GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Margaret E. Harding

July 28, 2005

FLN-2005-018

Document Control Desk
US Nuclear Regulatory Commission
Washington, DC 20852-2738

Subject: Transmittal of GNF-A Non-Proprietary Report, NEDO-33139-A, "Cladding Creep Collapse," dated July 2005.

References:
1. W. R. Butler (NRC), letter to I. Stuart (GE), April 1975.
2. "Creep Collapse Analysis of BWR Fuel Using SAFE-COLAPS Model", NEDE-20606-P-A, August 1976.
3. "USAEC Technical Report on Densification of Light Water Reactor Fuels", November 14, 1972.
4. "GE Fuel Technology Update", MFN-182-92, September 23, 1992.
5. Herbert N. Berkow (NRC), letter to M. Harding, 'Final Safety Evaluation for NEDC-33139P, "Cladding Creep Collapse" (TAC NO. MC1798)', May 31, 2005.

The Reference 1 letter documents NRC review and acceptance of Reference 2. Reference 2 presented the GE/GNF methodology developed to address the cladding creep collapse concerns described in Reference 3. The Reference 2 methodology was subsequently modified by incorporation of updated Zircaloy creep relations, as noted in Reference 4.

The original Reference 2 methodology was based upon a set of simplified, deliberately conservative assumptions and is thus currently unnecessarily constraining modern BWR fuel designs. The attached non-proprietary version of the approved LTR documents updated methodology and its approval through Reference 5.

If you have any questions, please call me at 910-675-5762.

Sincerely,

Margaret E. Harding

Margaret E. Harding
Manager, Fuel Engineering Services

cc: F. Akstulewicz (NRC)
J. Wermiel (NRC)
M. Fields (NRC)
J. F. Klapproth (GE)

Global Nuclear Fuel
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Cladding Creep Collapse
NEDO-33139-A

CLADDING CREEP COLLAPSE

Licensing Topical Report

Robert A. Rand

July, 2005

GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

Margaret E. Harding

January 9, 2004

FLN-2004-002

Cladding Creep Collapse
Sheet No ii
NEDO-33139-A

Document Control Desk
US Nuclear Regulatory Commission
Washington, DC 20852-2738

NE23411 6/7/04
This document has a duplicate fln number, it has been filed as fln_2004_012

Attention: Alan Wang

Subject: Transmittal of GNF-A Non-Proprietary Report, NEDO-33139, "Cladding Creep Collapse," dated December 2003.

References:
1. W. R. Butler (NRC), letter to I. Stuart (GE), April 1975.
2. "Creep Collapse Analysis of BWR Fuel Using SAFE-COLAPS Model", NEDE-20606-P-A, August 1976.
3. "USAEC Technical Report on Densification of Light Water Reactor Fuels", November 14, 1972.
4. "GE Fuel Technology Update", MFN-182-92, September 23, 1992.

The Reference 1 letter documents NRC review and acceptance of Reference 2. Reference 2 presented the GE/GNF methodology developed to address the cladding creep collapse concerns described in Reference 3. The Reference 2 methodology was subsequently modified by incorporation of updated Zircaloy creep relations, as noted in Reference 4.

The original Reference 2 methodology was based upon a set of simplified, deliberately conservative assumptions and is thus currently unnecessarily constraining modern BWR fuel designs. The attached LTR proposes an updated methodology that is similar to the Reference 2 methodology. However, some of the simplifying assumptions have been refined to reflect current BWR fuel fabrication processes and in-reactor performance characteristics. After NRC review and acceptance, GNF plans to use the updated methodology to license the new GNF2 fuel design for LUA application. In order to support GNF2 LUA insertion in 2004, GNF requests that the new methodology be approved by August 1, 2004.

If you have any questions, please call me at 910-675-5762.

Sincerely,

MTK - June 7, 2004 A signed copy of this letter was sent to the NRC Jan. 9, 2004

Margaret E. Harding
Manager, Fuel Engineering Services

M. T. Kiernan
Michael T. Kiernan

cc: F. Akstulewicz (NRC)
J. Wermiel (NRC)
J. F. Klapproth (GE)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

Cladding Creep Collapse
Sheet No iii
NEDO-33139-A

May 31, 2005

Mrs. Margaret Harding, Manager
Nuclear Fuel Engineering
Global Nuclear Fuel
P. O. Box 780
Wilmington, NC 28402

NE15419 6/6/05
FLN_2005_015

SUBJECT: FINAL SAFETY EVALUATION FOR NEDC-33139P, "CLADDING CREEP COLLAPSE" (TAC NO. MC1798)

Dear Mrs. Harding:

On January 9, 2004, Global Nuclear Fuel (GNF) submitted Licensing Topical Report (LTR) NEDC-33139P, "Cladding Creep Collapse," for U.S. Nuclear Regulatory Commission (NRC) staff review. In this LTR, GNF proposed a revised methodology for cladding creep collapse analysis. On May 9, 2005, an NRC draft safety evaluation (SE) regarding our approval of NEDC-33139P was provided to allow GNF to conduct a proprietary information and factual error review. By letter dated May 23, 2005, GNF replied that there were no issues with the technical content and that there was no proprietary information in the draft SE. This letter transmits the staff's final SE.

The staff has found that NEDC-33139P is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the LTR and in the enclosed SE. The SE defines the basis for acceptance of the LTR.

Our acceptance applies only to material provided in the subject LTR. We do not intend to repeat our review of the acceptable material described in the LTR. When the LTR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this LTR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that GNF publish accepted proprietary and non-proprietary versions of this LTR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include a "-A" (designating accepted) following the LTR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this LTR, GNF and/or licensees referencing it will be expected to revise the LTR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

Herbert N. Berkow, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 712

Enclosure: Final SE

cc w/encl: See next page

Global Nuclear Fuel

Project No. 712

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

NEDC-33139P, "CLADDING CREEP COLLAPSE"

GLOBAL NUCLEAR FUEL

PROJECT NO. 712

1.0 INTRODUCTION

In a letter dated January 9, 2004 (Agencywide Documents and Access Management System (ADAMS) Accession No. ML051230473), Global Nuclear Fuel (GNF) submitted licensing topical report (LTR) NEDC-33139P, "Cladding Creep Collapse," for NRC staff review and approval. GNF also submitted a non-proprietary version of this report in a letter dated January 9, 2004 (ADAMS Accession No. ML051230474). NEDC-33139P describes a revised methodology for cladding creep collapse analysis. The cladding creep collapse methodology analyzes the potential of flattening a fuel rod within a given time period for fuel designs in licensing applications. Through NEDC-33139P, GNF intends to demonstrate that the revised methodology continues to meet the licensing requirement of no clad flattening for all fuel designs.

Fuel pellets in light water reactors are subject to a densification effect during irradiation. The densification effect increases pellet density, which could result in pellet shrinkage and generate axial gaps along the fuel column. The axial gap size is generally proportional to the amount of densification. The large coolant system pressure causes the cladding to creep inward, closing the fuel-clad radial gap, and eventually collapsing the axial gap. To prevent the cladding from collapsing, the staff requires licensees to perform a creep collapse analysis considering combined effects of coolant pressure, temperature, fast neutron flux, cladding ovality, pellet hangup, and pellet densification. The cladding ovality measures the difference between the maximum and minimum diameters of a tube for quantifying the deviation from tube roundness.

Historically, the creep collapse analysis involves an assumption that depicts a free-standing and hollow tube, i.e., the cladding is unsupported by fuel pellets. The analysis starts with an initial ovality, then the ovality would gradually increase due to the combined effects. When the ovality reaches a critical value of imminent unstable geometry indicating that the tube could no longer maintain its roundness due to a large difference between the maximum and minimum diameters, the tube would deform and collapse during a pressurization event. The condition of imminent unstable geometry is called an elastic instability.

The GNF creep collapse methodology includes three components: (1) basic assumption, (2) supporting modeling, and (3) computer code. The basic assumption, as indicated above, refers to an unsupported cladding. The supporting modeling includes models of fission gas release, effective cladding overpressure, and oxide thickness for input to the creep collapse analysis. The computer code is the GNF creep collapse analytical tool described in

NEDE-20606-P-A, entitled "Creep Collapse Analysis of BWR Fuel Using CLAPS Model," previously approved by the NRC staff. GNF has been using the CLAPS code to confirm that creep collapse of a free-standing cladding would not occur for all fuel designs. Recently, based on new densification data, GNF proposed to revise the methodology for cladding creep collapse analysis. The revisions to the methodology proposed by GNF only affect the basic assumption and supporting modeling. The CLAPS code remains unchanged.

2.0 REGULATORY BASIS

The fuel system consists of arrays of fuel rods including fuel pellets and tubular cladding, spacer grids, end plates, and reactivity control rods. The objectives of the fuel system safety review are to provide assurance that (1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences, (2) fuel system damage is never so severe as to prevent control rod insertion when it is required, (3) the number of fuel rod failures is not underestimated for postulated accidents, and (4) coolability is always maintained. The NRC staff acceptance criteria are based on the NUREG-0800, "Standard Review Plan (SRP)," Section 4.2 "Fuel System Design." These criteria include three parts: (1) design bases that describe specified acceptable fuel design limits (SAFDLs) as depicted in General Design Criterion 10 to Appendix A of Title 10 of the *Code of Federal Regulations* (10 CFR), Part 50, (2) design evaluation that demonstrates that the design bases are met, and (3) testing, inspection, and surveillance plans that show that there are adequate monitoring and surveillance of irradiated fuel. The design bases include (1) fuel system damage, (2) fuel rod failure, and (3) fuel coolability. Cladding collapse is identified as a failure mechanism and part of the SAFDLs.

3.0 TECHNICAL EVALUATION

As indicated above, the revised methodology includes the basic assumption and supporting modeling. The CLAPS code remains unchanged. This NRC staff evaluation addresses the revisions only.

3.1 Revised Basic Assumption

The basis of the creep collapse mechanism is that fuel pellets could undergo anisotropic densification that results in a large axial gap along the fuel column. During the manufacturing process, various tubing ovalities could occur in the final cladding products. The combination of reactor coolant pressure, operating temperature, and fast neutron fluence will increase the cladding creep, and thus worsen the tubing ovality. If the cladding is assumed to be unsupported by the fuel column, which is a very conservative assumption, the ovality soon becomes large enough to induce elastic instability that leads to cladding flattening or collapse during a pressurization transient.

Through the years, improvements in fuel manufacturing processes have significantly reduced the densification potential, i.e., the maximum densification is controlled to only a few percent in the nuclear industry. The reduced densification potential, together with greater pellet uniformity, reduces the likelihood of large axial gap formation in the fuel column resulting from the in-reactor densification. GNF periodically examined the irradiated fuel for axial gaps using neutron radiography technique. Neutron radiography, similar to x-ray radiography in principle,

creates high resolution negative images using thermal neutron source beaming on fuel rods. The resulting neutrograph is an image of the fuel pellets including gaps between pellets. GNF confirmed that the axial gaps in the examined neutrographs were small, as expected. GNF also established a monitoring program to assure no pellet hangup using 100 percent scanning on finished rods during fuel fabrication.

GNF stated that the axial gaps, if they do occur, will be short enough and, in combination with the fuel pellets at each end of the gap, will provide sufficient mechanical support to prevent the cladding from collapsing. Accordingly, GNF revised the basic assumption from a free-standing cladding to a pellet-supported cladding. GNF commits to continue the monitoring program to validate the revised basic assumption.

The NRC staff reviewed densification data including neutrographs. Based on the recent history of no creep collapse observed and supporting densification data, the NRC staff concludes that the revised basic assumption of pellet-supported cladding maintains adequate conservatism, and is therefore acceptable for the creep collapse analysis.

3.2 Revised Supporting Modeling

The revised supporting modeling involves three models: (1) athermal fission gas release, (2) effective cladding overpressure, and (3) oxide thickness.

3.2.1 Athermal Fission Gas Release

The rod internal gas consists of initial helium-filled gas and fission gas released during irradiation. The rod pressure is the result of the accumulation of these gases. Initially, there is only helium gas within unirradiated fuel pins. As the fuel pins are irradiated, fission gas release from the fuel pellets will occur and the fission gas concentration will reach its peak value at the end of the irradiation. There are two components in fission gas release, one is thermal-dependent and another is athermal (non-thermal) -dependent. The athermal fission gas release is usually burnup dependent. For calculating the internal pressure in the fueled cladding in the revised supporting model, GNF selected only one component, the athermal component, from the approved fuel performance GESTR-Mechanical code. For creep collapse analysis, it is a conservative approach to minimize the internal pressure and hence maximize the external pressure.

Based on the approved GESTR-Mechanical code, the NRC staff concludes that the athermal fission gas release model is acceptable for the creep collapse analysis.

3.2.2 Effective Cladding OverPressure

In the approved creep collapse analysis, the external coolant system pressure is the main driving force for the unfueled cladding. The fueled cladding is supported internally by fuel pellets which partially offset the effect of external pressure. The resulting net effect of fuel pellet support and external pressure is the effective cladding overpressure, which becomes the driving force for the fueled cladding.

Based on the standard textbook "Theory of Plates and Shells," authored by Timoshenko and Woinowsky-Krieger, GNF derived an effective cladding overpressure solution. GNF then calculated the effective overpressure numerically using bounding fuel design parameters. The result showed that the effective overpressure of the fueled cladding is a fraction of the external coolant system pressure. For conservatism, GNF increased the effective overpressure of the fueled cladding, thus increasing the external forces on the cladding used in the safety analysis.

The NRC staff reviewed the GNF technical derivation and solution. Based on the standard textbook results, the staff concludes that the effective cladding overpressure model is acceptable for the creep collapse analysis.

3.2.3 Oxide Thickness

The oxide buildup on the cladding outer surface generally results in high temperature and thinning for the cladding. In the approved creep collapse analysis, GNF assumed a small amount of corrosion. Based on the recent fuel experience including high burnup, long cycle length, and water chemistry, GNF derived a new oxide thickness model with the intention to bound all operating conditions. The new model format is consistent with the model in the approved GESTR-Mechanical code with the new model predicting higher corrosion, which is conservative for the creep collapse analysis. The data base used in the oxide thickness model was derived from measurements performed by GNF on fuel rod cladding under a range of operating conditions, including plant water chemistry.

The NRC staff reviewed the oxide thickness model including data base and found that the model is conservative in predicting the results. Based on the conservative results, the NRC staff concludes that the oxide thickness model is acceptable for the creep collapse analysis.

3.3 Bounding Fuel Design Analysis

To examine the stability in creep collapse analyses, GNF applied an over-pressurization transient at the end of fuel rod lifetime when the cladding ovality reaches its peak. The over-pressurization transient simulates a core wide pressurization event. An increasing ovality after the transient would mean that the cladding becomes elastically unstable and will eventually collapse.

GNF exercised the revised creep collapse methodology using a conservative fuel rod design including mechanical parameters and operating conditions. The selected fuel rod design mechanical parameters bound all existing fuel designs through GE14 and also the next generation fuel design (GNF2). The operating conditions include high burnup regime, high linear heat generation rate, and an over-pressurization transient. The result shows that the cladding ovality reaches its maximum prior to the transient, and then returns to the same value after the transient. The result indicates that there is no elastic instability and thus no cladding collapse occurs for the selected bounding fuel design.

The NRC staff reviewed the analytical results. Based on the conservative mechanical parameters and operating conditions, the NRC staff concludes that the bounding fuel design is acceptable for the creep collapse analysis.

4.0 CONCLUSIONS

In NEDC-33139P, "Cladding Creep Collapse," GNF has revised the cladding creep collapse methodology that analyzes the potential of flattening a fuel rod within a given time period for fuel designs in licensing applications. The NRC staff has reviewed NEDC-33139P and, based on the staff evaluation discussed above, approves the proposed revised methodology for creep collapse analysis contained in this LTR.

The NRC staff finds NEDC-33139P, "Cladding Creep Collapse," to be acceptable for referencing in licensing applications. The NRC staff does not intend to repeat our review of the matters described in NEDC-33139P when the report appears as a reference in licensing applications, except to ensure that the material presented is applicable to the specific plant involved. The NRC staff's acceptance applies only to the cladding creep collapse methodology described in NEDC-33139P.

5.0 LIMITATIONS AND CONDITIONS

NEDC-33139P, "Cladding Creep Collapse," is based on generic analyses. The topical report demonstrates that creep collapse will not occur for GNF fuel designs within specified ranges of design and operation parameters. In addition to these recognized conditions in NEDC-33139P, the staff's approval is subject to the following condition:

1. GNF will continue to implement the established monitoring program to assure that no pellet hangup will occur during fuel fabrication using a 100 percent scanning technique on finished rods.

Principal Contributor: S. Wu

Date: May 31, 2005

DISCLAIMER OF RESPONSIBILITY

This document was prepared by or for Global Nuclear Fuel (GNF). The use of this information for any purpose(s) other than that which it is intended, is not authorized; and with respect to any unauthorized use, GNF makes no representation or warranty, expressed or implied, and assumes no liability as to the completeness, accuracy, or usefulness of the information contained in this document, or that its use may not infringe privately owned rights.

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1. "USAEC Technical Report on Densification of Light Water Reactor Fuels" , November 14, 1972.

2. "Ovality, Collapse and Axial Wrinkling of the Cladding on Zircaloy Clad Oxide Fuel Rods (LWBR Development Program)", Bettis Atomic Power Laboratory, West Mifflin, Pennsylvania.

3. "Creep Collapse Analysis of BWR Fuel Using CLAPS Model", NEDE-20606-P-A, August 1976.

4. "Densification Testing', draft LTR to be submitted to the NRC December 2003.

5. "Fuel Property and Performance Model Revisions", Special Report MFN-170-84-0, December 14, 1984.

6. Timoshenko and Woinowsky-Krieger, Theory of Plates and Shells, McGraw-Hill, 1959.

1. SUMMARY

The origin of the current creep collapse analysis procedure applied by GNF to each fuel design is the USAEC staff technical report on densification of light water reactor fuels issued in 1972 [1]. This report was issued in response to a phenomenon experienced in pressurized water reactors in the early 1970's [2]. In particular, it was observed that fuel pellets were densifying during operation in such a manner as to create large axial gaps in the fuel column in the high flux region of the core, leading to collapse of the cladding over axial gaps. Such collapse can occur due to a slow increase of cladding initial ovality due to creep resulting from the combined effect of reactor coolant pressure, temperature and fast neutron flux on the cladding over the axial gap. Since the cladding is unsupported by fuel pellets in the axial gap region, the ovality can become large enough to result in elastic instability and cladding collapse.

In response to [1], GE produced a number of documents that included the final creep collapse analysis procedure detailed in [3]. The analysis is performed to confirm that creep collapse of free standing cladding (cladding unsupported by fuel pellets) will not occur. The basic procedure detailed in [3] has been applied by GNF to each fuel design to demonstrate that creep collapse of the cladding will not occur. GNF has recognized since its introduction that the procedure is very conservative. This is particularly the case for modern GNF fuel designs with current fabrication processes and controls.

To obtain the fuel cycle economics and improved efficiency required for current and future fuel applications, GNF fuel designs are evolving such that the current creep collapse analysis procedure, with its inherent conservatism, unnecessarily limits product capabilities. The purpose of this report is to demonstrate that creep collapse will not occur for GNF fuel designs within specified ranges of design and operation parameters and that for fuel designs within these ranges current fabrication processes and controls are sufficient to confirm compliance with the requirement that cladding creep collapse will not occur. When and if GNF fuel designs move beyond these ranges, calculations similar to those documented in this report will be performed to confirm compliance.

2. *BACKGROUND*

Since the discovery of in-reactor densification of oxide nuclear fuels in 1972, and in response to a report from the USAEC Regulatory staff entitled "Technical Report on Densification of Light Water Reactor Fuels" [1], the impact of that densification on safety related issues has been routinely considered in GNF fuel design and fabrication. Those considerations include the effects of densification on linear heat generation rate due to shortening of the fuel pellet column, stored energy in the fuel due to an increase in the fuel-cladding gap, power peaking due to potential formation of axial gaps in the fuel pellet column, and the possibility of power spiking due to creep collapse of the cladding over those regions of the fuel where axial gaps in the column have occurred and the resulting increase in local moderation.

Additionally, the possibility of such creep collapse of the cladding over a long axial gap has been specifically addressed. Failures by such collapse were observed in pressurized water reactors (PWRs). Reference [1] was issued to address these failures. Although creep collapse failures were not observed in boiling water reactors (BWRs), and although there were inherent differences in fuel design parameters and operating conditions between GNF BWR fuel and PWR fuel produced during the period in which such failures were observed which made creep collapse of GNF BWR less likely, including (1) generally higher fuel density and lower densification for GNF fuel, (2) thicker cladding for GNF fuel, and (3) lower reactor coolant pressure for BWR fuel, in response to [1] GE produced a number of documents that included the final creep collapse analysis procedure detailed in NEDE-020606-P-A [3]. The analysis is performed to confirm that creep collapse of free standing cladding (cladding unsupported by fuel pellets) will not occur. The basic procedure detailed in [3] has been, and is currently, applied by GNF to each fuel design to demonstrate that creep collapse of the cladding will not occur.

The basic assumption behind the creep collapse mechanism is that fuel pellets could undergo anisotropic (axial) densification that could result in a large axial gap in the fuel column. The GNF tubing fabrication can result in small initial tubing ovality with-in controlled limits. The creep collapse concern arises from the possibility that the combined effect of reactor coolant pressure, temperature and fast neutron flux on the cladding over the axial gap will result in cladding creep that in turn will result in a slow increase of the initial ovality. Since the cladding is assumed to be unsupported by fuel pellets in the axial gap region, the ovality may become large enough to result in elastic instability, leading to collapse of the cladding during a pressurization event.

To prevent the undesirable thermal-hydraulic and critical power impacts of such collapse, the analysis procedure detailed in [3] is applied to each design to confirm that such collapse will not occur. GNF has recognized since its introduction that the procedure is conservative. As noted above, the primary conservatism is the assumption that fuel densification can result in large axial gaps in the fuel column,

although such densification has not been observed in GNF fuel rods. Additional conservative assumptions include the following:

- The cladding is assumed to have the maximum ovality permitted by the cladding specifications, although the actual as-fabricated ovality may be significantly less.
- The cladding is assumed to have the minimum thickness permitted by the cladding specifications, although the actual thickness is higher.
- The cladding oxide thickness (and resulting reduction in cladding thickness) is assumed to be the end of life value.
- The rod internal pressure is assumed to result only from the initial helium fill gas; no credit is taken for fission gases released during operation.
- The cladding temperature and fast flux are assumed to be worst case values.

Although the densification of GNF fuel has historically been small, even during the period when cladding creep collapse was identified as a concern, for reasons discussed below, the design and fabrication processes for GNF fuel rods have advanced significantly to achieve improved fuel cycle economics and performance, and to provide reduced product variability. However, to achieve desired fuel cycle economics and efficiency, GNF fuel designs have evolved to the point that they are being unnecessarily limited by the current creep collapse analysis procedure, with its large conservatisms. The purpose of this report is to present a modified creep collapse analysis procedure based upon the characterized ex-reactor densification performance and observed in-reactor performance of current GNF fuel and apply this modified procedure to demonstrate that creep collapse will not occur for current and future GNF fuel designs within specified ranges of design and operation parameters and that for fuel designs within these ranges current fabrication processes and controls are sufficient to confirm compliance with the requirement that cladding creep collapse will not occur. When and if GNF fuel designs move beyond these ranges, calculations similar to those documented in this report will be performed to confirm compliance.

3. *MODIFIED CREEP COLLAPSE ANALYSIS PROCEDURE*

3.1. Basis

Since the 1970's, the need for improved fuel cycle economics without reduction in reliability or safety has driven numerous changes in BWR fuel pellet and fuel bundle design. Although cladding creep collapse has never been observed by GNF fuel, indicating that the likelihood of such collapse is low, these changes are such as to further reduce the likelihood of cladding creep collapse. These changes, and current fabrication processes and controls to confirm that the changes are fully implemented, are the basis for the modified creep collapse procedure proposed by GNF in this report.

The major fuel pellet design modification in terms of impact on creep collapse is the migration of pellet density to progressively higher values to achieve increased fuel loadings and to capitalize on lower than previously anticipated needs to accommodate fuel swelling and fission gas release.

The history of the fuel pellet density requirements for GE/GNF fuel pellets is fully documented in Reference [4]. Reference [4] is being prepared to support reduced densification sampling and is intended to serve as a companion report to this report. In summary, the nominal pellet density has increased by since the discovery and control of fuel densification, from of theoretical density.

The lower extreme of acceptable densities has increased even more, from for individual pellets to for the lower 95/95-tolerance limit on pellets in a fuel reload project. Although it is now recognized that post fabrication (in-reactor) densification is not determined solely by the as-fabricated (initial) density, the earliest regulatory requirements for assessment of fuel densification assumed that terminal density was achieved at of geometric theoretical density [1], which is essentially equivalent to of true theoretical density. By that measure, modern GE/GNF fuel would nominally be immune to in-reactor densification.

It is generally true, however, that for a given powder fabrication and pelletizing process the propensity for densification is inversely related to the density of the as-sintered pellets. Therefore, the very substantial increase in the lower density limits has acted to strongly alleviate, if not eliminate, concerns about fuel pellets with large densification potentials.

The corresponding GE/GNF fuel densification requirement history is shown in Figure 1 (from Reference [4]). By contrast with the progressively increasing density requirements, the densification resistance requirements have remained essentially constant. Because of the general relationship between density and densification propensity, the increase in pellet density requirements with no

increase in densification resistance requirements have combined to substantially enhance the ability to meet the densification requirements and to reduce the potential for densification.

Figure 1
History of GE/GNF Densification Requirements

The reduced potential for densification, together with greater pellet uniformity, reduces the likelihood that in-reactor densification will result in the formation of axial gaps in the fuel column of sufficient length that creep collapse of unsupported cladding can occur. The gaps in the fuel column, if they do occur, will be short enough that the fuel pellets at each end of the gap will provide significant mechanical support to the cladding, greatly reducing the likelihood of creep collapse relative to that of free standing cladding.

The small likelihood of development of axial gaps in modern GNF fuel has been confirmed by periodic examination of GNF fuel. Representative results from the most recent examination of (9x9) GE11 LUA bundles, are presented in Appendix A. First, neutrographs for a full length UO_2 rod at a rod average exposure of ~56 GWd/MTU are presented. These neutrographs confirm that axial gaps between pellets are small and uniform over the entire fuel column. It is noted that since the

neutrographs were made at approximately room temperature that the gaps between pellets contain a component due to thermal contraction of the pellets relative to operating conditions and that the gaps at operation conditions will be smaller than those in the neutrographs. Second, profilometry from the same rod as the neutrographs, from a gadolinia rod from the same bundle, and from a UO_2 rod from a different bundle at ~70 GWd/MTU are presented. The uniformity of the profilometry, with no indications of reduced diameter other than small local reductions, provides indirect confirmation that no fuel column axial gaps with lengths larger than indicated by the neutrographs develop during irradiation for modern GNF fuel. These results are consistent with GNF's substantial database of profilomtery results from other GNF fuel designs.

Axial gaps in the fuel column could also result during fabrication. The results of ongoing examinations of irradiated fuel rods, as discussed above, indicate that the likelihood of such gaps is low. Additionally, GNF has developed and applies a very robust and accurate monitoring program to further reduce the likelihood of such gaps. A key feature of this program is 100 percent enrichment and density scanning of finished rods. This scanning has the capability to detect pellet axial gaps much smaller than would result in possible cladding creep collapse. A detailed discussion of the scanner and its implications in preventing low density (and thus less densification resistance) pellets is included in Reference [4]. In addition, the scanner is utilized to check for any pre-existing gaps in the fuel column. Also, the fuel column length is monitored during loading and the as-loaded fuel rod weight is checked for each rod. These checks provide additional assurance that axial gaps will not occur in fabricated fuel rods.

In addition to pellet density, some other fuel bundle design changes that reduce the likelihood of cladding creep collapse include modified fuel bundle lattice configurations, i.e., 7x7 → 8x8 → 9x9 → 10x10, with successively increasing numbers of fuel rods and generally decreasing maximum linear heat generation rates (LHGRs), particularly with the change from the 7x7 → 8x8 lattice. Additionally, GNF fuel rods are pre-pressurized with helium to improve fuel-clad thermal gap conductance and overall thermal-mechanical performance. The pre-pressurization has increased significantly since the 1970's and is currently 10 atmospheres for the 9x9 and 10x10 lattices. The lower LHGRs, and resulting lower cladding temperatures, and higher rod internal pressure have combined to reduce the likelihood of creep collapse significantly for modern GNF fuel designs relative to earlier designs.

In summary, on the basis of (1) the evolution of GNF fuel designs in terms of pellet density, (2) the fabrication of GNF fuel pellets and the associated monitoring and control of the density and densification performance of these pellets, (3) the monitoring of rods during fabrication to assure that axial gaps do not occur in fabricated rods, and (4) the results of examinations of irradiated fuel rods, GNF concludes that the assumption of creep collapse of unsupported cladding due to large axial gaps in the fuel column is unnecessarily conservative for modern GNF fuel designs. The purpose of this report is to present a modified creep collapse analysis procedure based upon the characterized ex-reactor densification performance and observed in-reactor performance of current GNF fuel that

explicitly addresses the support provided by the fuel pellets (and other identified conservatisms) in the creep collapse calculation. To ensure that the modified analysis procedure remains valid, GNF plans to continue the monitoring programs discussed above.

3.2. Procedure

On the basis of the current pellet density specified for GNF fuel designs and the observed low ex-reactor and in-reactor densification of GNF fuel with this density, other design changes as discussed above, and the improved monitoring to assure that fuel column axial gaps due to fabrication are reliably detected, GNF proposes the following analysis procedure to determine whether cladding creep collapse will occur for a particular fuel design.

This proposed procedure is similar in concept to the current creep collapse analysis procedure; in fact, the creep and elastic stability calculations are performed using the same basic finite element based model. The major changes are that some of the assumptions regarding inputs to the analysis have been changed to reflect the current fabrication GNF fabrication processes and the current densification performance of GNF fuel. Specifically, because current fabrication processes and densification performance result in very short axial gaps in the fuel column, the assumption of unsupported cladding is not realistic. In the proposed procedure, an 'effective' coolant overpressure that accounts for support provided by the fuel pellets at either end of fuel column axial gaps is used. The basis for this effective pressure is presented in Appendix B. Appendix B also illustrates the calculation of this effective overpressure by application to the bounding fuel design defined in the next section of this report.

Also, the current formulation is based upon generic bounding operation, so the impact of the release of gaseous fission products during irradiation is not accounted for, since this release depends in large

part upon the specific operation of a rod. However, subsequent to the formulation of the current procedure, a large data base of fission gas release measurements has become available that indicates a small, but not negligible, fraction of the fission gas release is due to athermal mechanisms such as recoil and knockout [5]. This component of release is a function of exposure but is otherwise independent of operation. The impact of this component on rod internal pressure is addressed in the proposed procedure. The calculation of rod internal pressure due to athermal release is based upon the athermal fission gas release model in Reference [5]. This model has been reviewed and accepted by the NRC. Appendix C illustrates the calculation of the rod internal pressure due to athermal release by application to the bounding fuel design defined in the next section of this report.

Finally, the oxide thickness on the cladding outer surface is input as a function of time rather than as a single end of life value as in the current procedure. This capability has always existed, and has always been supported by GNF oxide measurements, which indicate a gradually increasing and predictable oxide thickness. One change is that the oxide thickness is based upon measurements of corrosion on GNF fuel with typical corrosion resistance in plants with normal water chemistry (data from plants in which corrosion excursions have occurred are not included in the data base used to derive the oxide thickness relation). Other assumptions in the current process remain unchanged, including the following:

The modified process is illustrated by application to an assumed bounding fuel design. Because of the assumed design parameters and operating conditions, the assumed design bounds existing GNF fuel designs through GE14 in terms of margin to calculated creep collapse. The assumed design also bounds the GNF2 fuel design, which is currently being designed and when licensed will replace GE14 as the 'standard' GNF reload design.

4. CREEP COLLAPSE ANALYSIS FOR BOUNDING FUEL DESIGN

The proposed creep collapse analysis procedure is illustrated by application of the procedure to an assumed bounding fuel design with the following design parameters and operating conditions:

Details and results of the analysis are presented in Appendix C. The results are summarized in Figure 2. As per the proposed modified analysis procedure, an overpressurization transient representing a core wide pressurization event is applied and removed at the end of operation. The cladding ovality is maximum at this point, due to the integrated creep over the entire operation, and the fact that the ovality returns to the value before application of the pressurization transient confirms that elastic or plastic instability does not occur, and thus that cladding creep collapse will not occur for the assumed bounding fuel design.

Figure 2
Results of Modified Creep Collapse Analysis Procedure for Bounding Fuel Design

5. *CONCLUSION*

GNF has proposed a modified creep collapse analysis procedure to confirm that cladding creep collapse does not occur. The modified procedure is similar to the current procedure except that some of the assumptions regarding inputs to the analysis have been changed to reflect the current fabrication GNF fabrication processes and the current densification performance of GNF fuel. GNF has applied the modified analysis procedure to a bounding configuration that covers all current and potential GNF fuel designs, including the new GNF2 fuel design scheduled to be introduced in reload quantities in 2005. Results of the analysis confirm that creep collapse will not occur.

If the densification performance or fabrication and monitoring processes upon which the modified procedure is based changes, the adequacy of the bounding analysis will be confirmed. If a possible new fuel design is not covered by the bounding analysis, either in terms of design parameters or proposed operation, the modified analysis procedure will be applied specifically to that design to confirm that creep collapse will not occur.

Appendix A: Neutrographs and Profilometry Results for GE11 Rod at Rod Average Exposure of ~56 GWd/MTU

A.1 Neutrographs (by section from bottom to top of rod)

Figure A1.1
GE11 Assembly YJ1433, UO_2 Rod D9, 56.0 GWd/MTU

Figure A1.1
GE11 Assembly YJ1433, UO_2 Rod D9, 56.0 GWd/MTU

Figure A1.1
GE11 Assembly YJ1433, UO_2 Rod D9, 56.0 GWd/MTU

Figure A1.1
GE11 Assembly YJ1433, UO_2 Rod D9, 56.0 GWd/MTU

Figure A1.1
GE11 Assembly YJ1433, UO_2 Rod D9, 56.0 GWd/MTU

A.2 Profilometry Data

Figure A2.1
Exposure and Fast Neutron Fluence Distribution at End of Life
Limerick 1 Assembly YJ1433, UO_2 Rod D9

Figure A2.2
Cladding Diameter Relative to Axial Position
Limerick 1 Assembly YJ1433, UO_2 Rod D9 at 56.0 GWd/MTU Average Exposure

Figure A2.3
Exposure and Fast Neutron Fluence Distribution at End of Life
Limerick 1 Assembly YJ1433, $(U,Gd)O_2$ Rod D8

Figure A2.4
Cladding Diameter Relative to Axial Position
Limerick 1 Assembly YJ1433, $(U,Gd)O_2$ Rod D8 at 47.8 GWd/MTU Average Exposure

Figure A2.5
Exposure and Fast Neutron Fluence Distribution at End of Life
Limerick 1 Assembly YJ1437, UO_2 Rod D1

Figure A2.6
Cladding Diameter Relative to Axial Position
Limerick 1 Assembly YJ1437, UO_2 Rod D1 at 69.6 GWd/MTU Average Exposure

Appendix B: Derivation of 'Effective' Cladding Overpressure

A tube subjected to a point loading around its circumference will deform under the point of loading and to some distance away from the point of loading. For a specific material and temperature, this distance is a function of the tube diameter and wall thickness. If the tube is supported within this distance, the deformation at the point of loading will be less than for an unsupported tube subjected to the same loading. For GNF fuel rods, this response is used in conjunction with the maximum axial gap anticipated in the fuel column to determine an effective loading that produces the same deformation in an unsupported tube as the actual loading produces in a tube supported by pellets at both ends of the axial gap. This effective loading is converted to an effective overpressure. The effective overpressure is then applied in the cladding creep collapse analysis, as illustrated in Appendix C. The calculation of effective overpressure is illustrated below for the bounding fuel design considered in Appendix C.

From Reference [6], for a tube subjected to a point loading P around its circumference, as shown in Figure B1(a), the displacement under the point of loading (x = 0) is given by

$$\delta_0 = \frac{P}{8\beta^3 D}(\text{inches})$$

and the displacement at a distance x from the point of loading is given by

$$\delta_x = \delta_0 \vartheta(\beta x)$$

where

$$D = \frac{Et^3}{12(1-\upsilon^2)}$$

$$\beta^4 = \frac{3(1-\upsilon^2)}{r^2 t^2}$$

r = tube radius (inches)

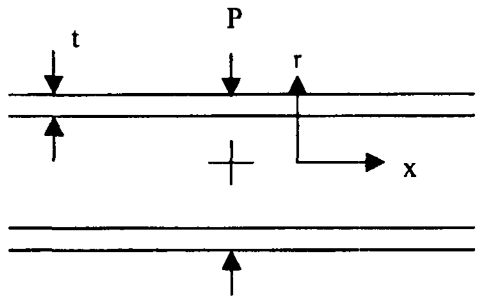
t = wall thickness (inches)

E = elastic modulus (psi)

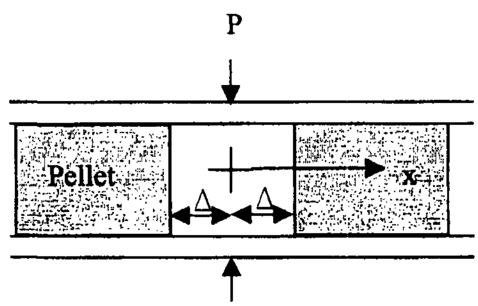
υ = Poisson's ratio

and

$$\vartheta(\beta x) = e^{-\beta x}(\cos(\beta x) + \sin(\beta x))$$



(a) Unfueled Tube



(b) Fueled Tube

Figure B1
Geometries for Effective Pressure Calculation

For a fueled tube with axial gap 2Δ between pellets, the pellets will provide support to the tube. Assuming that the tube and pellets are in contact at x = +/-Δ, as shown in Figure B1(b), the displacement under the point of loading will be

$$\delta_0' = \delta_0 - \delta_\Delta$$

where δ_Δ is the displacement that would occur at x = +/-Δ in an unfueled tube.

The derivation of effective overpressure for creep collapse summarized above includes the zirconium liner thickness in the value of wall thickness used in the calculation of the tube rigidity β. Since the derivation is based upon effective load and thus effective stress, and since the stresses during creep collapse are expected to be less than the yield strength of zirconium, except possibly at the end of operation when the ovality can become large, this is considered appropriate. Specifically, creep collapse is an integrated response over time, and any potential nonconservatism at the end of the analysis due to including the liner thickness in the analysis is more than compensated for by the integrated effects of the conservatisms noted above.

APPENDIX C: CREEP COLLAPSE CALCULATION FOR BOUNDING CONFIGURATION

C.1 Calculation of Rod Internal Pressure due to Athermal Fission Gas Release

From Reference [5], the athermal fission gas release fraction is given by

where

F = release fraction
E = (local) exposure (GWd/MTU)

For calculation of rod internal pressure due to athermal release, rod average exposure is most appropriate for calculation of F. For the bounding fuel design under consideration the peak peak exposure is 80 GWd/MTU and the corresponding rod average exposure is 70.2 GWd/MTU. Thus

indicating that at the end of operation of the fission gas atoms (primarily isotopes of xenon and krypton) generated by the fissioning process will have been released to the rod void space. Converting exposure in GWd/MTU to fissions and assuming that the yield of gas atoms is 0.3 atoms per fission [6], then the athermal release at end of operation is . For the design under consideration this corresponds to a rod internal pressure of at operating conditions.

C.2 Calculation of 'Effective' Overpressure for Creep Collapse

The initial helium fill gas pre-pressure is assumed to be at room temperature and at operating conditions. Thus the rod internal pressure due to the initial helium fill gas and athermal fission gas release is at start of operation and at end of operation. This result is applied in 2 equal time steps; the pressure for each step is taken to be the pressure at the midpoint of the step, as shown below. The corresponding actual overpressure and effective overpressure are also shown.

The effective overpressures for steps 1 and 2 are applied over the first half and second half of the creep collapse analysis, respectively. As noted below, at the end of operation, the effective overpressure is increased and then returned to the step 2 value to simulate an pressurization transient.

C.3 Oxide Thickness Calculation

The oxide thickness at end of operation is calculated on the basis of an oxide thickness model derived from measurements performed by GNF on fuel rod cladding under a range of operating conditions, including plant water chemistry. The model consists of an initial oxide thickness and an oxide rate. For the bounding design, the nominal oxide thickness is calculated to be inches at start of operation and inches at end of operation. This result is applied in 2 equal time steps; the oxide thickness for each step is taken to be the statistical 95/95 thickness at the end of the step.

C.4 Creep Collapse Analysis

The proposed creep collapse analysis procedure, including simulation of a pressurization transient at end of operation, is summarized in Figure C1. Application of the procedure yields tube ovality as a function of operating time, as shown in Figure 2. The sudden increase and subsequent decrease in ovality at the end of operation corresponds to simulation of the pressurization transient. As discussed below, the fact that the ovality returns to the value before simulation of the pressurization transient confirms that cladding creep collapse will not occur for the assumed bounding fuel design.

Figure C1
Proposed Modified Cladding Creep Collapse Analysis Procedure

C.5 Elastic Stability Calculation

Similarly to current creep collapse analysis procedure, the proposed modified analysis procedure includes application and removal of an overpressurization transient representing a core wide pressurization event at the end of operation. The cladding ovality is maximum at this point, due to the integrated creep over the entire operation, and if the ovality returns to the value before application of the pressurization transient, this confirms that elastic or plastic instability does not occur, and thus that cladding creep collapse will not occur for the assumed bounding fuel design.