan: 1) adequately review and identify fuel-related needs required for license application to support development of a high-level schedule and budget for those activities; and 2) provide enough detail on the planned activities so that independent reviews can be performed to verify the adequacy of the plans to address technical risks and regulatory needs. The scope of this effort is limited to individual fuel pins since other disciplines (Mechanical Design) are responsible for fuel bundle/assembly qualification activities, and a separate Fuel Assembly Qualification Plan has previously been issued [1]. Although the focus will be on individual fuel pins, applicable interfaces required to support fuel pin design criteria will be identified.

2 SUMMARY

A systematic assessment was made to identify the activities required to support fuel pin qualification. This assessment implements the advanced fuel qualification methodology, described in Reference [2], and was based on the previously identified Regulatory Acceptance Criteria (RAC) [3], which were adapted from the content in Section 4.2 of the Standard Review Plan [4]. As such, normal operations, anticipated operating occurrences, and design basis events are considered. In general, the ongoing activities appear adequate to address most of the qualification needs. A few key exceptions are efforts to address fretting and fatigue behavior, as well as additional testing/ analysis to address extreme transients, including coolability concerns. To be of most value, many of these activities require prototypic fuel bundle geometries and targeted plant operating conditions, so it likely makes sense to postpone initiation of the programs until updated fuel assembly and host core designs have been finalized; however, notional test plans should be created in the interim to enable rapid execution of the

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include fission gas release, HT9 mechanical behavior as a function of environmental conditions, Fuel Cladding Chemical Interaction (FCCI), and fuel thermal conductivity as a function of irradiation/porosity. In addition to these fuel-specific phenomena, several design/operating conditions were found to have high importance (e.g., cladding temperature, cladding displacements per atom

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3 BACKGROUND

The Traveling Wave Reactor® (TWR) commercialization strategy has had to undergo a series of adjustments due to business needs and technical and government policy challenges. Although the long-term goal is to utilize a long-lived fuel form that can support breed-and-burn operations, most

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4 ASSUMPTIONS

The primary assumptions used in developing this plan are summarized below with supporting justification.

Assumption Number	Description
4.1	TS
4.2	
4.3	
4.4	Revisions are in progress for the Fuel Design Criteria that were included in the Core Design Basis [5], but the assumption is that the final design criteria will remain largely consistent with those previously established along with recently identified deficiencies.

5 OPEN ITEMS

N/A

6 DISCUSSION

A Regulatory Compliance Plan (RCP) has been developed [3] that identifies and adapts the regulatory requirements that are described in Section 4.2 of the Standard Review Plan (NUREG-0800), which is devoted to the fuel system design. This adaptation did not only update the terminology more suited for metallic fuel in sodium fast reactors but included specific phenomena of concern for this fuel system/ reactor based on extensive review of the available data and historic operating experience. The referenced RCP [3] also establishes RAC to ensure compliance with the identified regulatory requirements. Fuel pin-specific design criteria and associated limits and bases were provided in the Core Design Basis [5] to ensure compliance of core/fuel designs with the established RAC. A key fuel testing need is to demonstrate the suitability of the established fuel design criteria and limits to prevent damage and/or failure, as well as maintain coolability of the core under all licensing basis events (LBEs). Extensive review of public and non-public data has been performed when establishing these fuel design criteria and limits. References to some of the compilations of data used to establish these criteria and limits are included in Section 9, with additional proposed activities to address any gaps summarized in Section 9. Beyond establishing the proper fuel pin design criteria, demonstrating compliance of the Type 1 fuel pins with these design criteria for the applicable operating domains is another important task to support licensing. Due to the inherently complex nature of nuclear fuels, multiple physical phenomena must be adequately captured/modeled to provide reliable predictions of fuel pin behavior. Test data are required over applicable ranges for high importance phenomena to validate sufficient understanding of these phenomena and overall reliability of the associated fuel pin models.

This assessment is organized to be roughly consistent with the Regulatory Compliance Plan [3], capturing applicable information and planned activities to address the key areas of review for nuclear fuel system designs (see Figure 6-1 for a flow chart). Specifically, 1) Fuel Design Criteria/Bases, 2) Fuel System Description, 3) Design Evaluation, 4) Testing and Inspection of New Fuel, and 5) Post Irradiation Surveillance Plans will be addressed. The expectation is that each of these areas will be covered in much more detail in subsequent Plans, so only the pertinent aspects to support the identification/justification of required activities and development of high-level planning will be addressed here. The primary emphasis will be on the Fuel Design Criteria/Bases and Design Evaluation aspects of the Regulatory Compliance Plan since they are the most dependent on testing support prior to the startup of a demonstration reactor. The more detailed test plans developed in subsequent efforts should evaluate the applicable operating range of the NATRIUM reactor, available applicable data, additional data needed to cover the most adverse conditions anticipated, and the number of data points required to reduce associated uncertainties to acceptable levels.

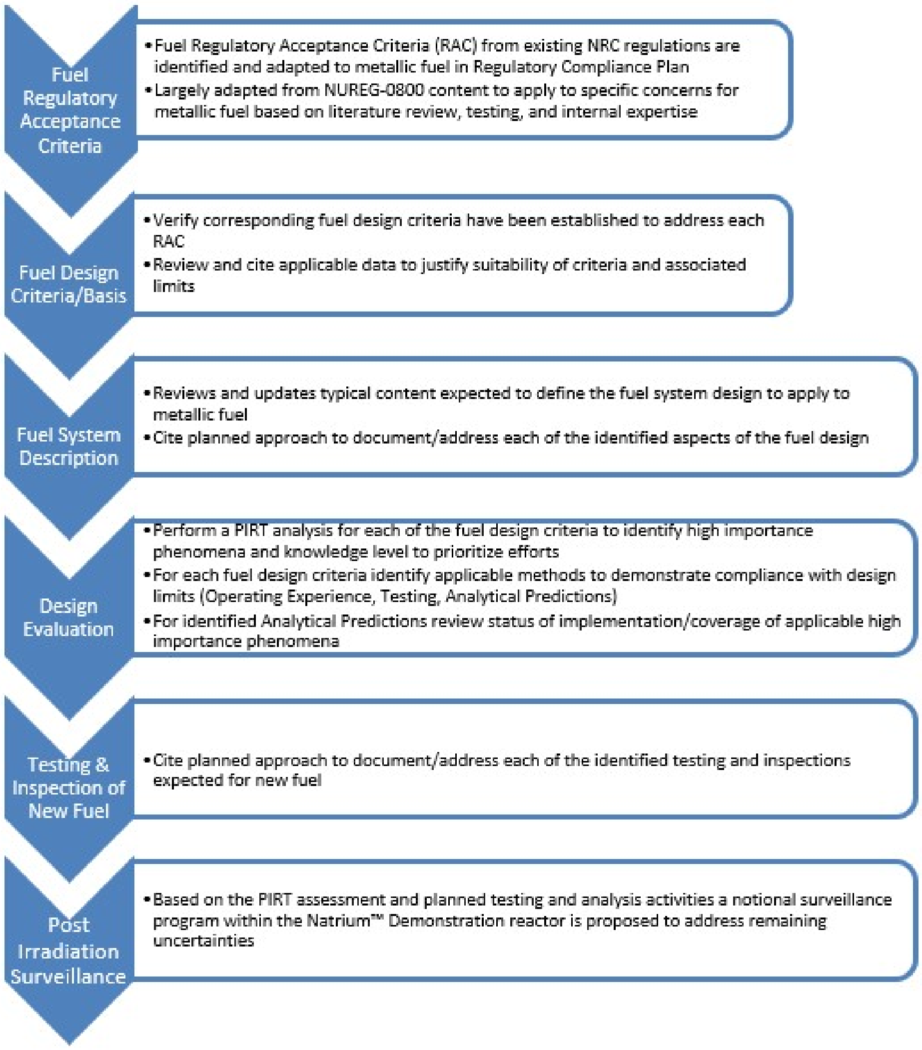

Figure 6-1: Overall Fuel Qualification Assessment Logic Flow

7 FUEL DESIGN CRITERIA

Fuel design bases/criteria must be set to achieve four key objectives: 1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), 2) the number of fuel pin failures is not underestimated for postulated accidents, 3) coolability is always maintained, and 4) fuel system damage is never so severe during postulated accidents as to prevent reactivity control/standby rod insertion when it is required. As stated above, a key testing and analysis need is to demonstrate the suitability of the established fuel design criteria and associated limits. To help ensure adequate coverage of each of the established fuel design criteria, Table 7-1, Table 7-2, and Table 7-3 summarize the existing RAC and associated design basis criteria, and available applicable test and analysis results. Table 7-1 covers design basis criteria and activities to prevent fuel damage, Table 7-2 addresses criteria and activities to predict fuel failure, and Table 7-3 addresses criteria and activities to maintain fuel coolability. Additional testing activities have been identified to supplement the currently available data to further justify established design basis limits, but these will be discussed in Section 9.4, where the proposed Testing Activities are summarized.

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Table 7-1: Design Basis Criteria and Supporting Information to Prevent Fuel Damage

Specific RAC	Acceptance Criterion	Applicable Design Basis Criteria	Available Supporting Data
4.2-1.1	Stress, strain, or loading limits for all fuel system components shall be established.	Total Diametral Clad Strain	TS
4.2-1.2	The cumulative number of strain fatigue cycles on all fuel system components shall be significantly less than the design fatigue lifetime.	Maximum allowable fuel pin fatigue cycles	

Specific RAC	Acceptance Criterion	Applicable Design Basis Criteria	Available Supporting Data
4.2-1.3	Limits on fretting wear at contact points on all fuel system components shall be established.	Cladding Wastage – Fretting	TS
4.2-1.4	Limits on erosion and corrosion shall be established for all fuel system components.	Cladding Wastage – Na Corrosion	
4.2-1.5	Limits on cladding damage (wastage) due to fuel-cladding chemical interaction (FCCI) shall be established.	Cladding Wastage – FCCI	
4.2-1.6	Limits on dimensional changes, such as pin swelling, shall be established to ensure that fuel assembly dimensions remain within operational tolerances or to prevent a situation where thermal hydraulic or neutronic design limits are exceeded.	Total Diametral Cladding Strain	
4.2-1.8	Design limits on fuel pin internal pressure for normal operation and AOOs shall be established or, alternatively, pin internal pressure shall be explicitly assessed in analyses demonstrating compliance with fuel system damage criteria that may be affected by pin internal pressure.	Total Diametral Cladding Strain limit requires internal fuel pin pressure to be assessed	

Table 7-2: Design Basis Criteria and Supporting Information to Predict Fuel Failure

Specific RAC	Acceptance Criterion	Applicable Design Basis Criteria	Available Supporting Data
4.2-2.1	Fuel system design limits shall be established and used for the prediction of fuel pin failure due to overheating of the cladding.	Peak cladding temperature limit	TS
4.2-2.2	Fuel system design limits shall be established and used for the prediction of fuel pin failure due to overheating of the fuel slug.	Peak fuel temperature limit	
4.2-2.3	Fuel system design limits shall be established and used for the prediction of fuel pin failure (loss of cladding integrity) due to deformation of the cladding from mechanical loads.	Cladding strain-thermal creep	
4.2-2.5	Fuel system design limits established and used for the prediction of fuel pin failure (loss of cladding integrity) shall address the effects of cladding wastage.	Cladding Wastage – FCCI	
		Cladding Wastage – Eutectic	
		Cladding Wastage –Na Corrosion	
		Cladding Wastage – Fretting	

Table 7-3: Design Basis Criteria and Supporting Information to Ensure Fuel Coolability

Specific RAC	Acceptance Criterion	Applicable Design Basis Criteria	Available Supporting Data
4.2-3.1	Fuel system design limits shall be established to ensure that cladding stress and strain during postulated accidents do not result in significant cladding damage that might prevent adequate core cooling.	Total Diametral Cladding Strain	TS
4.2-3.2	The maximum temperature of the cladding during postulated accidents shall be less than the melting temperature of the cladding.	Peak Cladding Temperature	
4.2-3.3	Evaluations of fuel assembly temperatures to demonstrate core coolability must account for the effects on core flow distribution and the potential for flow blockage caused by ballooning (swelling) of the cladding during postulated accidents.	Total Diametral Cladding Strain	
4.2-3.4	The maximum temperature of the fuel slug during postulated accidents shall be less than the melting temperature of the fuel.	Peak fuel temperature	

The Core Design Basis and referenced documents from these tables provide more details on the specifics of the items cited in Table 7-1, Table 7-2, and Table 7-3.

8 FUEL DESIGN DESCRIPTION

Fuel system design parameters are listed in Table 8-1. A schematic of the Type 1 fuel pin is shown in Figure 8-1.

Table 8-1: Summary of Fuel Parameters Including Comparison to FFTF/MFF and EBR-II

Parameter	Type 1[1] Fuel	FFTF/MFF [6]	EBR-II		
			MkIII Driver Fuel [7]	MkIV Driver Fuel [7]	X430 [8]
Cladding Outer Diameter (mm)	TS	6.86	5.84	5.84	7.37
Cladding Thickness (mm)		0.56	0.38	0.46	0.41
Cladding Thickness/ Diameter Ratio		0.082	0.065	0.079	0.0556
Fuel Length (m)		0.91	0.343	0.343	0.343
Plenum Length (m)		1.3	0.373	0.373	0.368
Fuel Type		U-10Zr	U-10Zr	U-10Zr	U-10Zr U-Pu-10Zr
Weight Fraction Zr		0.1	0.1	0.1	0.1
Fuel Smear Density Fraction		0.75	0.75	0.75	0.75
Bond		Sodium	Sodium	Sodium	Sodium
Cladding Material		HT9	D9	HT9	HT9
Pins per Assembly		169	61	61	37

[1] Type 1 values, such as fuel and plenum length, will likely evolve as the Natrium host core design matures

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Figure 8-1: TWR-300 Type 1 Driver Fuel Pin

Fuel system descriptions and design drawings are required as part of the Safety Analysis Reports (SARs) to provide the information necessary to verify that the fuel system design bases are met. The specific details required by the Standard Review Plan [4] are summarized by Table 8-2, along with the associated documentation/media planned to provide the required fuel design information. Note that only the information applicable to individual fuel pins are included in the table. Fuel assembly items will be addressed by the Fuel Assembly qualification plan, and control rod/assembly details will be addressed in the Absorber Qualification Plan.

Table 8-2: Summary of Completed and Planned Activities to Satisfy Fuel System Design Description Requirements (RAC 4.2-5)[1]

Expected Format of Information	Required Fuel System Information with Associated Tolerances	Sample Reference or Future Activity to Address
Design Description	Type and metallurgical state of the cladding	TS
	Cladding outside diameter	
	Cladding inside diameter	
	Cladding roughness	
	Slug density	
	Slug length	
	Slug grain size[2]	
	Slug alloy composition for metallic fuel	
	Allowable slug impurities	
	Shield slug parameters	
	Sodium bond height	
	Fuel column length	
	Overall pin length	
	Fill gas type and pressure	
	End plug dimensions	
	Wire wrapping dimensions	
	Fissile enrichment and isotopics	
Design Drawings	Fuel pin schematic	
	Wire wrap location	

9 FUEL SYSTEM DESIGN EVALUATION

Fuel system design evaluations are required as part of the SARs using acceptable methods to demonstrate that the fuel design bases are met. Acceptable design evaluation methods include operating experience, testing, and analytical predictions. Design evaluations must treat uncertainties in the values of important parameters in a conservative manner. Applicants should provide an evaluation of the fuel system design for the physically feasible combinations of chemical, thermal, irradiation, mechanical, and hydraulic interactions. The evaluation of these interactions should include the effects of normal operations, AOOs, and LBEs. [4] For the NATRIUM reactor, because of the limited availability of operating fast reactors, analytical predictions will be used to evaluate the specific fuel system compliance with the design basis limits, while pointing to Operating Experience of similar historic metallic fuel pin designs and relying on testing to help bridge the gap between historic experience/ designs and NATRIUM fuel design parameters. These tests will largely focus on providing confidence in the understanding of high-importance phenomena needed to evaluate for compliance to the fuel design bases. Several of the RAC are not directly applicable to fuel pin performance or, in

[1] Additional guidance related to required description of the fuel system is provided in Regulatory Guide 1.206 – Combined License Applications for Nuclear Power Plants.
[2] Measured for information only.

other cases, a single fuel pin design limit addresses multiple RAC. To aid in the identification of which RAC is addressed by fuel pin design limits, Table 9-1, Table 9-2, and Table 9-3 summarize the correspondence of fuel pin design limits with the RAC for fuel damage, failure, and coolability, respectively.

Table 9-1: Fuel Damage Regulatory Acceptance Criteria Addressed by Pin Design Limits

RAC ID	RAC Description	Applicable Fuel Pin Design Limit
RAC 4.2-1.1	Stress, strain, or loading limits for all fuel system components shall be established.	Total Diametral Strain Limit on Cladding
RAC 4.2-1.2	The cumulative number of strain fatigue cycles on all fuel system components shall be significantly less than the design fatigue lifetime.	Design Fatigue Lifetime
RAC 4.2-1.3	Limits on fretting wear at contact points on all fuel system components shall be established.	Cladding Wastage (Fretting)[1]
RAC 4.2-1.4	Limits on erosion and corrosion shall be established for all fuel system components.	Cladding Wastage (Na Corrosion/Erosion)[1]
RAC 4.2-1.5	Limits on cladding damage (wastage) due to fuel-cladding chemical interaction (FCCI) shall be established.	Cladding Wastage (FCCI)[1]
RAC 4.2-1.6	Limits on dimensional changes, such as <u>pin swelling</u>, shall be established to ensure that fuel assembly dimensions remain within operational tolerances or to prevent a situation where thermal hydraulic or neutronic design limits are exceeded.	Total Diametral Strain Limit on Cladding
RAC 4.2-1.8	Design limits on fuel pin internal pressure for normal operation and AOOs shall be established **or, alternatively, pin internal pressure shall be explicitly assessed in analyses demonstrating compliance with fuel system damage criteria that may be affected by pin internal pressure.**	Total Diametral Strain Limit on Cladding[2]

Table 9-2: Fuel Failure Regulatory Acceptance Criteria Addressed by Pin Design Limits

RAC ID	RAC Description	Applicable Fuel Pin Design Limit
RAC 4.2-2.1	Fuel system design limits shall be established and used for the prediction of fuel pin failure due to overheating of the cladding.	Peak Cladding Temperature Limit
RAC 4.2-2.2	Fuel system design limits shall be established and used for the prediction of fuel pin failure due to overheating of the fuel slug.	Peak Fuel Temperature Limit
RAC 4.2-2.3	Fuel system design limits shall be established and used for the prediction of fuel pin failure (loss of cladding integrity) due to deformation of the cladding from mechanical loads.	Cladding Thermal Creep Limit

[1] There is a single cladding wastage limit, but contributions from fretting, Na corrosion/erosion, and FCCI must all be evaluated to verify compliance with the total wastage allowed.
[2] Calculation of internal pin pressure is required while assessing cladding strains.

RAC ID	RAC Description	Applicable Fuel Pin Design Limit
RAC 4.2-2.5	Fuel system design limits established and used for the prediction of fuel pin failure (loss of cladding integrity) shall address the effects of cladding wastage.	Cladding Wastage (FCCI/Eutectic)

Table 9-3: Fuel Coolability Regulatory Acceptance Criteria Addressed by Pin Design Limits

RAC ID	RAC Description	Specific Limit
RAC 4.2-3.1	Fuel system design limits shall be established to ensure that cladding stress and strain during postulated accidents do not result in significant cladding damage that might prevent adequate core cooling.	Total Diametral Strain Limit on Cladding
RAC 4.2-3.2	The maximum temperature of the cladding during postulated accidents shall be less than the melting temperature of the cladding.	Peak Cladding Temperature Limit
RAC 4.2-3.3	Evaluations of fuel assembly temperatures to demonstrate core coolability must account for the effects on core flow distribution and the potential for flow blockage caused by ballooning (swelling) of the cladding during postulated accidents.	Total Diametral Strain Limit on Cladding
RAC 4.2-3.4	The maximum temperature of the fuel slug during postulated accidents shall be less than the melting temperature of the fuel.	Peak Fuel Temperature
RAC 4.2-3.5	Structural deformation of fuel assembly components due to the combined loads from accident conditions and natural phenomena shall not prevent the ability to adequately cool the core during postulated accidents.	Total Diametral Strain Limit on Cladding

9.1 PIRT Assessment

To aid in the identification of high-importance phenomena, a Phenomena Identification Ranking Table (PIRT) analysis was performed evaluating the applicable phenomena for each fuel pin design limit. These assessments were performed by convening a team of experts within TerraPower with representatives from the Fuels, Materials, Safety, and Mechanical teams to assess the applicable phenomena for each fuel pin design limit and the relative importance (I) and Knowledge Level of the respective phenomena. The internal definitions used for determining the Importance rankings and knowledge levels are summarized in Table 9-4 and Table 9-5, respectively.

Table 9-4: Importance Ranking Definitions

Importance Ranking	Definition
Low (L)	Small influence on demonstrating compliance ± 1σ variation of parameter/phenomenon has minimal impact on prediction of design criterion

Importance Ranking	Definition
Medium (M)	Moderate influence on demonstrating compliance ± 1σ variation of parameter/phenomenon has moderate impact on prediction of design criterion
High (H)	Significant influence on demonstrating compliance ± 1σ variation of parameter/phenomenon has significant impact on prediction of design criterion

Table 9-5: Knowledge Level Definitions

Knowledge Level	Definition
Known (K)	Approximately 70% to 100% of complete knowledge and understanding
Partially Known (P)	30% to 70% of complete knowledge and understanding
Unknown (U)	0% to 30% of complete knowledge and understanding

In Table 9-1, only three fuel pin design limits are utilized to address the seven fuel damage RAC that are applicable to fuel pin performance. Specifically, limits are maintained for Total Diametral Strain, Design Fatigue Lifetime, and Cladding Wastage to prevent fuel damage. The results from these PIRT assessments are summarized in Table 9-6, Table 9-7, and Table 9-8. Note that Table 9-2 and Table 9-3 show that five fuel pin design limits are utilized to address the four fuel failure and five fuel coolability RAC that are applicable to fuel pin performance. Specifically, limits are maintained for Peak Cladding Temperature, Peak Fuel Temperature, Thermal Creep Peak Cladding Strain, and Cladding Wastage to prevent fuel failure, with the addition of Total Diametral Strain Limit on Cladding to these other limits to address Fuel Coolability. The results from these PIRT assessments are summarized in Table 9-9, Table 9-10, Table 9-11, Table 9-12, and Table 9-13.

Table 9-6: Total Peak Cladding Strain PIRT – to Prevent Fuel Damage (RAC 4.2-1.1, 4.2-1.6, 4.2-1.8)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Fission gas release	H	P	• Fission gas release measurements for several EBR-II fuels of comparable design TS
	Fuel mechanical properties	L	P	• • TS

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
				TS
	Solid fission product swelling component	L	P	• Small impact expected due to low fuel burnups
	Pin power	M	K	• Impacts fuel temperatures • Low uncertainty of calculated pin power levels
	Fuel Burnup	H	P	• Low uncertainty of calculated burnups at design targets, but impact of burnup on load on cladding is less certain
Clad Response	HT9 mechanical response as a function of temperature, stress, irradiation, and time, with reliable description of individual components (i.e., irradiation vs. thermal driven creep)	H	K	TS • Some disparity in historic experiments/correlations for thermal creep of HT9, but enough margin to treat conservatively
	DPA on clad	H	K	• Peak clad strains typically occur near the midplane of the fuel column since that is where peak burnup and peak flux occur • Irradiation-induced swelling and creep are strongest contributors to strain in this region before transitioning to diffusional thermal creep at higher temperature regions of the fuel pin
	Clad temperatures	H	K	• Nonlinear irradiation creep, swelling, and diffusional thermal creep sensitive to temperature. Irradiation creep for linear component is athermal • Some conservatism in predictions due to hot channel factors
	Na corrosion: clad wastage	L	P	• Regions with high irradiation creep and swelling important at lower temperatures where Na corrosion is low • Very limited Na corrosion data of HT9 (<1-yr duration). Importance may change if updated correlation predicts higher loss TS
	FCCI: clad wastage	M	P	TS • Some uncertainty about impact on mechanical properties of decarburized regions in advance of visible FCCI regions
	Fretting: cladding wastage	L	U	• Historically, fretting has not been identified as a concern for fuel pins in EBR-II or FFTF as long as the fuel bundle design did not have excessive porosity [9] [10]

Table 9-7: Fatigue Limit PIRT – to Prevent Fuel Damage (RAC 4.2-1.2)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Fission gas release	H	K	• Assumed nominal fission gas release percentage. • Drives stress state of cladding. Pin design (plenum volume) mitigates this effect. • Expected stress variations are relatively small. • Calculated stress from input cycles (load following, startup/shutdown) are known relationships.
	Fuel mechanical properties	M	P	• Thermal expansion mismatch is largest factor. • Porosity effect not well understood. Hot pressing or sintering effect due to creep reduces load.
	Solid fission product swelling component	L	P	• Small impact expected due to low burnups • Potential effect due to changes to fuel porosity
	Detailed non-cyclic pin level power irradiation history	M	K	• Sets overall stress state.
	Detailed non-cyclic coolant temperature histories	M	K	• Sets overall condition of pin (e.g., nominal creep damage). • Thermal stress loads.
	Number of strain cycles on cladding (due to changes in temperature/pressure)	H	K	• Assumed strain cycles are defined as plant transients as part of the design basis. • Able to conservatively bound. • Multiple sources of strain cycles identified, but likely dominated by reactor operations (startup, shutdown, changes in power, unanticipated scram, etc.) • Thermal striping only applicable if assembly effects lead to strain cycles on pins.
	Magnitude of strain cycles	H	P	• Largest sources are thermal stresses and pressure changes due to temperature changes. • Some uncertainty due to contributions from fuel mechanical response, fuel/cladding mechanical interaction, pin-pin, and pin-duct interactions. May be addressed by analysis. • Pin bowing may be a factor.
	Fuel Burnup	H	P	• Low uncertainty of calculated burnups at design targets, but impact of burnup on load on cladding is less certain.
Clad Response	HT9 mechanical response as a function of temperature, stress, irradiation, and time	H	P	• Limited fatigue data for HT9 available in the literature. TS
	DPA on clad (irradiated fatigue)	H	P	• Potentially high importance. • Limited irradiated fatigue data on F/M steels. • No irradiated creep-fatigue data.
	Cladding temperatures (thermal	H	P	• Assume peak pin in thermal creep regime. Most significant response is creep-fatigue.

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
	aging and creep effects on fatigue)			• General dependence of fatigue on yield strength, which is a function of temperature.
	Na corrosion cladding wastage	L	P	[TS] • Experience of high temperature HT9-clad fuel pins operating for longer durations (2 to 3 years) with limited indications of Na corrosion
	FCCI clad wastage	M	P	[TS]

Table 9-8 Cladding Wastage PIRT – to Prevent Fuel Damage (RAC 4.2-1.3, 4.2-1.4, 4.2-1.5)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Cladding temperature	H	P	• Dominant term in FCCI and Na corrosion correlations • High-temperature fuel tests showed largest amount of FCCI and Na corrosion • Due to scatter in data and limited amount of data still uncertainty on the magnitude of the dependence on temperature
	Pin power	M	U	• Carmack speculated that increased pin power promotes fission TS • Often correlated to high cladding temperature
	Fuel Burnup	M	U	• Increased fuel burnup increases fission product concentration and pressure of fuel on cladding • Current correlations do not capture any burnup dependence
	DPA on Cladding	L	U	• Potential impact due to irradiation-induced defects in cladding assisting in diffusion of species TS
	Residence Time	H	P	• Time at temperature primary factor for determining amount of FCCI and Na corrosion
Clad Response	FCCI	H	P	• FCCI models exist, but large variability in the data, and targeted TS
	Na corrosion	L	P	• Very limited Na corrosion test data of HT9 (<1-yr duration). • Fuel pin data in excess of 2 years shows minimal Na corrosion except for 2σ HCF temperature conditions • Current correlation was developed to conservatively predict bulk corrosion depth, but does not include loss of constituents
	Fretting	M	U	• Historically, fretting has not been identified as a concern for fuel pins in EBR-II or FFTF as long as the fuel bundle design did not have excessive porosity [9] [10]
	Eutectic interactions	L	P	• Depending on the peak temperatures achieved during AOOs, there could be a small amount of eutectic interaction based on some testing (i.e., high Pu containing fuels saw onset of eutectic interactions as low as 650°C, but rates were extremely slow) TS

1 *I* represents the perceived importance of the phenomena on the assessed design limit

2 *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Table 9-9: Peak Cladding Temperature PIRT — to Predict Fuel Failure and Maintain Coolability (RAC 4.2-2.1, 4.2-3.2)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Thermal Load	Detailed pin level irradiation, power, and coolant temperature history (prior to transient)	H	K	• Assume limiting pins' starting condition and prior irradiation history is well known. The specific limiting pin will be determined from candidate list that can all be analyzed. • Dependent on core system response (e.g., radial feedback). • Impacts pin and duct strain prior to transient, impacting coolant channels during transient.
	Detailed transient power and coolant temperature histories	H	P	• Assume limiting pins starting condition (e.g., cladding strain) and prior irradiation history is well-known. • Known relationship of power to thermal load and calculated powers by neutronics. • Can use best estimate temperatures; however, cannot underestimate total number of failures. • Hot channel factors reduce the knowledge level, but instrumented tests could reduce uncertainties. • Hot channel factors' largest contributors are flow distribution and power relative factors (axial and radial peaking).
	Enthalpy of Phase Transformation/ Fuel Heat Capacity	L	P	• Assume lower impact than peak fuel temperature due to power-time response of ULOF compared to UTOP. • Some U-Zr data, but no irradiated data. • Recommend use of weighted atomic fraction of constituents for fission product species.
Thermal Response	HT9 Thermal Conductivity	M	P	• Conductivity is relatively high and thin wall. TS • Impact of irradiation/swelling on thermal conductivity is expected to be low, with limited swelling at high temperature regions of fuel pins. • Bounding assumptions likely sufficient.
	Na Corrosion impact on clad heat transfer	L	P	• Expect very low corrosion rate/magnitude. • Expect loss of constituents (Cr, C) would increase conductivity.
	FCCI intermetallic impacts	L	P	• Lower thermal conductivity than clad expected, but not significantly worse. • Limited since the magnitude of FCCI allowed is restricted by wastage limits.
	Na bond gap/fission gas bubble	M	K	• Able to assess impacts analytically.

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Table 9-10: Peak Fuel Temperature PIRT — to Predict Fuel Failure and Maintain Coolability (RAC 4.2-2.2,4.2-3.4)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Thermal Load	Detailed pin level irradiation, power, and coolant temperature history (prior to transient)	H	K	• Assume limiting pins' starting condition and prior irradiation history is well known. The specific limiting pin will be determined from candidate list that can all be analyzed. • Dependent on core system response (e.g., radial feedback). • Impacts pin and duct strain prior to transient, impacting coolant channels during transient.
	Detailed transient power and coolant temperature histories	H	P	• Assume limiting pins' starting condition (e.g., cladding strain) and prior irradiation history is well known. • Known relationship of power to thermal load and calculated powers by neutronics. • Can use best estimate temperatures; however, cannot underestimate total number of failures. • Hot channel factors reduce the knowledge level, but instrumented tests could reduce uncertainties. • Hot channel largest contributors are flow distribution and power relative factors (axial and radial peaking).
Thermal Response	Fuel Thermal Conductivity as a function of composition, burnup, porosity	H	P	• Some experimental values (Bauer) on as-irradiated fuels with Na bond [11]. TS • Burnup and porosity impacts are largest uncertainties.
	Enthalpy of Phase Transformation / Fuel Heat Capacity	M	P	• U-Zr data • No irradiated data. • Recommended property dependence is weighted atomic fraction of constituents
	Fuel Constituent Redistribution/ Segregation	M	P	• No significant effect expected during transient • Assume no Pu initially, so less applicable until high burnups • Pu not expected to redistribute significantly. TS
	Solid-fission product swelling rate	L	P	• Does not include importance on assumed condition at start of event. Importance only assigned for transient duration. • No accumulation of solid fission product swelling during transient. • Some uncertainty of behavior of solid fission phases at high temperature
	Fuel axial growth and as a function of irradiation history	M	U	• Very limited transient data with HT9. TS

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
	(Burnup and Temperature)			
	Fuel Radial Swelling vs. Temperature	M	P	• Ranking is during transient. Separate from starting condition of fuel, which is high importance.

Table 9-11: Peak Cladding Thermal Creep Strain PIRT — to Predict Fuel Failure (RAC 4.2-2.3, 4.2-2.5)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Fission gas release	H	P	• Fission gas release measurements for several EBR-II fuels of comparable design TS
	Fuel mechanical properties	L	P	• Large uncertainties in mechanical properties for irradiated fuels, but fuel performance modeling indicates limited impacts to prediction of cladding strains: TS
	Solid fission product swelling component	L	P	• Small impact expected due to low burnups • Highest burnup around pin mid-plane, while thermal creep is most active at high temperature regions near top of fuel pins
	Pin power	M	K	• Impacts fuel temperatures • Low uncertainty of calculated pin power levels.
	Fuel Burnup	H	K	• Low uncertainty of calculated burnups at design targets • Combined with fission gas release, provide main load on cladding; attribute main uncertainty in influence of burnup on cladding strain to variability in fission gas release
Clad Response	HT9 mechanical response as a function of temperature, stress, irradiation, and time, with reliable description of thermal creep vs. other creep components	H	K	• TS
	DPA on clad	L	P	• Expect minimal impact of irradiation on thermal creep behavior since thermal creep occurs at high temperature regions of fuel pins where irradiation damage is readily annealed out. • Cladding burst testing supports this premise with minimal differences seen in behavior between irradiated and unirradiated cladding tubes. [12]

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
	Cladding temperatures	H	K	• Strong temperature dependence of thermal creep • Low uncertainty of calculation tools beyond hot channel factors
	Na corrosion clad wastage	M	P	• Thermal creep at higher temperatures where Na corrosion is expected to be higher • Very limited Na corrosion data of HT9 (<1-yr duration) • Fuel pin data in excess of 2 years shows minimal Na corrosion except for 2σ temperature tests • Current correlation was developed to conservatively predict bulk corrosion depth but does not include loss of constituents
	FCCI clad wastage	H	P	• Thermal creep dominates at higher temperature region of pins, where greater FCCI is expected • Effectively thins cladding wall increasing cladding stress • FCCI models exist, but large variability in the data, and TS

Table 9-12 Cladding Wastage PIRT — to Predict Fuel Failure (RAC 4.2-2.5)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Temperature	H	P	• Dominant term in FCCI and Na corrosion correlations • High-temperature fuel tests showed largest amount of FCCI and Na corrosion • Due to scatter in data and limited amount of data, still uncertainty on the magnitude of the dependence on temperature
	Pin power	M	U	• Carmack speculated that increased pin power promotes fission product migration to cladding [6] • Often correlated to high cladding temperature
	Fuel Burnup	M	U	• Increased fuel burnup increases fission product concentration and pressure of fuel on cladding • Current correlations do not capture any burnup dependence
	DPA on Cladding	L	U	• Potential impact due to defects in cladding assisting in diffusion of species TS
	Residence Time	H	P	• Time at temperature primary factor for determining amount of FCCI and Na corrosion
Clad Response	FCCI	H	P	• FCCI models exist, but large variability in the data, and targeted TS
	Na corrosion clad wastage	L	P	• Very limited Na corrosion test data of HT9 (<1-yr duration)

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
				• Fuel pin data in excess of 2 years shows minimal Na corrosion except for 2σ temperature tests • Current correlation was developed to conservatively predict bulk corrosion depth, but does not include loss of constituents
	Eutectic Interactions	M	P	• Several historic studies on eutectic interactions for metallic fuels; TS
	Fretting	M	U	• Historically, fretting has not been identified as a concern for fuel pins in EBR-II or FFTF as long as the fuel bundle design did not have excessive porosity [9] [10]

Table 9-13: Total Peak Cladding Strain PIRT — to Maintain Coolability (RAC 4.2-3.1, 4.2-3.3, 4.2-3.5)

Category	Phenomena	I[1]	K.L.[2]	Additional Comments
Load on cladding	Fission gas release (FGR) prior to start of event	H	P	• Assume start of event FGR is high for fuel design; this reduces FCMI during transient. • Some uncertainty in retained fission gas at lower elevations (peak dpa). • Preliminary calculations temperature increase leads to pressure increase but not significant. • Largest contributor to load.
	Fuel mechanical properties	M	U	• Transient fuel performance Calc. Literature cites thermal expansion of fuel/cladding similar (UZr/316), but not as much for U/HT9 • Uncertainty to net effects on peak strain lower elevations near core mid-plane: lower temperatures and higher power effects on thermal expansion mismatch, and higher fuel strength. • Uncertainty in load from fuel due to competing effects. Porosity of fuel ”softness” vs higher thermal gradient and concomitant expansion vs cladding. • Note difference UTOP vs ULOF of larger delta T fuel/clad for UTOP.

[1] *I* represents the perceived importance of the phenomena on the assessed design limit
[2] *K.L.* represents the Knowledge Level for the perceived response of identified phenomena on the design limit

	Solid fission product swelling component	M	P	• Assumed condition at start of event is medium importance. • No accumulation of solid fission product swelling during transient. • Some uncertainty of behavior of fission product phases at high temperature. Some TS
	Pin power	M	P	• Relatively low normal operating powers result in lower transient overpowers (~+20%). • Very important to response of fuel mechanical properties. • Note difference UTOP vs ULOF of larger delta T fuel/clad for UTOP. • Uncertainty of core radial feedback impact on fuel pin power.
	Fuel Burnup	H	K	• Low uncertainty of calculated burnups at design targets. • Combined with fission gas release, provide main load on cladding; attribute main uncertainty in influence of burnup on cladding strain to variability in fission gas release.
Clad Response	HT9 mechanical response as a function of temperature, stress, irradiation, and time, with reliable description of thermal creep vs. other creep components	H	P	• HT9 data shows minimal irradiation effect on burst stress. TS • Phase transition temperature 754˚C. • Very little data at T>675˚C TS
	DPA on clad	H	P/K	• Assume significant DPA mechanical effect saturates at lower DPA. Very limited data at high DPA. • Important to assess DPA effects on state of cladding at start of transient but is expected to have negligible effects during transient. TS
	Cladding temperatures	H	P	• Assume peak temperature at 833˚C and >300 sec at 725˚C.

				• Assumption: Clad temperatures prior to transient has lower importance than during the transient. • Very little data >675˚C. • Impacts of clad temperature evolution due to coolant channel flow changes (e.g., transition to natural circulation). • Uncertainty in calculated system response – design dependent on components outside fuel system (e.g., EM pump with flow-inertia features)
	Na corrosion clad wastage	M	P	• TS • Very limited Na corrosion data of HT9 (<1-yr duration). Importance may change if updated correlation predicts higher loss. • Corrosion during transient is expected negligible and predictable using an Arrhenius dependence.
	FCCI clad wastage	H	P	• Regions with high swelling are lower temperature, so reduced FCCI expected. • FCCI models exist, but large variability in • TS • Assume known number of defected pins due to normal irradiation history up to beginning event. Uncertainty on risk of failing during event after irradiated effects.

9.2 High Importance Phenomena

The PIRT assessment summarized in Section 9.1 was performed to help identify the high importance phenomena that must be accounted for when evaluating the performance of Type 1 Fuel. The high-importance phenomena are summarized in Table 9-14, along with the corresponding design limits and associated RAC. When evaluating and consolidating the high-importance phenomena, it became clear that many of the identified phenomena are more aptly described as operating parameters/conditions (e.g., Cladding Temperature, Fuel Burnup) versus complex physical phenomena (e.g., Fission Gas Release, or FCCI), so these different categories were also noted in Table 9-14. In an effort to help prioritize activities, an “Overall Knowledge Level” ranking is also included in Table 9-14, which is the average Knowledge Level determined for each identified high-importance phenomena/parameter.

Table 9-14: Summary of Identified High-Importance Phenomena and Associated Design Limits and RAC

Category	High-Importance Phenomena/Parameters	Overall Knowledge Level	Applicable Design Limit	Applicable RAC
Fuel Pin Phenomena	Fission gas release	P	Total Peak Cladding Strain, Peak Cladding Thermal Creep	4.2-1.1, 4.2-1.6, 4.2-1.8, 4.2-2.3, 4.2-2.5, 4.2-3.1, 4.2-3.3, 4.2-3.5
	HT9 mechanical response as a function of temperature, stress, irradiation, and time	K	Total Peak Cladding Strain, Fatigue Limit, Peak Cladding Thermal Creep Strain	4.2-1.1, 4.2-1.6, 4.2-1.8, 4.2-2.3, 4.2-2.5, 4.2-3.1, 4.2-3.3, 4.2-3.4, 4.2-3.5
	FCCI	P	Cladding Wastage, Peak Cladding Thermal Creep Strain	4.2-1.3, 4.2-1.4, 4.2-1.5, 4.2-2.3, 4.2-2.5
	Fuel Thermal Conductivity	P	Peak Fuel Temperature	4.2-2.2,4.2-3.4
Fuel Pin Parameters/ Operating Conditions	Fuel Burnup	P	Total Peak Cladding Strain, Fatigue Limit, Peak Cladding Thermal Creep	4.2-1.1, 4.2-1.6, 4.2-1.8, 4.2-2.3, 4.2-2.5, 4.2-3.1, 4.2-3.3, 4.2-3.5
	DPA on clad	P	Total Peak Cladding Strain, Fatigue Limit	4.2-1.1, 4.2-1.6, 4.2-1.8
	Cladding temperatures	P	Total Peak Cladding Strain, Fatigue Limit, Cladding Wastage, Peak Cladding Thermal Creep Strain	4.2-1.1, 4.2-1.6, 4.2-1.8, 4.2-1.3, 4.2-1.4, 4.2-1.5, 4.2-2.3, 4.2-2.5, 4.2-3.1, 4.2-3.3, 4.2-3.4, 4.2-3.5
	Number of strain cycles on cladding	K	Fatigue Limit	4.2-1.2
	Magnitude of strain cycles	P	Fatigue Limit	4.2-1.2
	Residence Time	P	Cladding Wastage	4.2-1.3, 4.2-1.4, 4.2-1.5, 4.2-2.5
	Detailed pin level irradiation histories including power and cladding temperature	K	Peak Cladding Temperature, Peak Fuel Temperature	4.2-2.1, 4.2-3.2, 4.2-2.2,4.2-3.4
	Detailed coolant transient temperature and pin power histories	P	Peak Cladding Temperature, Peak Fuel Temperature	4.2-2.1, 4.2-3.2, 4.2-2.2,4.2-3.4

9.3 Operating Experience

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Table 9-15: Comparison of Fuel System Operational Parameters

Parameter	Type 1 Fuel (Inner Driver Assembly)	Type 1 Fuel (Outer Driver Assembly)	FFTF (MFF-2)[1]	EBR-II	
				X447[1]	X425[1]
Enrichment (%)		TS	32.41	49.1	47.87
Peak Burnup (%FIMA)			14.3	10.0	19.3
Peak DPA			80	37	82
Residence (EFPD)			853	619	1040
Peak Linear Heat Rate (kW/m)		TS	54.1	36.1	48.2
Peak Inner Cladding Temperature (°C)			618	668	590

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[1] Taken from Reference [48].

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Figure 9-1: Linear Heat Rate Distribution (left) and Burnup Distribution (right) in the Inner Driver Fuel Region

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Figure 9-2: Cladding Surface Temperature Distribution at Beginning of Life

Efforts have been performed to review, consolidate, and analyze all of the applicable fuel tests from EBR-II and FFTF to support their use for fuel performance model validation. A detailed plan

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Table 9-16: Relevant Historic Fuel Assemblies to Support Validation Activities [13]

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9.4 Testing

Table 9-17: Summary of Future Testing Activities to Validate Fuel Damage Limits

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
4.2-1.1	Total Diametral Clad Strain		TS	• Temperature • Stress • Fast fluence • Time at temperature	[14] [15] [16] [17] [18] [19]
					[20] [21]
				• Sub-channel geometry • Wire-wrap diameter and pitch • Pin power distribution	[22] [23]
				• Open space within the pin bundle	[24] [25]

[1] Note that some of these identified tests may be eliminated pending additional analysis or retrieval of additional historic data.
Legend: SEM = Scanning Electron Microscopy

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
4.2-1.2	Maximum allowable fuel pin fatigue cycles		TS	• Material • Pin stress states • Pin geometry • Number of cycles • Magnitude of cycles	
4.2-1.3	Cladding Wastage – Fretting			• Bundle geometry • Pin stiffness • Coolant velocity • Duration of test	
				• Force • Number of oscillations • Wire tension • Presence of Na • Temperature	[26] [27]
4.2-1.4	Cladding Wastage – Na Corrosion			• Temperature • Na oxygen content • Na velocity	

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
4.2-1.5	Cladding Wastage – FCCI		TS	• Temperature • Time at temperature • Burnup	[28] [29]
					[30]
					[31]
4.2-1.6	Total Diametral Cladding Strain				
4.2-1.8	Total clad strain and thermal creep strain limits require internal fuel pin pressure to be assessed			• Axial position • Fuel pin irradiation conditions	
				• Fuel Temperature • Fuel smeared density	[30]
					[31]

Table 9-18: Summary of Future Testing Activities to Predict Fuel Failure

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
4.2-2.1	Peak cladding temperature limit		TS	• Fuel composition (Zr and Pu content) • Fuel burnup • Size of existing interaction zone • Time at temperature	
				• Fuel burnup • Fuel pin irradiation history • Temperature • Time at temperature • Fuel composition	
				• Fuel geometry (porous/solid) • Transient conditions	[32]
				• Fuel pin irradiation history (burnup, PICT, etc.) • Transient conditions (power-to-flow ratio, coolant temperature, duration)	

[1] Note that some of these identified tests may be eliminated pending additional analysis or retrieval of additional historic data.

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
4.2-2.2	Peak fuel temperature limit		TS	• Fuel composition (Zr and Pu content) • Fuel burnup • Phases present in burnup alloy piece	
				• Fuel composition (Zr and Pu content) • Fuel burnup • Amount of FCCI • Phases present in fuel piece	
				• Fuel geometry (porous/solid) • Transient conditions	[32]
				• Fuel pin irradiation history (burnup, PICT, etc.) • Transient conditions (power-to-flow ratio, coolant temperature, duration)	
4.2-2.3	Cladding strain-thermal creep			• Stress/pressure • Temperature • Time at temperature • HT9 heat used	

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern	References
			TS	• Fuel burnup • Fuel pin irradiation history • Temperature • Time at temperature • Fuel composition	
				• Fuel pin irradiation history (burnup, PICT, etc.) • Transient conditions (power-to-flow ratio, coolant temperature, duration)	
4.2-2.5	Cladding Wastage – FCCI				
	Cladding Wastage – Eutectic				
	Cladding Wastage –Na Corrosion				
	Cladding Wastage – Fretting				
	Cladding Wastage – FCCI				

Table 9-19: Summary of Future Testing Activities to Ensure Fuel Coolability is Maintained

RAC	Design Basis Criteria	Identified Activity[1]	Main Objectives	Primary Factors of Concern
4.2-3.1	Total Diametral Cladding Strain-Coolability		TS	• Pin bundle geometries (coolant channel gaps for distorted geometries) • Coolant velocity • Amount of decay heat to remove
4.2-3.2	Peak Cladding Temperature			
4.2-3.3	Total Diametral Cladding Strain-Coolability			
4.2-3.4	Peak fuel temperature			

[1] Note that some of these identified tests may be eliminated pending additional analysis or retrieval of additional historic data.

Table 9-20: Summary of Tests to Address High-Importance Phenomena

High Importance Phenomena	Applicable Design Limit	Overview of Testing[1]
Fission gas release	Total Peak Cladding Strain, Peak Cladding Thermal Creep	TS
HT9 mechanical response as a function of temperature, stress, irradiation, and time	Total Peak Cladding Strain, Fatigue Limit, Peak Cladding Thermal Creep Strain	
FCCI	Cladding Wastage, Peak Cladding Thermal Creep Strain	
Fuel Thermal Conductivity	Peak Fuel Temperature	

9.5 Analytical Predictions

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[1] Note that some of these identified tests may be eliminated pending additional analysis or retrieval of additional historic data.

Table 9-21, Table 9-22, and Table 9-23. In general, the capability exists within ALCHEMY to perform assessments for all of the applicable fuel pin design limits, including high-importance

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Table 9-21: Status of Fuel Performance Prediction Capabilities to Assess Fuel Damage

Applicable Design Limit	Applicable RAC	High-Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
Total Peak Cladding Strain	4.2-1.1, 4.2-1.6, 4.2-1.8	Fission gas release	TS	
		HT9 mechanical response as a function of temperature, stress, irradiation, and time		
		FCCI		
		Fuel Burnup		

Applicable Design Limit	Applicable RAC	High-Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
		DPA on cladding		TS
		Cladding temperatures		
Cladding Fatigue Lifetime	4.2-1.2	HT9 mechanical response as a function of temperature, stress, irradiation, and time		
		Fuel Burnup		
		DPA on cladding		
		Cladding temperatures		
		Number of strain cycles on cladding		

Applicable Design Limit	Applicable RAC	High-Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
		Magnitude of strain cycles		TS
Cladding Wastage	4.2-1.3, 4.2-1.4, 4.2-1.5	FCCI		
		Cladding temperatures		
		Residence Time		

Table 9-22: Status of Fuel Performance Prediction Capabilities to Assess Fuel Failure

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
Peak Cladding Temperature	4.2-2.1	Detailed pin level irradiation histories including power and cladding temperature		TS
		Detailed coolant transient temperature and pin power histories		

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
Peak Fuel Temperature	4.2-2.2	Fuel Thermal Conductivity		TS
		Detailed pin level irradiation histories including power and cladding temperature		
		Detailed coolant transient temperature and pin power histories		
Peak Cladding Thermal Creep Strain	4.2-2.3	Fission gas release		
		HT9 mechanical response as a function of temperature, stress, irradi-ation, and time		
		FCCI		
		Fuel Burnup		

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
		Cladding temperatures		TS
Cladding Wastage	4.2-2.5	FCCI		
		Cladding temperatures		
		Residence Time		

Table 9-23: Status of Fuel Performance Prediction Capabilities to Assess Fuel Coolability

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
Total Peak Cladding Strain	4.2-3.1, 4.2-3.3, 4.2-3.5	Fission gas release		TS

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
		HT9 mechanical response as a function of temperature, stress, irradi-ation, and time		TS
		Fuel Burnup		
		Cladding temperatures		
Peak Cladding Temperature	4.2-3.2	Detailed pin level irradiation histories including power and cladding temperature		
		Detailed coolant transient temperature and pin power histories		
Peak Fuel Temperature	4.2-3.4	Fuel Thermal Conductivity		
		Detailed pin level irradiation histories including power		

Applicable Design Limit	Applicable RAC	High Importance Phenomena/ Parameters	Applicable Tool	Status/Comments
		and cladding temperature		TS
		Detailed coolant transient temperature and pin power histories		

Table 9-24: Status of Fuel Performance Prediction Capabilities to Assess Phenomena Related to Fuel Temperatures

Phenomena/ Parameters	Applicable Tool	Status/Comments
		TS

Phenomena/ Parameters	Applicable Tool	Status/Comments
		TS

10 TESTING AND INSPECTION OF NEW FUEL

RAC 4.2-7 states that “Testing and inspection shall be performed for new fuel to ensure that the fuel is fabricated in accordance with the design basis and that it reaches the plant site and is loaded in the core without damage.” The bulk of the required activities will be specified in the fuel and cladding specifications, but to help ensure all testing and inspections are adequately captured, Table 10-1 summarizes the identified needs from RAC 4.2-7 along with the anticipated approach to address them.

Table 10-1: Summary of New Fuel Testing and Inspection Needs and Planned Approach

Requirement	Planned Approach to Address	Comments/Specifics
Cladding integrity		TS
Fuel system dimensions		
Fuel enrichment and chemical composition		
Program for onsite inspection of new fuel assemblies after they have been delivered to the plant		

11 ONLINE FUEL SYSTEM MONITORING FOR FUEL PIN FAILURE

RAC 4.2-8 states that "Online methods or surveillance programs shall be developed to detect fuel pin failure or reactivity control/ absorber pin failure." Design and development of the online fuel monitoring system is addressed by the Reactor Plant area and will not be addressed here. As the design matures, its capabilities will be considered when developing the fuel surveillance program.

12 POST IRRADIATION SURVEILLANCE

RAC 4.2-9 states that "A post-irradiation examination and surveillance program to detect anomalies or confirm expected performance shall be established for each fuel and reactivity control assembly

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Table 12-1: Fuel Performance Uncertainties and Potential Impacts to Reactor Operations

Major Open Items of Concern at Startup	Potential Mitigation
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13 CONCLUSIONS

A systematic assessment was made to identify the activities required to support fuel pin qualification. In general, the ongoing activities appear adequate to address most of the qualification needs. A few key exceptions are efforts to address fretting and fatigue behavior, as well as additional testing/ analysis to address extreme transients, including coolability concerns. To be of most value, many of these activities require prototypic fuel bundle geometries and targeted plant operating conditions, so it likely makes sense to postpone initiation of the programs until updated fuel assembly and host core designs have been finalized; however, notional test plans should be created in the interim to enable

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fuel phenomena identified for all of the applicable fuel design limits include fission gas release, HT9 mechanical behavior as a function of environmental conditions, FCCI, and fuel thermal conductivity as a function of irradiation/porosity.

[TS]

14 REFERENCES

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END OF DOCUMENT

Enclosure 3

TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))

I, Peter C. Gaillard, hereby state:

1. I am Director, Regulatory Affairs, and I have been authorized by TerraPower, LLC (TerraPower) to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the TerraPower reactor and its associated fuel, structures, systems, and components, and to apply for its withholding from public disclosure on behalf of TerraPower.
2. The information sought to be withheld, in its entirety, is contained in TerraPower's Enclosure 1, which accompanies this Affidavit.
3. I am making this request for withholding and executing this Affidavit as required by 10 CFR § 2.390(b)(1).
4. I have personal knowledge of the criteria and procedures utilized by TerraPower in designating information as a trade secret, privileged, or as confidential commercial or financial information that would be protected from public disclosure under 10 CFR § 2.390(a)(4).
5. TerraPower's information contained in Enclosure 1 accompanying this Affidavit contains non-public details of the TerraPower regulatory and developmental strategies intended to support NRC staff review.
6. Pursuant to 10 CFR § 2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information in Enclosure 1 should be withheld:
    a. The information has been held in confidence by TerraPower.
    b. The information is of a type customarily held in confidence by TerraPower and not customarily disclosed to the public. TerraPower has a rational basis for determining the types of information that it customarily holds in confidence and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application and substance of that system constitute TerraPower policy and provide the rational basis required.
    c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR § 2.390, it is received in confidence by the Commission.
    d. This information is not available in public sources.

e. TerraPower asserts that public disclosure of this non-public information is likely to cause substantial harm to the competitive position of TerraPower, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on February 25, 2021

Peter C. Gaillard

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Peter C. Gaillard
Director, Regulatory Affairs
TerraPower, LLC