NUCLEAR ENERGY INSTITUTE

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October 10, 2000

Mr. Gary M. Holahan
Director
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation
Mail Stop O10-A1
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: Draft Topical Report on Licensing Criteria for Fuel Burnup Extensions Beyond 62 GWd/tU

PROJECT NUMBER: 689

Dear Mr. Holahan:

The industry and your staff have had interactions during the past year regarding the extension of fuel burnup limits beyond 62 GWd/tU. Discussions on the licensing criteria appropriate to high burnup fuel have led the industry to develop an evaluation process to assist in establishing licensing criteria for fuel rods at these higher burnup levels. The objective of the evaluation process is to assess the need for modifications or additions to existing licensing criteria, or to demonstrate the applicability of the present limits at burnup levels beyond 62 GWd/tU.

Enclosed is a draft of the report, *"Licensing Criteria for Fuel Burnup Extensions Beyond 62 GWd/tU-Industry Guide Rev. 5,"* prepared by Working Group 2 of the EPRI Robust Fuel Program. An early draft of the enclosed document was discussed with NRC staff during a March 30, 2000 public meeting. We request NRC review of the enclosed draft in preparation for a meeting with industry representatives on December 6, 2000.

NRC comments received during and subsequent to this meeting have been addressed in the preparation of the enclosed draft. Comments contained in a letter from Jared Wermiel, NRC, to Terrance Rieck, Commonwealth Edison, dated May 3, 2000, are specifically addressed in Enclosure 1.

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Tie to NRC Performance Goals

This topical report is of importance to over 75 domestic operating reactors. The NRC staff review is considered to be relevant to the NRC performance goals as identified below.

(1) Maintain Safety

Safety is maintained through the establishment of a clear, technically based tie between licensing criteria and the applicable regulatory requirements to be met by fuel licensed for operation beyond 62 GWd/tU.

(2) Maintain Public Confidence

Public confidence will be maintained through the development, review and subsequent use of a more scrutable process that clearly identifies the manner and basis for demonstration that reactor fuel can be operated at higher fuel burnup levels.

(3) Improve Efficiency and Effectiveness of Regulation

Efficiency and effectiveness of regulation will be improved. The establishment of a single comprehensive set of licensing criteria that can be used by licensees, fuel vendors and NRC will serve to promote increased review efficiency and will enable a reduction in overall costs to industry.

(4) Reduce Unnecessary Burden

The development and approval of the licensing criteria to be applied to high burnup fuel will reduce unnecessary regulatory burden in two ways. First, the upfront identification of the criteria against which new fuel applications will be reviewed will enable licensees and fuel vendors to more easily factor licensing and regulatory interactions into planning efforts and avoid costly surprises during the review process. Secondly, we anticipate that the use of technically based licensing criteria will help to streamline the review and approval process.

Basis for Request for Waiver of Part 170 Fees

We believe any NRC staff review of the topical report should be exempt from the fee recovery provision contained in 10 CFR Part 170. This submittal provides information that might be helpful to NRC staff when evaluating licensee and fuel vendor submittals intended to achieve approval of extended fuel burnup limits. Consequently, such reviews are exempt under §170.21, Schedule of Facility Fees. Footnote 4 to the Special Projects provision of §170.21 states, "Fees will not be assessed for requests/reports submitted to the NRC...[a]s means of exchanging information between industry organizations and the NRC for the purpose of supporting generic regulatory improvements or efforts."

NRC staff feedback and review comments on this draft report are needed to support completion of the report. Any comments that NRC can provide prior to the December meeting will help make the discussion more meaningful.

Please contact John Butler (jcb@nei.org, 202-739-8108) should you have any questions on this letter. Questions regarding the content in the enclosure should be directed to Rosa Yang (ryang@epri.com, 650-855-2481).

Sincerely,

David J. Modeen

JCB/maa
Enclosures

c: Mr. Peter Wen, U.S. Nuclear Regulatory Commission
Mr. Jared Wermiel, U.S. Nuclear Regulatory Commission (by e-mail)
Ms. Margaret Chatterton, U.S. Nuclear Regulatory Commission (by e-mail)
Dr. Rosa Yang, EPRI (by e-mail)
Dr. Terrance Rieck, Commonwealth Edison (by e-mail)

Response to the NRC Comments on
"Licensing Criteria for Fuel Burnup Extensions Beyond 62 GWd/tU-Industry Guide Rev. 4,"
Provided in a May 3, 2000 Letter from Jared Wermiel to Terry Rieck

Response to General Comments

1.How will new limits or analysis methods that are not currently used but which may be needed for burnup extension be identified? For example: a limit on corrosion and spallation

The purpose of the review is to identify the burnup considerations and data needs associated with the licensing limits used for fuel and assembly design analysis above 62 GWd/tU. The review process relies on the current design approach specified in licensee fuel design topical reports and the guidelines outlined in the SRP Section 4.2 to indicate the important fuel response behaviors that require design limits. To ensure that the review encompasses a broad enough spectrum to capture all the important burnup effects which may influence fuel rod or assembly behavior, the review also includes the fuel-related General Design Criteria specified in 10CFR50 Appendix A to recognize the consequences that fuel limits are designed to guard against. More importantly, the review draws from the extensive technical insight available from international experimental programs such as Halden, CABRI, Robust Fuel Program and NFIR, as well as, post-irradiation examination results on high burnup fuel to identify the fuel behavior/ phenomena that are impacted by burnup. An example demonstrating how the review process will combine the burnup influence with the design limits is shown in Table 1. Through the integration of all the information the review will develop the technical bases to support the existing design limits that are burnup independent and identify areas that require burnup dependent considerations. During the review process, if any known phenomenon is not addressed by any of the existing fuel design limits, then a new fuel limit will need to be proposed to address the burnup-related phenomenon.

Table 1. Cross Reference of Phenomena and Fuel Design Limits

Comprehensive list of Fuel Behavior Impacted by Burnup	**Fuel Design Limits that address the burnup-related fuel behavior** (the numbers refer to Table 0-1 of the Industry Guide Rev.5 or Table 2 below)
Fuel Thermal Conductivity	1.1, 1.2, 1.3, 1.10 2.5, 2.6, 2.7 3.2
Cladding Oxidation	1.1, 1.2, 1.3, 1.5, 1.6, 1.7, 1.9, 1.10 2.7, 2.8, 2.9 3.1, 3.4, 3.5
Swelling	1.1, 1.2, 1.3, 1.10 2.2
Irradiation Growth	1.8, 1.9, 1.11
Etc…	Etc…

2. In areas where data are needed, data should be developed up to the requested target burnup with prototypical operating conditions including power distributions and power histories.

Within the document, references to data from fuel rods that are required to demonstrate compliance will indicate that the operating conditions should be prototypical of the application.

3. There are several types of data that will be needed including data to (1) establish the effect of burnup on a particular parameter or phenomena, (2) data to justify an existing criterion or justify revised criteria, and (3) data to show compliance with the criteria. It would be useful to include tables differentiating between data needed to justify or establish criteria and data needed to verify compliance with criteria. These tables should include the type of data needed, where and how it will be obtained, the time frame for acquisition and analysis, the amount of data, the test conditions and other pertinent details.

An important aspect of the review process is the identification of the data needed to support fuel operation beyond 62 GWd/tU. The required data for burnup extension can be separated into three categories. First, fuel and cladding material and behavioral data are needed to establish the impact of burnup on particular fuel phenomena and parameters that define fuel rod performance. This type of data includes thermal and mechanical properties such as thermal conductivity, specific heat, melting temperature, creep and ductility. Also included in this category are behavioral data including fission gas release and irradiation growth/swelling. This type of data will come from different sources including separate effects tests, special irradiation programs in test reactors such as Halden, Studsvik, etc., and material property tests. The industry review of the current licensing bases will utilize this data in the evaluation process to quantify the burnup effects on fuel rod phenomena important to licensing criteria.

The second category consists of data that the review process will use to justify an existing criterion or justify revisions to the licensing bases up to burnup levels of 75 GWd/tU. This data will be used within the review process to ensure that the existing or revised criteria establish sufficient safety margins. The sources of data include material property tests, separate effects tests, and poolside and destructive examinations. This data will come from the existing experience of fuel operation and as a result the operating conditions, defined by power level, residence time, and burnup may not be prototypical of the anticipated conditions for high burnup operation. Engineering evaluations based on the extensive industry experience will be used to apply this data as part of the review process.

The third category is the data that will be required to demonstrate compliance to the new design bases for high burnup operation. This data will be obtained from mechanical property tests and poolside and/or destructive examinations. The fuel material used to obtain the required data will come from fuel assemblies operated under prototypical power and coolant chemistry conditions. Generally, this data will be reported in licensee fuel topical reports. The type of data required in Category 3 will be identified in the review process. It will be the responsibility of the fuel licensee to collect and report the required data.

An example of the data that will be identified in the review process for Categories 2 and 3 is shown in Table 2.

Response to NRC Specific Comments

The specific comments were addressed in different sections of the enclosed Rev. 5 of the Industry Guide: in several places, it was specifically stated that the bounding power history has to be used; the regulatory requirement for excessive fuel enthalpy was rearranged and we have modified the paragraph relative to the impact of hydrides on mechanical properties.

Table 2. Data to Support Burnup Extension to 75 GWd/tU

Design Basis Limits/Criteria	Data to Justify Limit at 75 GWd/tU	Data to Demonstrate Compliance
1. Fuel System Damage		
1.1 Design Stress	Yield Strength/Ultimate Tensile Strength	Yield Strength/Ultimate Tensile Strength
1.2 Design Strain	Uniform Elongation/Total Elongation	Uniform Elongation/Total Elongation
1.3 Strain Fatigue	Use Existing Fatigue Data	Use Existing Fatigue Data
1.4 Fretting Wear	Use Existing Fretting Wear Data	Use Existing Fretting Wear Data
1.5 Oxidation	TBD	Maximum Oxide Thickness
1.6 Hydriding	TBD	Hydrogen Content
1.7 Crud	TBD	Crud Thickness
1.8 Rod Bow	Not Required	Rod-to-Rod Gap Closure
1.9 Irradiation Growth	Not Required	Fuel Rod/Assembly Length
1.10 Internal Gas Pressure	Not Required	Internal Gas Pressure
1.11 Hydraulic Lift Loads	TBD	Holddown Spring Force
2. Fuel Rod Failure		
2.1 Internal Hydriding	Not Required	Not Required
2.2 Cladding Collapse	Not Required	Not Required
2.3 Fretting	See Above	See above
2.4 Overheating of Cladding	Not Required	Vendor Flow Loop Tests (Maybe not necessary)
2.5 Overheating of Fuel Pellets	Halden/?	Fuel Centerline Temperature Calcs.
2.6 Excess Fuel Enthalpy	CABRI	Fuel Enthalpy Calcs
2.7 Pellet/Cladding Interaction	Uniform Elongation/Total Elongation	Uniform Elongation/Total Elongation
2.8 Clad Rupture	EdF-Edgar and ANL	TBD
2.9 Mechanical Fracturing	Yield Stress	Yield Stress
3. Fuel Coolability		
3.1 Cladding Embrittlement	EdF/JAERI/ANL	Quench Tests
3.2 Violent Expulsion of Fuel	CABRI	3-D Neutronic Calc's
3.3 Generalized Clad Melting	Not Reqiured	Not Required
3.4 Fuel Rod Ballooning	EdF-Edgar and ANL	TBD
3.5 Structural Deformation	Yield Stress	Yield Stress

Enclosure 2

Licensing Criteria for Fuel Burnup Extension Beyond 62 GWd/tU - Industry Guide

Prepared by

Robust Fuel Program
Working Group 2

October 2000

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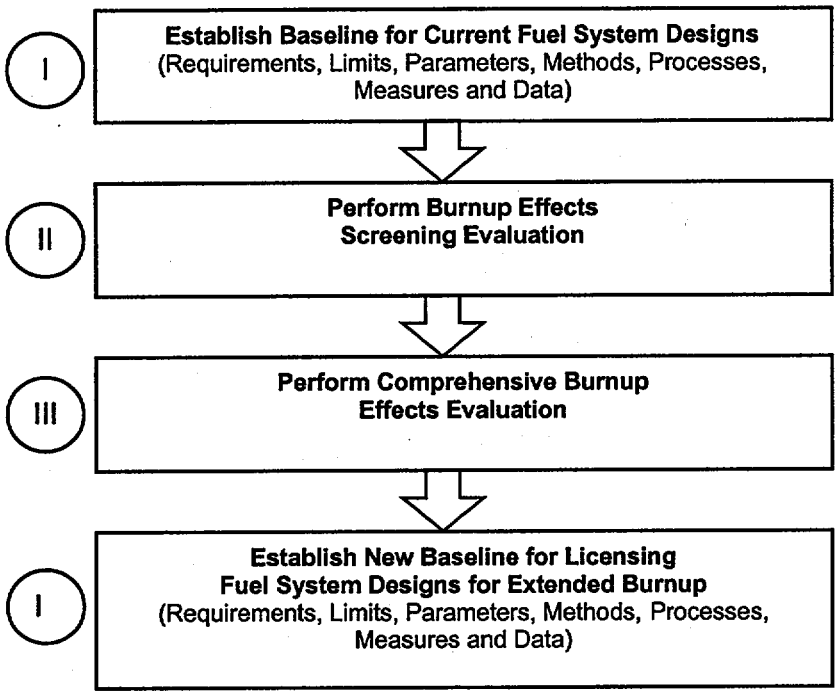
Introduction

An evaluation process has been developed by Working Group 2 of the Robust Fuel Program to assist in establishing licensing criteria for fuel rods at burnup extensions beyond 62 GWd/tU. The process involves the review of the licensing limits defined in Standard Review Plan (SRP) Section 4.2, SRP Chapter 15 from NUREG-0800 and other regulatory guides, as well as, the design methods used by licensees to demonstrate compliance to these design criteria . The objective of the evaluation process is to assess the need for modifications or additions to the existing licensing criteria, or to demonstrate the applicability of the present limits at burnup levels beyond 62 GWd/tU.

Review Process

A systematic process has been established to review and assess the applicability of the existing fuel design bases above 62 GWd/tU. The purpose of the review is to identify the burnup considerations and data needs associated with the licensing limits used for fuel and assembly design analysis. The review process relies on the current design approach specified in licensee fuel design topical reports and the guidelines outlined in the SRP Section 4.2 to indicate the important fuel response behaviors that require design limits. To ensure that the review encompasses a broad enough spectrum to capture all the important burnup effects which may influence fuel rod or assembly behavior, the review also includes the fuel-related General Design Criteria specified in 10CFR50 Appendix A to recognize the consequences that fuel design limits are specified to guard against. Also, the review draws from the extensive technical experience available from international experimental programs such as Halden, CABRI, and NFIR, as well as, post-irradiation examination results on high burnup fuel to identify the fuel behavior phenomena that are impacted by burnup. Through the integration of all this information, the review will develop the technical bases to support the existing design bases that are burnup independent, identify areas that require burnup dependent considerations, modifications, or additions, and specify the data needed to justify the design bases and to demonstrate compliance at high burnup.



Using a systematic, well-documented, and technically-based approach to assess the impact of burnup on the current licensing bases will provide a defensible position from which to proceed to burnup extensions beyond 62 GWd/tU. The process developed to conduct this review is shown in Figure 1 and consists of four stages;

I. Establish Baseline for Current Fuel System Designs
II. Perform Burnup Effects Screening Evaluation
III. Perform Comprehensive Burnup Effects Evaluation
IV. Establish New Baseline for Licensing Extended Burnup.

Figure 1. Four Stage Review Process

Stage I, shown in the flow diagram in Figure 2, is an overall review of the design bases used to license fuel rod designs . The objective of Stage I is to establish the baseline for the current design approach. This baseline consists of the current regulatory requirements, licensing limits, and design methods used to demonstrate compliance. Establishing a clear link between the current regulatory requirements and the fuel design

limits used to demonstrate compliance will facilitate the evaluation of burnup extension on the fuel licensing bases.

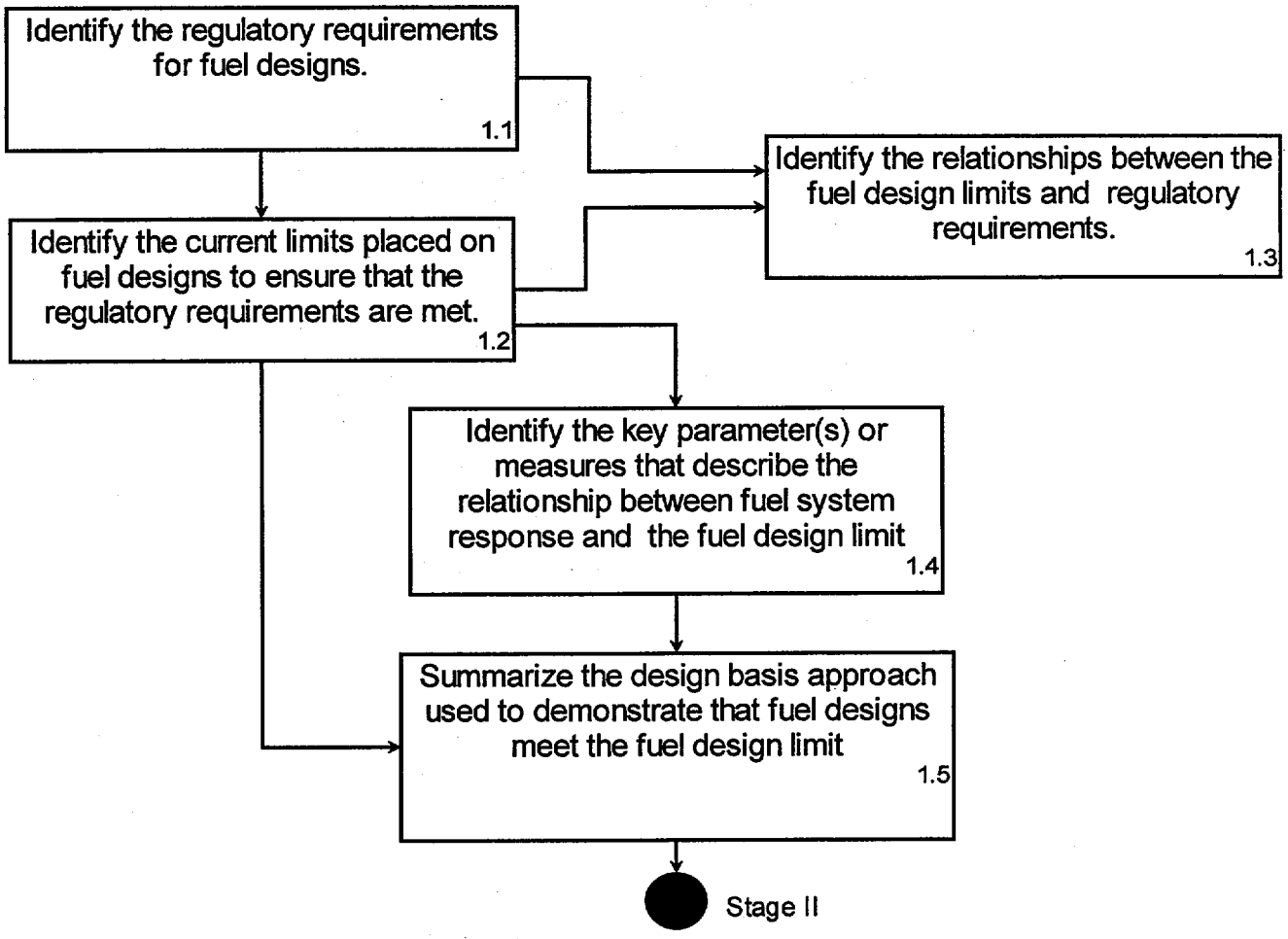


Figure 2. Stage I: Establish Baseline for Current Fuel System Designs

Stage I consists of five (5) steps:

Step 1 - The regulatory requirements for fuel designs defined in 10 CFR Part 50 and 10 CFR Part 100 will be identified.

Step 2 - The current limits placed on fuel designs to ensure that the regulatory requirements are satisfied will be identified and categorized into limits related to normal operation, anticipated operational occurrences (AOO's) and postulated

accidents. The fuel design limits will be obtained from approved fuel-related topical reports, the Standard Review Plan, and Regulatory Guides.

Step 3 – The relationship between the fuel design limit and regulatory bases will be established.

Step 4 – The key fuel rod parameter or measure used to compare to the fuel design limit will be identified.

Step 5 - The design basis approach used to demonstrate compliance to the fuel design limits will be summarized. The methods and approaches used by industry to license fuel are specific to a particular application and contain proprietary methods. As a result, only a general review is provided which identifies the key elements of the methods that should consider the effect of extended burnup operation and the applicable data that are required to support the approach.

Much of Stage I is the collection and organization of information that is readily available in regulatory and licensing documentation for current fuel designs.

Stage II is the burnup effects screening evaluation used to identify the impact of burnup extension on the design bases for a specific fuel design limit. Figure 3 displays a flow diagram outlining the Stage II process. This stage utilizes a series of questions to classify fuel design limits and design methods into those that already apply to extended burnup and those that require a more in-depth review. The questions used in this demonstration include:

2.1: Does burnup have an effect on the key parameter(s) or measures identified for the fuel design limit?

2.2: Does burnup have an effect on the current fuel design limit?

2.3: Can effect of burnup be addressed through expansion of current methods, processes, programs or data?

Stage III represents the in-depth evaluation to identify the effect of burnup on a particular license limit or method used to demonstrate compliance. A conceptual flow diagram for the Stage III process is shown in Figures 4 and 5.

The Stage III activity is an extension of the NRC PIRT process to assess the design bases for an event. The objective of the NRC PIRT is to assist NRC in the methods development and experimental design to address high burnup behavior for RIA and LOCA transients. On the other hand, the industry review performed under Stage III is focused on supporting existing or newly defined licensing limits used to demonstrate compliance to the regulations.

The results of the NRC PIRT identification and ranking activities will be used to developed the initial phenomena considered in the Stage III review of the design bases for those limits/accidents that fail to pass the Stage II review. Because of the different focus of the industry review, it is envisioned that a subset of the phenomena from the outcome of the NRC PIRT will be contained in the Stage III process.

For the Stage III review, the phenomena will be separated into two main categories: Analysis Methods and Licensing Limits. For the Analysis Methods category, key parameters will be selected that represent the outcome of the licensing methods that are used to compare to licensing limits (e.g. deposited energy). The key parameters for the Licensing Limits category will be the fuel rod failure and the core coolability design limits for the accident under review.

The Stage III process includes two separate steps to identify the impact of burnup on the design bases for a particular limit. Step 1 consists of the phenomena identification and ranking process and the assessment of burnup impact on the phenomenon rank. The NRC PIRT outcome is used for the phenomena identification and ranking activity. The assessment of burnup impact on the phenomenon rank is accomplished by the following questions:

1. Can burnup have an effect on the phenomenon? If so,
2. Does burnup effect increase importance rank?

The second step in the Stage III process evaluates the change in the phenomenon rank on the key parameter. For the Analysis Methods category, the following question is used;

a. Can current methods processes, programs, or data account for changes in the key parameter caused by burnup effects on _____?

Each phenomenon identified for a particular key parameter is inserted in the blank spaces in the above questions.

For the Licensing Limits category, the following questions are used:;

a. Can the current fuel rod failure design limit account for changes in the cladding failure mechanisms caused by burnup effects on _____?
b. Can the current core coolability design limit account for changes in the mechanisms leading to loss of coolable geometry caused by burnup effects on _____?

Stage IV is the development of the rationale and justification required to support the existing licensing bases and any changes required for extended burnup. The rationale will include identifying the data required to support extended burnup and the changes in the design approach to demonstrate compliance.

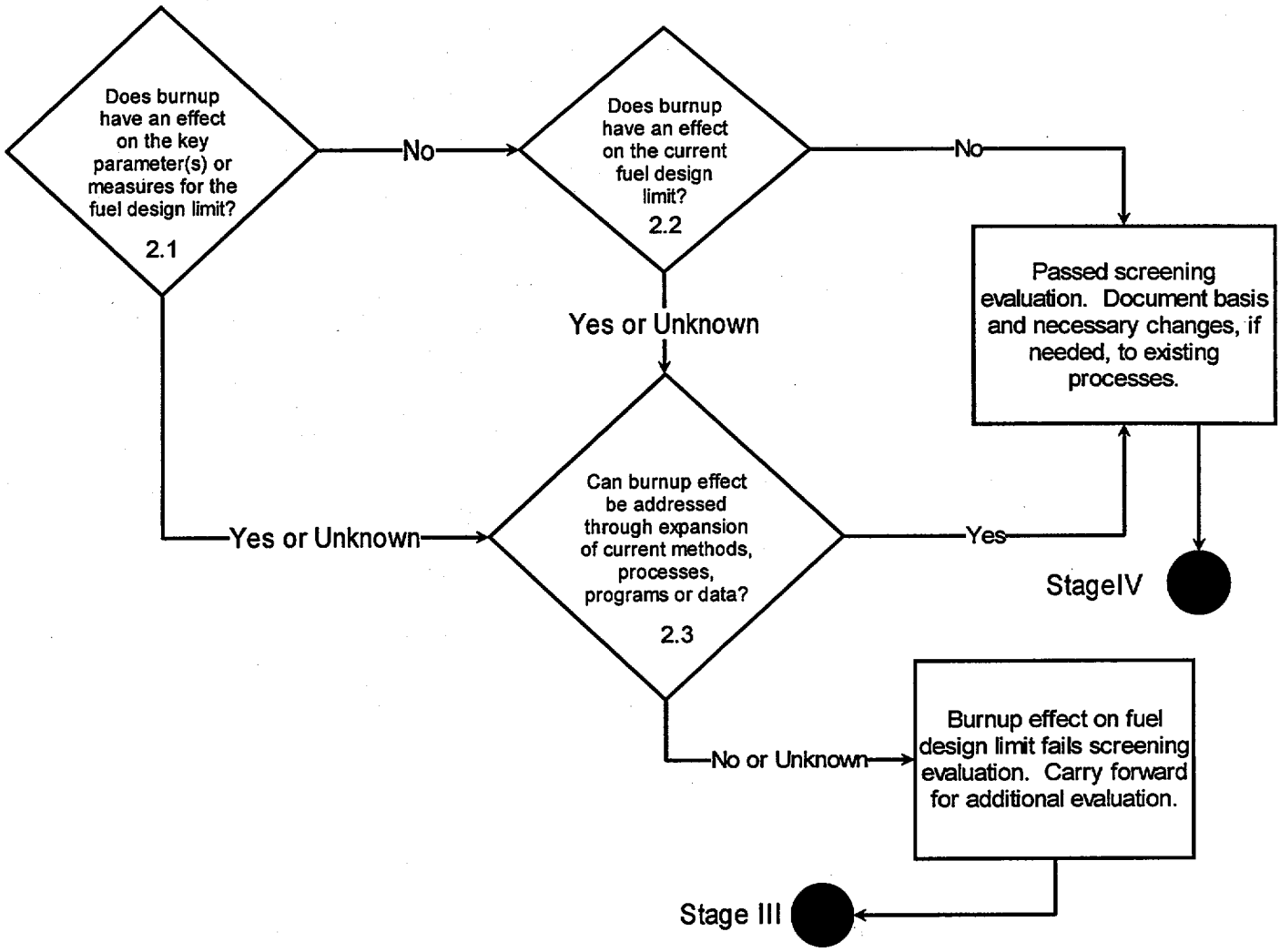


Figure 3. Stage II: Burnup Effects Screening Evaluation

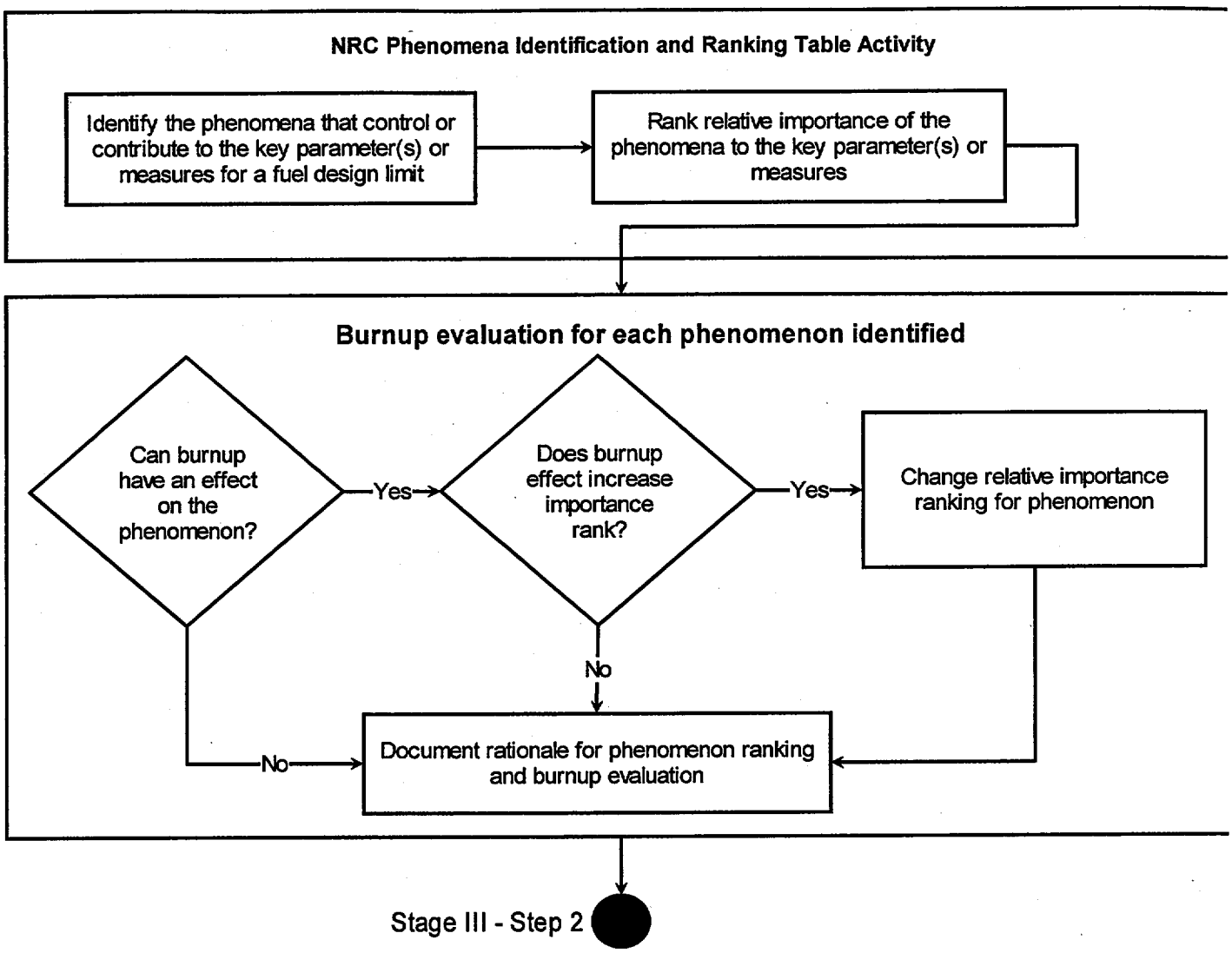


Figure 4: Stage III-Step 1: Comprehensive Burnup Effects Evaluation

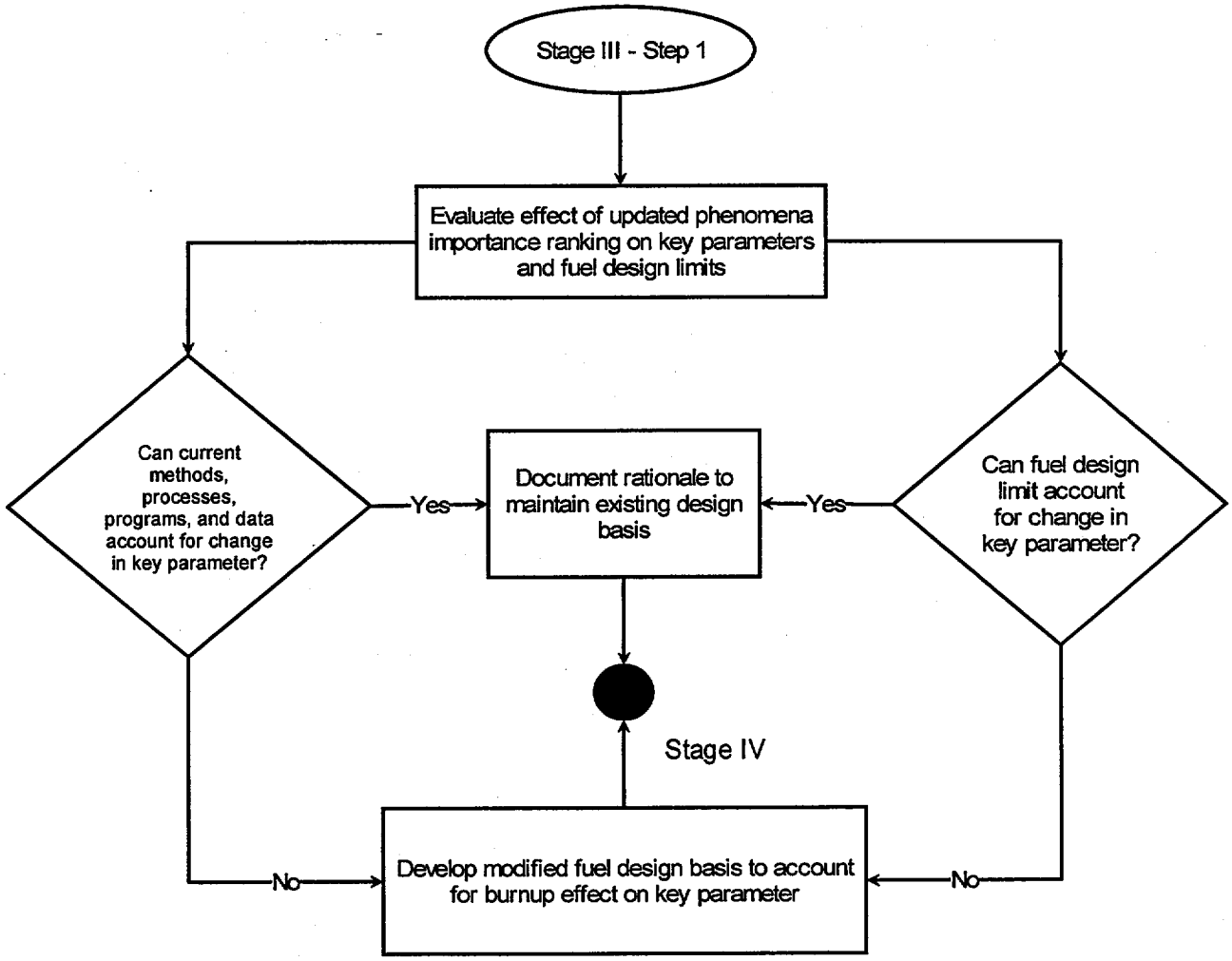


Figure 5: Stage III-Step 2: Comprehensive Burnup Effects Evaluation

Data Requirements

An important aspect of the review process is the identification of the data needed to support fuel operation beyond 62 GWd/tU. The required data for burnup extension can be separated into three categories.

First, fuel and cladding material and behavioral data are needed to establish the impact of burnup on particular fuel phenomena and parameters that define fuel rod performance. This type of data includes thermal and mechanical properties such as thermal conductivity, specific heat, melting temperature, creep and ductility. Also included in this category are behavioral data including fission gas release and irradiation growth/swelling. This type of data will come from different sources including separate effects tests, special irradiation programs in test reactors such as Halden, Studsvik, etc., and material property tests. The industry review of the current licensing bases will utilize these data in the evaluation process to quantify the burnup effects on fuel rod phenomena important to licensing criteria.

The second category consists of data that the review process will use to justify an existing criterion or justify revisions to the licensing bases up to burnup levels of 75 GWd/tU. This data will be used within the review process to ensure that the existing or revised criteria establish sufficient safety margins. The sources of data include material property tests, separate effects tests, and poolside and destructive examinations. This data will come from the existing experience of fuel operation and as a result the operating conditions, defined by power level, residence time, and burnup may not be prototypical of the anticipated conditions for high burnup operation. Engineering evaluations based on the extensive industry experience will be used to apply this data as part of the review process.

The third category is the data that will be required to demonstrate compliance to the new design bases for high burnup operation. This data will be obtained from mechanical property tests and poolside and/or destructive examinations. The fuel material used to obtain the required data will come from fuel assemblies operated under prototypical power and coolant chemistry conditions. Generally, this data will be reported in licensee fuel topical reports. The type of data required in Category 3 will be identified in the review process. It will be the responsibility of the fuel licensee to collect and report the required data.

An example of the data that will be identified in the review process for Categories 2 and 3 is shown in Table 0-1.

Table 0-1. Data to Support Burnup Extension to 75 GWd/tU

Design Basis Limits/Criteria	Data to Justify Limit at 75 GWd/tU	Data to Demonstrate Compliance
1. Fuel System Damage		
1.1 Design Stress	Yield Strength/Ultimate Tensile Strength	Yield Strength/Ultimate Tensile Strength
1.2 Design Strain	Uniform Elongation/Total Elongation	Uniform Elongation/Total Elongation
1.3 Strain Fatigue	Use Existing Fatigue Data	Use Existing Fatigue Data
1.4 Fretting Wear	Use Existing Fretting Wear Data	Use Existing Fretting Wear Data
1.5 Oxidation	TBD	Maximum Oxide Thickness
1.6 Hydriding	TBD	Hydrogen Content
1.7 Crud	TBD	Crud Thickness
1.8 Rod Bow	Not Required	Rod-to-Rod Gap Closure
1.9 Irradiation Growth	Not Required	Fuel Rod/Assembly Length
1.10 Internal Gas Pressure	Not Required	Internal Gas Pressure
1.11 Hydraulic Lift Loads	TBD	Holddown Spring Force
2. Fuel Rod Failure		
2.1 Internal Hydriding	Not Required	Not Required
2.2 Cladding Collapse	Not Required	Not Required
2.3 Fretting	See Above	See above
2.4 Overheating of Cladding	Not Required	Vendor Flow Loop Tests (Maybe not necessary)
2.5 Overheating of Fuel Pellets	Halden/?	Fuel Centerline Temperature Calcs.
2.6 Excess Fuel Enthalpy	CABRI	Fuel Enthalpy Calcs
2.7 Pellet/Cladding Interaction	Uniform Elongation/Total Elongation	Uniform Elongation/Total Elongation
2.8 Clad Rupture	EdF-Edgar and ANL	TBD
2.9 Mechanical Fracturing	Yield Stress	Yield Stress
3. Fuel Coolability		
3.1 Cladding Embrittlement	EdF/JAERI/ANL	Quench Tests
3.2 Violent Expulsion of Fuel	CABRI	3-D Neutronic Calc's
3.3 Generalized Clad Melting	Not Required	Not Required
3.4 Fuel Rod Ballooning	EdF-Edgar and ANL	TBD
3.5 Structural Deformation	Yield Stress	Yield Stress

Demonstration of Approach

Four licensing limits were selected from SRP 4.2 for evaluation that offer differing challenges to burnup extension. The limits reviewed were;

- Design Stress
- Rod Internal Pressure
- Excessive Fuel Enthalpy
- Violent Expulsion of Fuel

The design stress limit was selected to demonstrate the process for a licensing limit and design method that is least affected by burnup and, as such, is not subjected to greatly reduced margins under increasing burnup. Design stress already accounts for burnup effects in the design methods and does not require an in-depth review for burnup extension. The rod internal pressure limit was selected because the factors that control rod internal pressure are more strongly affected by burnup and therefore may require more consideration in the design process. However, the internal rod pressure limit still does not require an in-depth review for burnup extension. The excessive fuel enthalpy and the violent expulsion of fuel design limits were selected to demonstrate the process for licensing limits that will require an in-depth (Stage III) review for burnup extension.

The information summarized below encompasses material collected for Stage I, the burnup evaluation performed in Stage II, preliminary results from the detailed burnup assessment for Stage III, and some discussion prepared that will be necessary for Stage IV. The review material used in Stage I and II includes:

- Nonproprietary generic fuel assembly Topical Reports prepared by SPC, FCF, W, GE and ABB-CE
- Technical Evaluation Reports prepared by PNL on the SPC, W, GE and FCF Topical Reports
- Standard Review Plan Section 4.2, 15.4.8/Appendix A, 15.4.9/Appendix A
- Regulatory Guide 1.77 "Assumptions Used for Evaluating a Control Rod Ejection Accident for Pressurized Water Reactors"
- 10 CFR 50 Appendix A – "General Design Criteria for Nuclear Power Plants"

- 10 CFR 100 Part 11 – "Determination of Exclusion Area, Low Population Zone, and Population Center Distance"
- NRC PWR RIA Phenomena Identification and Ranking Tables Report
- ASME Boiler and Pressure Vessel Code
- Zircaloy alloy publications
- MATPRO

For each limit, the following is included in the review.

Stage I

- Application – the conditions for which the limit is applied
- Standard Review Plan Section 4.2 – reiteration of the SRP 4.2 requirement
- Regulatory Requirement – a summary of the regulatory basis for the limit
- Design Limit – a summary of the basis for the current limit used by licensees in the fuel design process
- Design Basis Approach – a summary of the analysis methods/processes used to show compliance to the limit

Stage II

- Burnup Effects Screening Evaluation – review of burnup effects on the limit and on the methods/processes used to demonstrate compliance to the limit.

Stage III (Excessive Fuel Enthalpy and Violent Expulsion of Fuel only)

- Comprehensive Burnup Effects Evaluation – a detailed assessment of burnup extension effect on the phenomena associated with the design limit and the methods/processes used to demonstrate compliance to the limit.

Stage IV

- Assessment – recommendations/actions to address burnup extension.

1.1

Design Stress

Stage I - Baseline for Current Fuel System Designs:

Application: Fuel system damage during normal operation or anticipated operational occurrences (AOO's).

Standard Review Plan Section 4.2: Stress, strain, or loading limits for spacer grids, guide tubes, thimbles, fuel rods, control rods, channel boxes, and other fuel system structural members should be provided. Stress limits that are obtained by methods similar to those given in Section III of the ASME Code are acceptable. Other proposed limits must be justified.

Regulatory Requirement: Design stress represents a Specified Acceptable Fuel Design Limit (SAFDL) as defined or referenced in 10CFR50 Appendix A - General Design Criteria 10, 12, 17, 20, and 25. These criteria require that the reactor core, coolant, control, and protection systems shall be designed to assure appropriate margin to SAFDL's during normal operation or anticipated operational occurrences.

Design Limit: In general, two methods are used to establish the Design Stress Limit for fuel rods. The first method employs the use of design ratios, defined as the ratio of effective stress to a stress limit. In this method, the stress limit is a conservative estimate of the unirradiated ultimate tensile stress. The design stress ratio approach is based on ANSI/ANS-57.5, "Light Water Reactor Fuel Assembly Mechanical Design and Evaluation". In the second method, the Design Stress Limits are derived from the ASME Boiler and Pressure Vessel Code design criteria defined in Article III-2000 for Class 1 components. A total of four stress limits are used for fuel rod cladding. These limits are based on the design stress intensity value (S_m) which is specified in Article III-2000 as the minimum of 2/3 the yield strength or 1/3 the ultimate tensile strength at either room or operating temperature. A detailed description of each limit is discussed in the Design Basis Approach Section. These cladding design stress limits ensure

that stresses experienced by the cladding do not produce cladding failure or gross distortion during normal operation and AOO's.

Design Basis Approach: The fuel damage criteria for cladding stress ensures that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis.

Cladding stress loads are calculated for conditions that bound normal operation and AOO's. Both finite element analysis methods and ASME stress analysis methods are employed to calculate the stress loads from the different mechanical contributions. The stress calculations are based on worst case conditions from either BOL or EOL and typical considerations include:

- Minimal wall thickness to account for fabrication tolerances and corrosion
- Minimum and maximum rod internal pressure and coolant pressure
- Hot and cold coolant temperatures
- Locations in the cladding, e.g., inner surface vs. outer surface and mid-span vs. spacer grid

The stress loads applied to fuel rods include hydrostatic pressure, spacer-grid contact, flow-induced vibrations, ovality, thermal and mechanical bow, thermal gradient, and pellet-cladding interaction. In the design ratio approach, the stress loads from the different sources are combined using stress superposition and used to calculate the effective stress. The design stress ratio is determined from the effective stress and the ultimate tensile stress. Statistical methods are utilized to demonstrate that the upper 95th percentile of the design ratio is less than unity.

For those methods based on Section III of the ASME Boiler and Pressure Vessel Code, guidelines are provided to classify and combine the various stress loads. The classifications include Primary Membrane Stress (P_m), Primary Bending Stress (P_b), Primary Local Membrane Stress (P_L), and Secondary Stress (Q). Typical sources of cladding stress loads and classification include;

Loading Source	Stress Category
hydrostatic pressure	Primary Membrane Stress

grid spacer contact	Primary Local Membrane Stress
flow-induced vibrations	Primary Bending Stress
ovality	Primary Bending Stress
thermal and mechanical bow	Secondary Stress
thermal gradients	Secondary Stress

Once the stress loads are calculated and combined to provide the different stress categories, the values are compared to the design stress intensity limits for each category. The design stress intensities are provided below;

P_m must not exceed S_m
P_L must not exceed $1.5S_m$
P_m+P_b must not exceed $1.5S_m$
$P_L + P_b + Q$ must not exceed $3.0S_m$

Stage II - Burnup Effects Screening Evaluation:

Q2.1: Does burnup have an effect on the key parameter(s) or measures identified for the fuel design limit?

Yes – Burnup does affect the factors that contribute (or control) the cladding stress loads. These factors include rod internal pressure, cladding wall thickness, pellet-cladding gap thickness, pellet and cladding mechanical properties, amount of rod axial growth, and grid spring relaxation.

Q2.2: Does burnup have an effect on the current fuel design limit?

No – Burnup does not have an effect on the design stress intensity or design ratio limits provided the yield strength and ultimate tensile strength at extended burnup remain above the values used to establish design limits. As is well known, experimental data from mechanical property tests on Zircaloy alloys show that accumulation of fast neutron fluence causes the yield strength and ultimate tensile strength to increase above unirradiated levels. This increase is also accompanied by a decrease in Zircaloy ductility. Mechanical property tests applicable to the target burnup level, maximum oxide layer thickness, and zirconium hydride content and

distribution are required to demonstrate that the irradiated yield strength remains above the values used to establish the stress limit.

Q3: Can effect of burnup be addressed through expansion of current methods, processes, programs or data?

Yes – The analysis methods used to calculate the stress loads included in the design approach should consider the following changes caused by irradiation.

- Bounding cladding wall thickness reduction caused by corrosion layer and hydride rim thickness formation.
- Maximum rod internal pressure.

Stage IV - New Baseline for Licensing Extended Burnup

Assessment: The Design Stress Limits used for fuel rod cladding appropriately address the effect of burnup extension within the Design Process. No change in the existing design limit is required for burnup extension. Mechanical property data applicable to the target burnup level, the maximum oxide thickness, and the zirconium hydride distribution is required to demonstrate that the cladding yield stress at extended burnup remains larger than the value used to establish the design stress limit and does not display a decreasing trend with burnup. Corrosion data is required to demonstrate that the wall thickness reduction used in the stress calculations bounds the wall thickness reduction anticipated for all burnup and power levels.

1.10

Internal Pressure

Stage I - Baseline for Current Fuel System Designs:

Application: Fuel system damage during normal operation.

Standard Review Plan Section 4.2: Fuel and burnable poison rod internal gas pressures should remain below the nominal system pressure during normal operation unless otherwise justified.

Regulatory Requirement: Rod internal pressure represents a Specified Acceptable Fuel Design Limit (SAFDL) as defined or referenced in 10CFR50 Appendix A - General Design Criteria 10, 12, 17, 20, and 25. These criteria require that the reactor core, coolant, control, and protection systems shall be designed to assure appropriate margin to SAFDL's during normal operation or anticipated operational occurrences.

Design Limit: The Rod Internal Pressure (RIP) Limit used for licensing current fuel rod designs is larger than the nominal coolant pressure. For modern fuel designs, the RIP limit has been established at a level below that required to cause 1) fuel-cladding gap reopening due to cladding creepout during constant and increasing fuel rod power conditions under normal operation, when the rod internal pressure exceeds the system pressure, and 2) extensive DNB propagation to occur. Thermal and mechanical calculations have been performed to provide the engineering justification for using a RIP limit that exceeds the reactor coolant system (RCS) pressure.

Design Basis Approach: The fuel damage criteria for rod internal pressure ensures that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis. The typical design approach employs the use of fuel performance computer codes that calculate the evolution of the rod internal pressure as a function of fuel design, burnup and operating conditions. In general, the methods include the effects of initial helium pressure/inventory, initial internal void volume, fission gas release, helium release from the fuel pellet and burnable poisons, total rod internal void volume, and the

temperature of the various internal void volumes. The input power history is developed using NRC-approved methods and may include several limiting AOO transients to add conservatism to the analysis. Some approaches may apply conservatisms on best-estimate models to ensure bounding calculations for maximum rod internal pressure.

Stage II - Burnup Effects Screening Evaluation:

Q2.1: Does burnup have an effect on the key parameter(s) or measures identified for the fuel design limit?

Yes – Burnup has an effect on the constituents that control the maximum rod internal pressure. Those constituents affected include fission gas release, helium release from the fuel pellet and burnable poisons, fuel pellet swelling, fuel rod growth, and fuel pellet thermal conductivity.

Q2.2: Does burnup have an effect on the current fuel design limit?
No - The fuel-cladding gap reopening limit is not affected by burnup. However, the thermo-mechanical methods used to establish the rod internal pressure that causes fuel-cladding gap reopening must be evaluated to assess the effect of burnup is considered.

For conditions where the rod internal pressure exceeds the coolant pressure, the RIP limit is based on restricting conditions that would produce fuel-cladding gap reopening. To satisfy this situation, the cladding outward strain rate should be less than or equal to the fuel pellet outward swelling strain rate.

The factors that control the cladding creep rate include irradiation damage, cladding temperature, initial material composition, and stress level. Except for the initial material composition, burnup influences these factors in various degrees. Cladding temperature is indirectly related to burnup through the combined effects of power history, oxide layer thickness, and heat conduction from the pellet. Cladding irradiation damage is associated with the fast flux which is only a function of power history (core location). The cladding stress level depends on the rod internal pressure and the amount of wall thinning due to oxidation. If the existing rod internal pressure limit at 62 GWd/tU remains unchanged for further burnup extension, the stress level is also unaffected by the burnup increase. However, increasing the RIP limit produces higher stress levels and correspondingly, higher cladding strain rates that could exceed the fuel

pellet swelling rate. Conversely, The fuel pellet swelling rate at high burnup is very nearly a linear function of the burnup accumulation rate. In general, the burnup accumulation rate depends on the fuel rod linear power, which tends to decrease for high burnup fuel.

As a consequence of these factors, the thermo-mechanical methods used to determine the rod internal pressure required to initiate full-cladding gap reopening must consider the impact of burnup extension on the cladding creep rate and pellet swelling rate.

Q2.3: Can effect of burnup be addressed through expansion of current methods, processes, programs or data?

Yes – The design bases methods used to calculate the rod internal pressure should include the effects of burnup on such parameters as the fuel pellet thermal conductivity, fuel pellet swelling, fuel rod growth, cladding creep, helium release from the fuel pellet and burnable poisons, and fission gas release. The input power history used in the analysis should be developed to maximize the effects of burnup on the constituents that define maximum rod internal pressure. These methods should demonstrate conservative rod internal pressure calculations. Validation should include applicable data for the expected burnup range.

Stage IV - New Baseline for Licensing Extended Burnup

Assessment: The design of rod internal pressure for operation to extended burnup has two considerations: 1) the analysis methods used to demonstrate compliance, and 2) the fuel-cladding gap reopening limit. The conservatism of the design basis calculations for rod internal pressure should be demonstrated using applicable data for the burnup range. This includes comparison of analysis results to rod internal pressure measurements for high burnup fuel.

Extended burnup operation that requires an increase in the existing rod internal pressure will need re-qualification of the design bases used to justify the new RIP limit based on fuel-cladding gap reopening. The re-qualification should include cladding creep data for irradiated cladding at the fluence, flux, temperature and stress levels anticipated for high burnup fuel operation at prototypical power levels.

2.6

Excessive Fuel Enthaply

Stage I - Baseline for Current Fuel System Designs:

Application: Fuel rod failure during postulated reactivity initiated accidents including control rod ejection (CREA) or control rod drop (CRDA) accidents.

Standard Review Plan Section 4.2: For a severe reactivity initiated accident (RIA) in a BWR at zero or low power, fuel failure is assumed to occur if the radially averaged fuel rod enthalpy is greater than 170 cal/g (711 J/g) at any axial location. For full-power RIAs in BWR and all RIAs in a PWR, the thermal margin criteria (DNBR and CPR) are used as fuel failure criteria to meet the guidelines of Regulatory Guide 1.77 as it relates to fuel rod failure. The 170 cal/g (711 J/g) enthalpy criterion is primarily intended to address cladding overheating effects, but it also indirectly addresses pellet/cladding interactions (PCI). Other criteria may be more appropriate for an RIA, but continued approval of this enthalpy criterion and the thermal margin criteria may be given until generic studies yield improvements.

Regulatory Requirement: The fission product release resulting from fuel rod failure during a postulated accident is required by 10 CFR Part 100.11 to calculate the radiation dose for the exclusion area boundary (EAB) and low population zone (LPZ) boundary. The calculated whole-body and thyroid doses at the EAB and LPZ for an RIA event must be well within the exposure guideline values in 10 CFR Part 100.11. Appendix A of Standard Review Plan section 15.4.8 and 15.4.9 defines "well within" as 25% of the 10 CFR 100.11 exposure guidelines: 75 rem for thyroid and 6 rem for whole-body doses. The assumptions used in calculating the source term activity for fuel rod failure are defined in Reg. Guide 1.77 Appendix B. For fuel rod failure, the accumulated fuel-cladding gap activity should be assumed to be 10% of the iodines and 10% of the noble gases accumulated at the end of core life, assuming continuous maximum full power operation. The activity inventory should take no allowance for radioactive decay prior to the accident.

Regulatory Guide 1.77 specifies the acceptable assumptions and analytical methods that should be used in evaluating a control rod ejection accident (CREA) for PWRs. Regulatory Guide 1.77 states "The number of fuel rods experiencing clad failure should be calculated and used to obtain the amount of contained fission product inventory released to the reactor coolant system." Reg. Guide 1.77 furthermore defines that clad failure should be assumed to occur when the calculated heat flux equals or exceeds the departure from nucleate boiling ratio (DNBR).

The fuel rod failure limit used in BWR's is defined in Standard Review Plan sections 4.2 and 15.4.9 as 170 cal/g for CRDA events initiated from zero or low power and fuel cladding dryout for rated power initial conditions.

General Design Criteria 28 (GDC 28) defined in 10 CFR Part 50 Appendix A specifies that reactivity control systems should be designed to assure that the effects of a postulated reactivity accident neither (1) result in damage to the reactor coolant pressure boundary greater than limited local yielding, nor (2) sufficiently disturb the core, its support structures, or other reactor pressure vessel internals to cause serious impairment of core cooling capability. These limits are related to pressure vessel integrity and core coolability and are not concerned with cladding failure (loss of fuel rod hermeticity).

Design Limit: The excessive fuel enthalpy limit was established to address fuel rod failure during reactivity accidents that produce rapid energy deposition into the fuel pellet. RIA tests conducted in the SPERT reactor showed fuel rod failure coincident with the development of post-DNB cladding temperatures. For test rods with zero or low burnup conditions, cladding failure normally occurred during quench following some period of high temperature operation produced by the energy deposition. Since establishing a mechanical stress or strain based limit associated with cladding quench was difficult, the accepted practice of using a thermal margin limit defined by DNBR to conservatively indicate rod failure was adopted for RIA accidents as indicated in Reg. Guide 1.77 for PWRs. A radially averaged fuel enthalpy limit was used for BWR's because of the difficulty in defining a Critical Power Ratio limit for a CRDA.

The radially averaged fuel enthalpy limit used for fuel rod failure in PWRs is a function of the DNB/CHF performance of a particular fuel assembly and reactor design. The controlling

parameters include the coolant flowrate, temperature and pressure, operating power level, and fuel assembly design. Thermal-hydraulics calculations performed show that the radially averaged fuel enthalpy which produces heat flux levels exceeding the DNBR vary between 80 and 120 cal/g for zero or low power accidents. A radially average fuel enthalpy limit of 170 cal/g is used for fuel rod failure in BWR RIA events that initiate from zero or low power conditions.

Departure from nucleate boiling is used as the limit for RIA events initiating from hot-full power conditions in both PWRs and BWRs.

Design Basis Approach: The approach to demonstrate compliance to the excessive fuel enthalpy limit for an RIA consists of the following steps:

- calculate the energy deposition following a rapid insertion of reactivity using conservative neutron kinetics methods and assumptions,
- perform a conservative thermal analysis using the energy deposition to determine the maximum radially averaged fuel enthalpy.

The methods and assumptions used to perform the neutron kinetics calculations are dependent on the specific methodology, fuel design and fuel management scheme. The areas that require conservative considerations are defined in Reg Guide 1.77 for PWRs and include:

- ejected rod worth
- reactivity insertion rate
- delayed neutron fraction and prompt neutron lifetime
- coolant pressure, inlet temperature, and mass flow rate
- fuel rod heat transfer properties
- moderator temperature and Doppler coefficients
- reactivity insertion during trip versus time and reactor trip delay time

The results of static core depletion calculations are used to initialize the nuclear parameters and define fuel assembly peaking factors for worst-case conditions, typically EOC. Based on the nuclear parameters listed above, either point, 1-D, 1.5-D or 3-D spatial kinetics methods are used to calculate the core average power pulse transient for the ejection/drop of the highest worth control rod.

The hot spot power transient is calculated from the assembly peaking factors based on the limiting xenon distribution during the entire cycle. This information is input into the thermal heat conduction analysis to calculate the radially average fuel pellet enthalpy. Normally, adiabatic pellet heat-up is assumed in the calculation of the fuel enthalpy to obtain maximum values.

The number of fuel rods exceeding the fuel enthalpy limit based on DNB or 170 cal/g are calculated from the thermal analysis. Using the fission product inventory assumptions defined in Reg Guide 1.77, the fission product release into the RCS can be determined for use in the source term analysis. In some cases the licensee may demonstrate that the number of rods calculated to fail in the RIA analysis is bounded by the radiological consequences from another analyzed event, such as LOCA, thus eliminating an explicit radiological release analysis.

Stage II - Burnup Effects Screening Evaluation:

Q2.1: Does burnup have an effect on the key parameter(s) or measures identified for the fuel design limit?

Yes – Burnup (fuel duty defined by power level and residence time) has an effect on the key parameters for the excessive fuel enthalpy limit. The two key parameters for the excessive fuel enthalpy limit are the maximum radially averaged fuel enthalpy and the fission product inventory in the fuel-cladding gap.

The fuel rod deposited energy produced by the reactivity insertion during a RIA event controls the maximum radially averaged fuel enthalpy for a fuel rod. Heat conduction only plays a minor role in the fuel enthalpy, depending on the rate of energy deposition, because during a RIA event energy deposition is nearly adiabatic. The deposited energy is dependent on two main factors; (1) the nuclear parameters including the cross-section data, control rod worth, Doppler coefficient, and delayed neutron fraction (β) that define the amount of reactivity inserted and (2) the proximity of the fuel rod to the control rod ejected/dropped. Burnup influences the excess reactivity of a fuel rod, which is defined by the nuclear parameters. In general, the excess reactivity decreases with burnup due to the presence of neutron absorbing fission products. Experimental results using irradiated test rods indicate that for a constant reactivity insertion and initial U^{235} enrichment the deposited energy decreases at higher burnup. Also, high burnup fuel assemblies are typically loaded in lattice positions in the reactor core that are not adjacent to a control rod. This decreases the fuel assembly to core average power peaking factor because of the localized effect of a control rod ejection/drop. The combination of the lower reactivity and the proximity of the fuel assembly to the ejected/dropped control rod limits the amount of deposited energy that a high burnup fuel rod experiences during a RIA event. In contrast, the increase of the radial peaking factor across a pellet causes higher local deposited energy. Typically, higher burnup fuel rods have higher radial peaking factors across the pellet due to the depletion of fissionable material in the central part of the pellet and the production of Pu isotopes in the pellet periphery. This situation can produce a local peak in the fuel enthalpy that can have a detrimental effect of the fuel rod performance (see discussion below).

Burnup influences the fission product inventory in the fuel-cladding gap available for release following cladding failure. Generally, fission gas release (noble gases) into the fuel-cladding

gap increases during burnup accumulation. Recent experimental data obtained from high burnup fuel operated under steady state conditions indicate that the fission gas release rate also increases with burnup. More importantly, recent RIA experimental data suggest that the transient fission gas release for high burnup fuel can exceed 25% for rapid power pulses.

Q2.2: Does burnup have an effect on the current fuel design limit?

Yes – The results from RIA experiments performed on irradiated test rods indicate that burnup related changes can effect the fuel rod failure response. RIA experiments using zero or low burnup test rods show that cladding failure occurs primarily by thermal quench following excessive cladding temperatures during DNB. A transition from cladding failure dominated by high temperatures to cladding failure by PCMI stresses is observed in RIA test results at burnup levels beyond 30 GWd/tU. Tests performed in the NSRR facility in Japan and the CABRI facility in France using test rods refabricated from commercial PWR fuel rods irradiated to burnup levels between 50 and 63 GWd/tU exhibited cladding failure during the power pulse at fuel enthalpy levels that are below those expected based on cladding failure from DNB and high cladding temperatures. Detailed examination of these test results has revealed that, while the level of PCMI loading from the fuel can depend directly on burnup, the actual mechanisms leading to cladding failure are more related to cladding ductility which is a function of oxide layer thickness, hydride concentration and distribution, and temperature. As a consequence, cladding failure response during a RIA may depend on the cladding corrosion and hydrogen performance during irradiation.

At zero and low burnup levels, the fuel-cladding gap is open and PCMI is negligible during a reactivity accident. However, the reactivity worth of the fuel rod is large because of the amount of fissionable material and the lack of neutron absorbing fission products. This condition increases the potential for large fuel enthalpy increases and high cladding temperatures which could lead to DNB, depending on the reactivity worth of the ejected control rod. Irradiation decreases the fissionable material and introduces fission products, decreasing the fuel rod reactivity. A decreasing trend in the maximum achievable fuel enthalpy is observed in RIA experiments when the results are correlated with test rod burnup.

At intermediate and high burnup levels, fuel pellet swelling and cladding creepdown during irradiation causes closure of the fuel-cladding gap. As a consequence, fuel pellet thermal expansion resulting from a rise in fuel enthalpy can increase the PCMI stresses experienced by

the cladding. Another potential contributor to increased PCMI stresses is related to the high burnup pellet rim region. Neutron absorption due to self-shielding increases the local Pu concentration and power production in the outer 100-200 μm near the pellet surface. Local burnup in this region can exceed 100 GWd/tU, producing high concentrations of fission gases that reside in a complex network of intergranular and intregranular bubbles. The almost adiabatic heat production during a RIA causes the pellet rim temperature to exceed the average fuel temperature by 1.5 to 2.5 times due to the sharply peaked power distribution across the fuel pellet. The high temperature in the rim region can cause expansion of the fission gas bubbles, increasing the PCMI forces on the cladding. Depending on the power pulse width, the increase in cladding stress by these mechanisms can occur at a rate that is faster than the temperature rise in the cladding by heat conduction from the fuel pellet. Cladding failure occurs by PCMI when the fuel pellet expansion during the power pulse exhausts the ductility of the cladding.

Other than the fabrication characteristics, the mechanical properties of irradiated cladding depend on the fast fluence, hydrogen content and distribution, and temperature. Mechanical property tests on irradiated cladding material display an increase in the yield stress with increasing fast fluence. This is accompanied by a decrease in the cladding ductility compared to unirradiated material. Hydrogen from Zircaloy corrosion can also impact the cladding yield strength and ductility. The level of impact depends on the hydrogen content, the distribution and orientation of the hydride platelets, and the temperature level. Irradiated cladding in PWRs generally show hydride concentrations that vary across the cladding thickness, with higher concentrations near the outer radius and low concentrations at the inner radius. The level of this variation depends on the cladding oxide layer thickness, power level and irradiation time. The through-thickness variation of hydrides can decrease the effective cladding ductility due to the presence of crack initiation sites in the hydrided rim region near the outer surface. Hydride redistribution caused by oxide layer spallation can result in regions of heavy hydride concentrations. This condition can further affect the cladding ductility. Finally, the cladding stress biaxiality and triaxiality can reduce the cladding ductility. Under PCMI conditions during an RIA, generally a biaxial stress state exists in the cladding, which when combined with the fast fluence and hydride concentration effects, can result in an overall decrease of the effective cladding ductility for irradiated cladding.

The combination of increased PCMI stresses and decreased cladding ductility may result in cladding failure before DNBR can occur (i.e. during the power pulse) or at fuel enthalpy levels

below those required to produce DNB for high burnup fuel. Experiments performed on test rods with burnup levels greater than 50 GWd/tU and low residual cladding ductility caused by localized hydride concentrations or low cladding temperatures have experienced cladding failure during the power pulse or at fuel enthalpy levels below those required to produce DNB and high cladding temperatures.

The results of RIA tests and analyses indicate that the current approach, which assumes a burnup-independent fuel enthalpy limit (170 cal/g or DNBR), does not account for the change in cladding failure from thermally-driven to PCMI-driven processes.

Q2.3: Can effect of burnup be addressed through expansion of current methods, processes, programs or data?

Yes - The methods used to demonstrate compliance with the excessive fuel enthalpy limit are performed at both BOC and EOC conditions to capture the effects of burnup on the nuclear parameters (cross-section data, control rod worth, Doppler coefficient, and delayed neutron fraction (β)) and the fuel assembly and fuel rod power peaking factors. Refinement of the spatial resolution of the neutron kinetics analysis method can provide an improved calculation of the deposited energy as a function of fuel rod burnup.

Stage III - Comprehensive Burnup Effects Evaluation: (not completed)

The comprehensive burnup effects evaluation for the excessive fuel enthalpy limit used the results of the NRC PWR RIA PIRT activity as the starting point to develop the list of phenomena to include in the evaluation. The review process separated the phenomena list into two main categories associated with the key parameters. The two main categories are: Analysis Methods and Licensing Limit. For the analysis methods used for licensing PWR control rod ejection and BWR control rod drop accidents, the key parameters are energy deposition and fuel enthalpy increase. Fuel rod failure is the licensing limit for the excessive fuel enthalpy limit and is defined by key parameters of either DNB or 170 cal/gm. The first step in the process is to identify and rank the phenomena associated with the key parameters for the Analysis Methods and Licensing Limit categories and then assess the impact of burnup on the ranking for each phenomenon. As mentioned the

phenomena list and initial ranking were obtained from the outcome of the NRC PWR RIA PIRT. Only a subset of these phenomena were used in the Stage III review. Also, additional phenomena were added to address areas not covered in the NRC activities. The phenomena used in the Stage III review are listed in Table 2.6-1 through 2.6-3 along with the importance rankings relative to the key parameters. The burnup impact assessment was accomplished by passing the list of phenomena through a series of questions. These results are also given in Table 2.6-1 through 2.6-3.

The second step is to evaluate that the current design bases (composed of methods, processes, programs, or data and the licensing limits) can account for the effects on burnup on the different phenomena. Tables 2.6-4 through 2.6-6 contain the results of this evaluation. For the Analysis Methods category, the following questions are used:

a. Can current methods, processes, programs, or data to account for changes in energy deposition caused by burnup effects on _____?
b. Can current methods, processes, programs, or data to account for changes in fuel enthalpy increase caused by burnup effects on _____?

Each phenomena shown in Tables is inserted in the above questions. The evaluation results for the Analysis Methods are shown in Table 2.6-4 and 2.6-5. The review found that most of the phenomena associated with energy deposition for a REA or CRDA are dependent on burnup. The effect of burnup does not change the importance ranking for any of the phenomena reviewed. Furthermore, the review found that the current methods, processes, programs, or data can account for the effect of burnup on these phenomena in calculating the energy deposition. Similar results were obtained for the fuel enthalpy increase.

For the Licensing Limit category, the following questions are used:

a. Can the current fuel design limit of DNB or 170 cal/gm account for changes in cladding failure at high temperature caused by burnup effects on _____?

b. Can the current fuel design limit of DNB or 170 cal/gm account for changes in nominal temperature PCMI cladding failure caused by burnup effects on _____?

Each phenomena shown in the Table is inserted in the above questions. The evaluation results for the Licensing Limit is shown in Table 2.6-6. The fuel rod failure limit assessment is divided into two separate questions to address the different potential failure mechanisms: high temperature (Post-DNB) and nominal temperature (PCMI). High temperature failure during a REA or CRDA is defined by DNB in PWRs and a maximum radially averaged fuel enthalpy of 170 cal/gm for BWRs. The review found that DNB is influenced by burnup, but the importance of DNB on cladding failure remains high. This similar for the 170 cal/gm limit for high temperature cladding failure in BWRs. The phenomena associated with PCMI failure are a function of burnup and the review found that none of the rankings changed as a result of this burnup dependency. The results summarized in Table 2.6-6 show that the current fuel failure limits of DNB and 170 cal/gm may not adequately account for changes in nominal temperature PCMI failure mechanisms caused by burnup (or duty). The limit does not consider the loss of cladding ductility that may occur as a consequence of irradiation and hydrogen uptake during corrosion.

Table 2.6-1 Step 1 - Impact of Burnup on Phenomenon Controlling Energy Deposition

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Energy Deposition and Pulse Width	Ejected Rod Worth	High		
	Rate of Reactivity Insertion	Medium		
	Moderator Feedback	Medium		
	Temperature Feedback	High		
	Delayed-neutron fraction	High		
	Fuel Cycle Design	High		

Table 2.6-2 Step 1 - Impact of Burnup on Phenomenon Controlling Fuel Enthalpy Increase

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Fuel Enthalpy Increase	Pellet, Gap, and Cladding Heat Resistances	Medium		
	Cladding to Coolant Heat Transfer	Medium		
	Pellet and Cladding Heat Capacities	High		
	Pellet Radial Power Distribution	Medium		
	Pin Peaking Factors	High		

Table 2.6-3 Step 1 - Impact of Burnup on Phenomenon Controlling Fuel Rod Failure

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Cladding Failure at High Temperature	DNB	High		
	High Temperature Oxidaiton	Medium		
	Clad Melting	High		
	Quench Fracture	Medium		
	Coolant Conditions	Medium		

Table 2.6-3 (cont'd) Step 1 - Impact of Burnup on Phenomenon Controlling Fuel Rod Failure

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Cladding Failure by Nominal Temperature PCMI	Fuel-Cladding Gap Size	High		
	Cladding Oxidation	Medium		
	Cladding Oxide Spallation	High		
	Hydrogen Content	Medium		
	Hydrogen Distribution	High		
	Fast Fluence	Low		

Table 2.6-3 (cont'd) Step 1 - Impact of Burnup on Phenomenon Controlling Fuel Rod Failure

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Cladding Failure by Nominal Temperature PCMI (cont'd)	Pellet Rim Size	Medium		
	Fission Gas Induced Pellet Swelling	Medium to High		
	Cladding Temperature	High		

Table 2.6-4 Step 2 - Impact of Burnup on Energy Deposition

Key Parameter	Phenomena	Ranking	Can current methods processes, programs, or data account for changes in energy deposition caused by burnup effects on.....?
Energy Deposition and Pulse Width	Ejected Rod Worth	High	
	Rate of Reactivity Insertion	Medium	
	Moderator Feedback	Medium	
	Temperature Feedback	High	
	Delayed-neutron fraction	High	
	Fuel Cycle Design	High	

Table 2.6-5 Step 2 - Impact of Burnup on Fuel Enthalpy Increase

Key Parameter	Phenomena	Ranking	Can current methods processes, programs, or data account for changes in fuel enthalpy increase caused by burnup effects on.....?
Fuel Enthalpy Increase	Pellet, Gap, and Cladding Heat Resistances	Medium	
	Cladding to Coolant Heat Transfer	Medium	
	Pellet and Cladding Heat Capacities	High	
	Pellet Radial Power Distribution	Medium	
	Pin Peaking Factors	High	

Table 2.6-6 Step 2 - Impact of Burnup on Fuel Rod Failure Limit

Key Parameter	Phenomena	Ranking	Can current fuel design limit of DNB or 170 cal/gm account for changes in cladding failure at high temperature caused by burnup effects on.....?
Cladding Failure at High Temperature	DNB	High	
	High Temperature Oxidaiton	Medium	
	Clad Melting	High	
	Quench Fracture	Medium	
	Coolant Conditions	Medium	

Table 2.6-6 (cont'd) Step 2 - Impact of Burnup on Fuel Rod Failure Limit

Key Parameter	Phenomena	Ranking	Can current fuel design limit of DNB or 170 cal/gm account for changes in nominal temperature PCMI cladding failure caused by burnup effects on.....?
Cladding Failure by Nominal Temperature PCMI	Fuel-Cladding Gap Size	High	
	Cladding Oxidation	Medium	
	Cladding Oxide Spallation	High	
	Hydrogen Content	Medium	
	Hydrogen Distribution	High	
	Fast Fluence	Low	

Table 2.6-6 (cont'd) Step 2 - Impact of Burnup on Fuel Rod Failure Limit

Key Parameter	Phenomena	Ranking	Can current fuel design limit of DNB or 170 cal/gm account for changes in nominal temperature PCMI cladding failure caused by burnup effects on.....?
Cladding Failure by Nominal Temperature PCMI (cont'd)	Pellet Rim Size	Medium	
	Fission Gas Induced Pellet Swelling	Medium to High	
	Cladding Temperature	High	

Stage IV - New Baseline for Licensing Extended Burnup (not completed)

Assessment: The approach used to estimate the number of fuel failures resulting from a RIA uses a conservative core-wide calculation to obtain the maximum fuel enthalpy distribution and compares these results to a burnup-independent fuel enthalpy limit (170 cal/g or DNBR). Implicit in this approach is the assumption that the fuel rod mechanical capacity (or response) is similar throughout the core and thermal margin limits are more applicable (controlling). However, fuel rod response data from both RIA tests and mechanical property tests indicate a decrease in cladding ductility with irradiation, leading to a fuel enthalpy at failure that is lower than the current limits. This change in fuel rod response is coincident with a reduction in the energy deposition as burnup increases. These observations must be included in the excessive fuel enthalpy limit and the analysis methodology for extended burnup application. To accommodate this change in the approach used to estimate the number of fuel rod failures during an RIA requires the fuel rod failure limit (excessive fuel enthalpy) to be a function of irradiation, either burnup, oxide layer thickness or hydrogen content. Such a change in the limit will also require an accompanied shift in the neutronics methods to calculate the fuel enthalpy during a RIA. The core-wide point kinetics or 1-D calculation methods used currently produce overly conservative results that may not satisfy more restrictive limits. A burnup-dependent fuel enthalpy limit will require more realistic assumptions for such neutronic parameters as control rod worth and Doppler coefficient, and may necessitate the use of multidimensional analysis methods.

A more detailed review of how this limit is used to license high burnup fuel is required before establishing an excessive fuel enthalpy limit applicable to RIA. The in-depth review should consider the controlling mechanisms for the limit as well as the analysis methods used to demonstrate compliance to the limit.

3.2

Violent Expulsion of Fuel

Stage I - Baseline for Current Fuel System Designs:

Application: Fuel coolability during postulated reactivity initiated accidents including control rod ejection (CREA) or control rod drop (CRDA) accidents.

Standard Review Plan Section 4.2: In severe reactivity initiated accidents, such as rod ejection in a PWR or rod drop in a BWR, the large and rapid deposition of energy in the fuel can result in melting, fragmentation, and dispersal of fuel. The mechanical action associated with fuel dispersal can be sufficient to destroy the cladding and the rod bundle geometry of the fuel and to produce pressure pulses in the primary system. To meet the guidelines of Regulatory Guide 1.77 as it relates to preventing widespread fragmentation and dispersal of the fuel and avoiding the generation of pressure pulses in the primary system of a PWR, radially averaged enthalpy limit of 280 cal/g (1.17 KJ/g) should be observed. This 280 cal/g (1.17 KJ/g) limit should also be used for BWRs.

Regulatory Requirement: General Design Criteria 28 (GDC 28) defined in 10 CFR Part 50 Appendix A specifies that reactivity control systems shall be designed to assure that the effects of a postulated reactivity accident neither (1) result in damage to the reactor coolant pressure boundary greater than limited local yielding, nor (2) sufficiently disturb the core, its support structures, or other reactor pressure vessel internals to cause serious impairment of core cooling capability. GDC 28 further specifies that reactivity initiated accidents shall include consideration of rod ejection (unless prevented by positive means), rod drop, steam line rupture, changes in coolant temperature and pressure, and cold water addition

Design Limit: Regulatory Guide 1.77 specifies the acceptable assumptions and analytical methods that may be used in evaluating a control rod ejection accident (CREA) for PWRs. Furthermore, Regulatory Guide 1.77 states that by using these assumptions and methods it should be shown that;

1. Reactivity excursions will not result in a radial average fuel enthalpy greater than 280 cal/g at any axial location in any fuel rod.
2. Maximum reactor pressure during any portion of the assumed transient will be less than the value that will cause stresses to exceed the Emergency Condition stress limits as defined in Section III of the ASME Boiler and Pressure Vessel Code.

The fuel enthalpy limit is based on a Regulatory staff review of the available data (prior to 1974) from the SPERT and TREAT experimental programs describing the fuel failure consequences following a high rate of reactivity insertion. The review found that there exists a potential for prompt rupture of a fuel rod and the rapid heat transfer from finely dispersed molten UO_2 at high fuel energy depositions. Prompt fuel element rupture is defined in Regulatory guide 1.77 as a rapid increase in internal fuel rod pressure due to extensive fuel melting, followed by rapid fragmentation and dispersal of cladding into the coolant. The review concluded that the failure consequences of UO_2 fuel rods were insignificant for total energy depositions below 300 cal/g for both unirradiated and irradiated fuel rods. As a result, a peak radially averaged fuel enthalpy of 280 cal/g was considered to be a conservative maximum limit to ensure that core damage will be minimal and that both short-term and long-term core cooling capability will not be impaired.

The violent expulsion of fuel design limit specified in SRP 4.2 is based on the 280 cal/g peak radially averaged fuel enthalpy limit defined in Regulatory Guide 1.77 and is applied to both PWR and BWR reactivity initiated accidents.

<u>Design Basis Approach:</u> The approach to demonstrate compliance to the violent expulsion of fuel design limit for an RIA consists of the following steps:

- calculate the maximum energy deposition following a rapid insertion of reactivity using conservative neutron kinetics methods and assumptions,
- perform a conservative thermal analysis using the maximum energy deposition to determine the maximum radially averaged fuel enthalpy.

The methods and assumptions used to perform the neutron kinetics calculations are dependent on the specific methodology, fuel design and fuel management scheme. The areas that require conservative considerations are defined in Reg Guide 1.77 for PWRs and include:

- ejected rod worth
- reactivity insertion rate

- delayed neutron fraction and prompt neutron lifetime
- coolant pressure, inlet temperature, and mass flow rate
- fuel rod heat transfer properties
- moderator temperature and Doppler coefficients
- reactivity insertion during trip versus time and reactor trip delay time

The results of static core depletion calculations are used to initialize the nuclear parameters and define fuel assembly peaking factors for worst-case conditions, typically EOC. Based on the nuclear parameters listed above, either point, 1-D, 1.5-D or 3-D spatial kinetics methods are used to calculate the core average power pulse transient for the ejection/drop of the highest worth control rod.

The hot spot power transient is calculated from the assembly peaking factors based on the limiting xenon distribution during the entire cycle. This information is input into the thermal heat conduction analysis to calculate the radially average fuel pellet enthalpy. Normally, adiabatic pellet heat-up is assumed in the calculation of the fuel enthalpy to obtain maximum values.

Stage II - Burnup Effects Screening Evaluation:

Q2.1: Does burnup have an effect on the key parameter(s) or measures identified for the fuel design limit?

Yes – The key parameter for the violent expulsion of fuel design limit is the maximum radially averaged fuel enthalpy. Burnup (fuel duty defined by power level and residence time) has an effect on the key parameter for the violent expulsion of fuel design limit.

The deposited energy produced by the reactivity insertion during a RIA event controls the maximum radially averaged fuel enthalpy for a fuel rod. Heat conduction only plays a minor role in the fuel enthalpy, depending on the rate of energy deposition, because during a RIA event energy deposition is nearly adiabatic. The deposited energy is dependent on two main factors; (1) the nuclear parameters including the cross-section data, control rod worth, Doppler coefficient, and delayed neutron fraction (β) that define the amount of reactivity inserted and (2) the proximity of the fuel rod to the control rod ejected/dropped. Burnup influences the excess reactivity of a fuel rod, which is defined by the nuclear parameters. In general, the excess reactivity decreases with burnup due to the presence of neutron absorbing fission products. Experimental results using irradiated test rods indicate that for a constant reactivity insertion and initial U^{235} enrichment the deposited energy decreases at higher burnup. Also, high burnup fuel assemblies are typically loaded in lattice positions in the reactor core that are not adjacent to a control rod. This decreases the fuel assembly to core average power peaking factor because of the localized effect of a control rod ejection/drop. The combination of the lower reactivity and the proximity of the fuel assembly to the ejected/dropped control rod limits the amount of deposited energy that a high burnup fuel rod experiences during a RIA event. In contrast, the increase of the radial peaking factor across a pellet causes higher local deposited energy. Typically, higher burnup fuel rods have higher radial peaking factors across the pellet due to the depletion of fissionable material in the central part of the pellet and the production of Pu isotopes in the pellet periphery. This situation can produce a local peak in the fuel enthalpy that can have a detrimental effect of the fuel pellet performance.

Q2.2: Does burnup have an effect on the current fuel design limit?

Yes – The fuel coolability limit of 280 cal/gm for the maximum radially averaged fuel enthalpy, defined in Reg. Guide 1.77, was defined based on experiments performed on unirradiated test

rods that experienced severe fuel and clad melting during the energy deposition. A review of the data by MacDonald, et. al., which supports this limit, found that although the violent expulsion of fuel design limit is stated in terms of radially average fuel enthalpy, the limit is actually based on the total energy deposition. The maximum radially averaged fuel enthalpy is less than the associated total energy deposition due to heat conduction from the fuel and energy deposition from delayed neutrons. Based on tests performed in the SPERT and TREAT facilities, the consequences of maximum radially averaged fuel enthalpies greater than 240 cal/gm were fragmentation and loss of rod geometry. These observations indicate that the 280 cal/gm may not be conservative with respect to maintaining core coolability. A value of 230 cal/gm for the maximum radially averaged fuel enthalpy would be more appropriate for the violent expulsion of fuel design limit at zero and low burnup.

Several RIA-simulation tests, performed on test rods previously irradiated between 3 and 33 GWd/tU, failed at fuel enthalpy levels between 150 and 200 cal/gm with minimal post-failure consequences. Also, two of these rods experienced additional energy depositions of 45 to 75 cal/gm without loss of pellet material or rod geometry. However, rods previously irradiated to 5 GWd/tU and tested at a maximum radially averaged fuel enthalpy of 285 cal/gm showed extensive fission product-induced swelling of molten fuel with loss of rod geometry and flow blockage. These results tend to confirm the maximum radially averaged fuel enthalpy limit from the zero burnup tests. Based on this data, the violent expulsion of fuel design limit at 30 GWd/tU should remain near 230 cal/gm or may decrease slightly to a value between 180 and 200 cal/gm.

The data on fuel rod failure at burnup levels beyond 30 GWd/tU come from tests performed in NSRR and CABRI. The data from these tests show that up to 40 GWd/tU test rod failure at fuel enthalpy levels as high as 160-170 cal/gm have minimal consequences, i.e. no fuel dispersal or loss of rod geometry. A single test at 30 GWd/tU, which failed at 185 cal/gm, reached a maximum of 210 cal/gm and displayed only minor loss of fine fuel particles from the pellet periphery in the region of the cladding crack. A majority of the fuel pellets were contained within the cladding. Between 40 and 50 GWd/tU, three rods in NSRR were tested to maximum fuel enthalpy levels ranging from 73 to 107 cal/gm. Each of these rods failed and experienced minor loss of fine fuel particles from the pellet periphery. Again, a majority of the fuel pellets were contained within the cladding for these tests. Significant fuel pellet loss was only seen in the test at 50 GWd/tU due to complete fracturing of the lower endcap. The results from this test are not

relevant to the assessment of rod coolability because the endcap fracture is strongly an artifact of the test rod geometry. A total of three rods tested in CABRI at burnup levels between 60 and 65 GWd/tU experienced cladding failure (Na-1, Na-8, and Na-10). No fuel dispersal was observed in Na-8 and Na-10 up to a fuel enthalpy increase of 95 cal/gm, even though cladding failure occurred at ~65 cal/gm. However, extensive fuel dispersal, loss of rod geometry, and flow blockage occurred in CABRI Na-1. This test failed at a fuel enthalpy increase of 15 cal/gm and then continued energy deposition to a maximum fuel enthalpy increase of 100 cal/gm at the end of the power pulse. The fuel dispersal associated with this test is due to the large amount of energy deposited into the fuel pellets after loss of cladding confinement. The lack of mechanical confinement from the cladding allowed uncontrolled expansion of the pellets, resulting in gross fuel movement into the flow channel. It is difficult to make use of this result because of the unusually low energy level of cladding failure.

Two main observations can be made based on the data summarized above:

(1) violent expulsion of fuel and loss of rod geometry during an RIA event occurs by two different modes: a) expansion of molten fuel and loss of structural confinement by clad melting and b) post-cladding failure energy deposition leading to uncontrolled fuel pellet expansion and fragmentation.

(2) the violent expulsion of fuel design limit appears to decrease with burnup beyond 30 or 40 GWd/tU.

It is difficult to define the violent expulsion of fuel design limit beyond 30 GWd/tU because of the lack of relevant data at high energy depositions. One method to develop a limit beyond 30 GWd/tU could use a level of energy deposition after cladding failure. For tests that failed but did not experience loss of rod geometry, an additional energy deposition can be added to the failure enthalpy to provide the limit for coolability. The level of additional energy deposition can be defined based on the CABRI Na-1 test that received an additional 85 cal/gm after cladding failure. As stated above, this test experienced loss of rod geometry following cladding failure. Using this approach, the coolability limit can be developed using the cladding failure enthalpy. For example, a test at 45 GWd/tU failed the cladding at a fuel enthalpy of 75 cal/gm and reached a maximum fuel enthalpy level of 100 cal/gm without loss of rod geometry. The coolability limit for this test would be 160 cal/gm (75 + 85). This approach can be used to define a curve based on the failure response of rods tested in CABRI and NSRR.

Q2.3: Can effect of burnup be addressed through expansion of current methods, processes, programs or data?

Yes - The methods used to demonstrate compliance with the violent expulsion of fuel design limit are performed at both BOC and EOC conditions to capture the effects of burnup on the nuclear parameters (cross-section data, control rod worth, Doppler coefficient, and delayed neutron fraction (β)) and the fuel assembly and fuel rod power peaking factors. Refinement of the spatial resolution of the neutron kinetics analysis method can provide an improved calculation of the deposited energy as a function of fuel rod burnup. In addition, less conservative assumptions and methods can be used to derive the nuclear parameters.

Stage III - Comprehensive Burnup Effects Evaluation: (not completed)

The comprehensive burnup effects evaluation for the violent expulsion of fuel design limit used the results of the NRC PWR RIA PIRT activity as the starting point to develop the list of phenomena to include in the evaluation. . For the analysis methods used for licensing PWR control rod ejection and BWR control rod drop accidents, the key parameters are energy deposition and maximum radially averaged fuel enthalpy. Since these are the same as those for the excessive fuel enthalpy design limit, the Stage III review will rely on the outcome summarized in Section 2.6. Core coolability is the licensing limit for the violent expulsion of fuel design limit and is defined as a maximum radially averaged fuel enthalpy of 280 cal/gm. The fuel design limit for fuel coolability is established to preclude pressure pulse generation following fuel-coolant interaction.. Therefore, the Licensing Limit key parameter used in the review was the pressure pulse generation from fuel-coolant interaction. The first step in the process is to identify and rank the phenomena associated with the key parameters for the Licensing Limit category and then assess the impact of burnup on the ranking for each phenomenon. As mentioned the phenomena list and initial ranking were obtained from the outcome of the NRC PWR RIA PIRT. Only a subset of these phenomena were used in the Stage III review. Also, additional phenomena were added to address areas not covered in the NRC activities. The phenomena used in the Stage III review are listed in Table 3.2-1 along with the importance rankings relative to the key parameters. The burnup impact assessment was accomplished by passing the list of phenomena through a series of questions. These results are also given in Table 3.2-1.

The second step is to evaluate that the current design bases (composed of methods, processes, programs, or data and the licensing limits) can account for the effects on burnup on the different phenomena. Tables 3.2-2 contain the results of this evaluation. For the Licensing Limit category, the following questions are used:

c. Can the core coolability limit of 280 cal/gm account for changes in pressure pulse generation by fuel coolant interaction caused by burnup effects on _____?

Each phenomena shown in the Table is inserted in the above questions. The evaluation results for the Licensing Limit is shown in Table 3.2-2.

Table 3.2-1 Step 1 - Impact of Burnup on Phenomenon Controlling Core Coolability

Key Parameter	Phenomena	Ranking	Can burnup have an impact on the phenomenon?	Does burnup effect increase importance ranking?
Pressure Pulse Generation by Fuel-Coolant Interaction	Amount of fuel material dispersed	High		
	Temperature of Dispersed Fuel Material	High		
	Particle Size of Dispersed Fuel Material	Medium-High		
	Heat transfer from dispersed fuel material to coolant	Medium-High		
	Coolant Conditions	Medium		

Table 3.2-2 Step 2 - Impact of Burnup on Core Coolability

Key Parameter	Phenomena	Ranking	Can current core coolability limit of 280 cal/gm account for changes in pressure pulse generation by fuel-coolant interaction caused by burnup effects on.....?
Pressure Pulse Generation by Fuel-Coolant Interaction	Amount of fuel material dispersed	High	
	Temperature of Dispersed Fuel Material	High	
	Particle Size of Dispersed Fuel Material	Medium-High	
	Heat transfer from dispersed fuel material to coolant	Medium-High	
	Coolant Conditions	Medium	

Stage IV - New Baseline for Licensing Extended Burnup (not completed)

Assessment: The use of a burnup independent limit for the violent expulsion of fuel (loss of rod geometry) at a maximum radially average fuel enthalpy of 280 cal/gm is not appropriate from two main reasons:

- The basis for the 280 cal/gm was incorrect because of mis-interpretation of the deposited energy and radial average fuel enthalpy. Tests at zero or low burnup display significant consequences for maximum radially averaged fuel enthalpy levels above 240 cal/gm. A more appropriate limit at zero and low burnup would be a value of 230 cal/gm for the maximum radial average fuel enthalpy.
- A change in the mechanism for loss of rod geometry is observed for fuel at high burnup and high fuel enthalpy levels. The data indicate a transition in the loss of rod geometry by the mechanism of molten fuel and cladding (Mode 1) to a mechanism dependent on the post-cladding failure energy deposition leading to unccontrolled fuel expansion and fragmentation (Mode 2). The maximum radially average fuel enthalpy required to produce loss of rod geometry by Mode 2 is below 230 cal.gm beyond 30 or 40 GWd/tU.

A more detailed review of the technical basis for coolability limit for high burnup fuel is required before establishing a violent expulsion of fuel design limit applicable to RIA. The in-depth review should consider the controlling mechanisms for the limit as well as the analysis methods used to demonstrate compliance to the limit.