U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

December 2008
Division 1

DRAFT REGULATORY GUIDE

Contact: J. Voglewede
(301) 251-7555

DRAFT REGULATORY GUIDE DG-1189

(Proposed Revision 2 of Regulatory Guide 1.126, dated March 1978)

AN ACCEPTABLE MODEL AND RELATED STATISTICAL METHODS FOR THE ANALYSIS OF FUEL DENSIFICATION

A. INTRODUCTION

This guide describes an analytical model and related assumptions and procedures that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable for predicting the effects of fuel densification in light-water-cooled nuclear power reactors. To meet these objectives, the guide describes statistical methods related to product sampling that will ensure that this and other approved analytical models will adequately describe the effects of densification for each initial core and reload fuel quantity produced.

The regulatory framework that the NRC has established for nuclear power plants consists of a number of regulations and supporting guidelines, including General Design Criterion 10, "Reactor Design," as set forth in Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," of the *Code of Federal Regulations* (10 CFR Part 50) (Ref. 1). Specifically, Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50 requires that the steady-state temperature distribution and stored energy in the fuel before a hypothetical loss-of-coolant accident (LOCA) be calculated, taking fuel densification into consideration.

The NRC issues regulatory guides to describe to the public methods that the staff considers

---

This regulatory guide is being reissued in draft form to continue involvement of the public in discussions on this topic. This version has not received final staff review or approval and does not represent an official NRC final staff position.

Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rulemaking, Directives, and Editing Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; emailed to nrcrep.resource@nrc.gov; submitted through the NRC's interactive rulemaking Web page at http://www.nrc.gov; faxed to (301) 415-5144; or hand-delivered to Rulemaking, Directives, and Editing Branch, Office of Administration, US NRC, 11555 Rockville Pike, Rockville, MD 20852, between 7:30 a.m. and 4:15 p.m. on Federal workdays. Copies of comments received may be examined at the NRC's Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by February 9, 2009.

Electronic copies of this draft regulatory guide are available through the NRC's interactive rulemaking Web page (see above); the NRC's public Web site under Draft Regulatory Guides in the Regulatory Guides document collection of the NRC's Electronic Reading Room at http://www.nrc.gov/reading-rm/doc-collections/; and the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under Accession No. ML081700257.

acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and conformity with them is not required.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

In-reactor densification (shrinkage) of oxide fuel pellets affects fuel temperatures in several ways—(1) gap conductance may be reduced because of the decrease in pellet diameter, (2) the linear heat generation rate is increased because of the decrease in pellet length, and (3) the decrease in pellet length may cause gaps in the fuel column and may produce local power spikes and the potential for cladding collapse. Dimensional changes in pellets in the reactor do not appear to be isotropic, so axial and radial pellet dimension changes will be treated differently. Furthermore, items (1) and (2) above are single-pellet effects, whereas item (3) is the result of simultaneous changes in a large number of pellets. These distinctions must be considered in applying analytical models.

The NRC staff has reviewed the available information concerning fuel densification. NUREG-0085, "The Analysis of Fuel Densification," issued July 1976, contains the technical basis for the regulatory position of this guide (Ref. 2). The model presented in Sections C.1 and C.2 of this guide is not intended to supersede NRC-approved vendor models.

The statistical methods (Section C.3), measurement methods (Section C.4), and isotropy assumptions (Section C.5) are compatible with most vendor models. Therefore Sections C.3, C.4, and C.5 could be applied to densification models that differ from the one presented in Sections C.1 and C.2.

C. REGULATORY POSITION

1. Maximum Densification

The density of a fuel pellet[†] in the reactor increases with burnup and achieves a maximum value at a relatively low burnup (generally less than 10,000 megawatt days per metric ton (MWd/t)). For analytical purposes, this maximum density minus the initial density (i.e., the maximum density change) is assumed to be the same as the density change that would occur outside the reactor in the same pellet during resintering ($\Delta\rho_{sntr}$) at 1700 °C (3092 °F) for 24 hours:[‡].

Where the ex-reactor resintering results in a negative density change (i.e., swelling), zero in-reactor densification should be assumed.

[†] The model presented in this guide is applicable to UO_2, UO_2-PuO_2, and UO_2-Gd_2O_3 fuel pellets.

[‡] The Terms of Equations at the back of this guide defines some of the terms and symbols used in this document.

2. Densification Kinetics

For pellets that have a resintering density change $\Delta\rho_{sntr}$ of less than 4 percent of theoretical density (TD), the in-reactor density change $\Delta\rho$ as a function of burnup (BU) may be taken as the following:

$$\Delta\rho = 0$$
(for BU < 20 MWd/t);
$$\Delta\rho = m \log(BU) + b$$
(for 20 < BU < 2000 MWd/t);

and

$$\Delta\rho = \Delta\rho_{sntr}$$
(for BU > 2000 MWd/t),

where the coefficients m and b are given by

$$0 = m \log(20) + b$$

and

$$\Delta\rho_{sntr} = m \log(2000) + b.$$

For pellets exhibiting a resintering density change in excess of 4-percent TD, the in-reactor density change as a function burnup may be taken as the following:

$$\Delta\rho = 0$$
(for BU < 5 MWd/t);
$$\Delta\rho = m \log(BU) + b$$
(for 5 < BU < 500 MWd/t);

and

$$\Delta\rho = \Delta\rho_{sntr}$$
(for BU > 2000 MWd/t),

where the coefficients m and b are given by

$$0 = m \log(5) + b$$

and

$$\Delta\rho_{sntr} = m \log(500) + b.$$

In applications of these equations, $\Delta\rho_{sntr}$ will have the value $\Delta\rho^{*}_{sntr}$ or $\Delta\rho^{**}_{sntr}$, which will be described in Section C.3. The burnup unit MWd/t in the above expressions is megawatt days per metric ton of heavy metal (uranium or uranium plus plutonium in mixed-oxide (MOX) fuels).

3. Statistical Methods

To apply the above model or any densification model that depends on an ex-reactor resintering density change, a random sample of the pellet population of interest should be resintered. Resintering the pellets in the sample will result in a set of density changes $\Delta\rho_{sntr}$. Several characteristics of these values are needed to complete the densification analysis.

The population of analytical interest may be composed of subsets of pellets from either a single material population or a group of material populations. A "material population" is defined as a group of pellets manufactured from a single powder source under the same range of fabricating conditions in such a manner that the pellets exhibit consistent resintering behavior. For those subsets taken from material populations that exhibit consistent resintering behavior, the sample data from the material population taken as a whole may be used to characterize the densification behavior of the subsets.

3.1 Single-Pellet Effects

Analyses of the effect of densification on stored energy and linear heat generation rate must account for pellets that have the greatest propensity for densification. To accomplish this with a resintering-based model such as that described in Sections C. 1 and C.2, a resintering density change value $\Delta\rho^{**}_{sntr}$ that conservatively bounds 95 percent of the population $\Delta\rho_{sntr}$ values with 95-percent confidence should be used. The population of analytical interest is the initial core loading or reload quantity of fuel for which the safety analysis, and hence the densification analysis, is being performed, and this population may be composed of subsets from a number of material populations. Once the material populations and their respective contributions (i.e., subsets) to the population of analytical interest are determined, random sampling procedures may be used to characterize the resulting population. When random sampling of the resulting population is not feasible, a conservative characterization may be obtained by using the largest of the characterizations of the contributing subsets.[§]

If the distribution of $\Delta\rho_{sntr}$ values of a population is normal, methods of evaluating normally distributed data may be used. If the "W" test or D' test (when 50 or more data points are used) (Ref. 3) demonstrates nonnormality at the 1-percent level of significance, nonparametric statistical methods should be used unless a different functional form can be satisfactorily justified to describe the distribution of the $\Delta\rho_{sntr}$ values. Thus $\Delta\rho^{**}_{sntr}$ is the upper one-sided 95/95 tolerance limit for the density changes and can be obtained from the sample values using one of the methods outlined below.

3.1.1 *Normal Distribution*

In this case, $\Delta\rho^{**}_{sntr}$ is given by the following:

$$\Delta\rho^{**}_{sntr} = \overline{\Delta\rho}_{sntr} + c's,$$

§ It is incorrect to prorate the characterizations of the contributing subsets by computing weighted averages over the subsets.

where $\overline{\Delta\rho}_{sntr}$ is the mean of the sample data, s is the standard deviation of the sample data, and c' is given in Table 1 (from Ref. 4).

Table 1 Values To Be Used for c' To Determine $\Delta\rho^{**}_{sntr}$ with Normal Distribution

Number of Observations	c'
4	5.15
5	4.20
6	3.71
7	3.40
8	3.19
9	3.03
10	2.91
11	2.82
12	2.74
15	2.57
20	2.40
25	2.29
30	2.22
40	2.13
60	2.02
100	1.93
200	1.84
500	1.76
∞	1.64

3.1.2 *Nonnormal Distribution*

In this case, $\Delta\rho^{**}_{sntr}$ is given by the following:

$$\Delta\rho^{**}_{sntr} = \Delta\rho^{(m)}_{sntr},$$

where $\Delta\rho^{(m)}_{sntr}$ is the mth largest $\Delta\rho_{sntr}$ value in a ranking of the observed values of $\Delta\rho_{sntr}$ from the sample. The integer m depends on the sample size according to Table 2 (from Ref. 5).

This method requires a minimum of 60 observations to produce a meaningful result.

Table 2 Values To Be Used for m To Determine $\Delta\rho_{sntr}^{**}$ with Nonnormal Distribution

Number of Observations	m
50	–
55	–
60	1
65	1
70	1
75	1
80	1
85	1
90	1
95	2
100	2
110	2
120	2
130	3
140	3
150	3
170	4
200	5
300	9
400	13
500	17
600	21
700	26
800	30
900	35
1000	39

3.2 Multiple-Pellet Effects

Average pellet behavior determines changes in fuel column length, which can result in axial gaps in the pellet stack. In this case, however, the population to be considered is not the core or reload quantity characterized above, but rather the material population (or subset thereof) within that quantity that exhibits the largest mean of the $\Delta\rho_{sntr}$ values from the sample. The distribution of $\Delta\rho_{sntr}$ values for the selected material population may be assumed to be normal.

To analyze effects related to column-length changes, resintering-based densification models should use a density change value $\Delta\rho_{sntr}^{*}$ that bounds the selected material population mean with 95-percent confidence. Thus, $\Delta\rho_{sntr}^{*}$ is the upper one-sided 95-percent confidence limit on the mean density change and can be obtained from the sample values using the following expression:

$$\Delta\rho^{*}_{sntr} = \overline{\Delta\rho'}_{sntr} + cs',$$

where $\overline{\Delta\rho'}_{sntr}$ is the mean of the sample data from the selected material population, s' is the standard deviation of the sample data from the selected material population, and c is given in Table 3 (from Ref. 4).

Table 3 Values To Be Used for c To Determine $\Delta\rho^{*}_{sntr}$

Number of Observations	c
4	1.18
5	0.95
6	0.82
7	0.73
8	0.67
9	0.62
10	0.58
11	0.55
12	0.52
15	0.45
20	0.39
25	0.34
30	0.31
40	0.27
60	0.22
100	0.17
200	0.12
500	0.07
∞	0

4. Measurement Methods

To measure the density change $\Delta\rho_{sntr}$ during resintering, either geometric or true densities may be used, so long as the same method is used before and after resintering. Techniques such as vacuum impregnation/water immersion, mercury immersion, gamma-ray absorption, and mensuration are acceptable. It is also acceptable to infer the density change from a diameter change, using the isotropic relation $\Delta\rho_{sntr} / \rho = 3\,\Delta D_{sntr} / D$, where ΔD_{sntr} is the diameter change experienced during resintering.

Resintering should be performed in a furnace with a known temperature distribution in the working region. Temperatures during resintering should be measured using either thermocouples or calibrated optical methods with established blackbody conditions. Furnace temperatures should be maintained so that specimen temperatures are no lower than the desired test temperature (1700 °C or

3092 °F for 24 hours in the model above) after temperature measurement errors have been taken into account.

In considering fuel stoichiometry, an oxygen-to-metal ratio of approximately 2.00 should be maintained. This may be accomplished by using dry tank hydrogen or dry gas mixtures (e.g., N_2-H_2) and avoiding temperatures in excess of about 1800 °C (3272 °F).

5. Isotropy Assumptions

To use predicted density changes in a calculation of the effects of in-reactor densification, it is necessary to make some assumption about the isotropy of fuel densification. For changes in pellet diameter D, isotropic densification may be assumed, so that $\Delta D/D = \Delta\rho/3\rho$. For changes in pellet or fuel column length L, anisotropic densification is assumed such that $\Delta L/L = \Delta\rho/2\rho$. For further discussion of the conservative nature of these assumptions, see Section III. D of NUREG-0085.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC's plans for using this draft regulatory guide. The NRC does not intend or approve any imposition or backfit in connection with its issuance.

The NRC has issued this draft guide to encourage public participation in its development. The NRC will consider all public comments received in development of the final guidance document. In some cases, applicants or licensees may propose an alternative or use a previously established acceptable alternative method for complying with specified portions of the NRC's regulations. Otherwise, the methods described in this guide will be used in evaluating compliance with the applicable regulations for license applications, license amendment applications, and amendment requests.

REGULATORY ANALYSIS

1. Statement of the Problem

In 1976, the NRC staff reviewed the available information concerning in-reactor densification of nuclear fuel. The current revision (Revision 1) of Regulatory Guide 1.126 (Ref. 6) reflected a refinement in NRC practice and superseded the previously accepted assumption that all fuels densify to a maximum density of 96.5 percent of their theoretical density as measured geometrically. The technical basis for the current regulatory position is contained in NUREG-0085. More recently, the following issues have emerged regarding continued implementation of this regulatory guide:

- *It is unclear whether the guidance on densification remains applicable to current fuel designs.*

  Comparison of more recent in-reactor densification and out-of-reactor resintering data has confirmed that densification in current fuel types is adequately represented by resintering data (particularly in MOX fuels) as described in Regulatory Guide 1.126.

  Recently, the NRC became aware that out-of-reactor densification of MOX may underestimate in-reactor densification for this fuel type. As a result, the NRC directed its contractor, Pacific

Northwest National Laboratory (PNNL), to review in-reactor densification data on MOX fuel as well as data from the associated thermal resintering test. These two data sets were compared to determine if the standard resintering test specified in Regulatory Guide 1.126 is applicable to MOX fuel.

In Reference 7, PNNL describes the data comparisons and results of its reexamination of the applicability of the standard resintering test to MOX fuel. The laboratory concludes that, "despite limited experimental data and opposing views regarding the mechanisms of in- and out-of-reactor densification of MOX, there is evidence that the values obtained from the out-of-reactor tests are equivalent to the maximum densification observed in reactor." Consequently, the NRC staff is not proposing a change in the applicability of Regulatory Guide 1.126.

- *Since Regulatory Guide 1.126 deals more with statistical analysis than densification, it may be more appropriate to promulgate this guidance elsewhere than among Division 1 (Power Reactor) regulatory guides.*

  While it is true that Regulatory Guide 1.126 deals more with statistical analysis than with densification, this is not the case within the technical basis for the regulatory position (Ref. 2). Regulatory Guide 1.126 deals with a process (densification) that occurs in fresh fuel during each core reload. Further, large populations (millions of fuel pellets) are involved for which statistical methods are highly appropriate. For these reasons, the NRC anticipates no change in the placement of this regulatory guide or its composition.

- *In considering single-pellet effects, Regulatory Guide 1.126 requires a density change that bounds 95 percent of the population with 95-percent confidence. In analysis of the LOCA, this may unfairly promote independent and simultaneous application of maximum uncertainties from other sources considered in the safety analysis.*

  Regulatory Guide 1.126 provides statistically appropriate guidance for single- and multiple-pellet effects. It does not (correctly) provide guidance on how these uncertainties must be combined or convoluted with uncertainties from other portions of the LOCA analysis. This issue is subject to review in the staff's evaluation of LOCA analysis methods rather than in the evaluation of conformity with the provisions of Regulatory Guide 1.126.

- *Modern fuel types are less prone to densification, and the problems associated with densification, than those used at the time of the first publication of Regulatory Guide 1.126. The guidelines provided in the guide may no longer be necessary.*

  The model and methods described in Regulatory Guide 1.126 are applicable to fuel materials exhibiting low in-reactor density change. Conformity with the guidance does not justify elimination of the guidance.

- *The technical references used in Regulatory Guide 1.126 are old and difficult to obtain. This suggests that the guidance itself may be obsolete.*

  The statistical guidance provided in Regulatory Guide 1.126 is not obsolete. To minimize the need for external sources, the tables in the guide incorporate pertinent information. The same information is available from more current sources.

2. Objective

The objective of this regulatory action is to confirm that existing guidance on in-reactor densification remains applicable to current fuel designs.

3. Alternative Approaches

In conducting this review, the NRC staff considered the following alternative approaches:

- Do not reissue Regulatory Guide 1.126.
- Reissue unmodified Regulatory Guide 1.126.
- Update Regulatory Guide 1.126.

3.1 Alternative 1: Do Not Reissue Regulatory Guide 1.126

Under this alternative, the NRC would not revise this guidance, and the original version (Revision 1) of this regulatory guide would continue to be used. This alternative is considered the baseline or "no action" alternative and, as such, involves no value/impact considerations.

3.2 Alternative 2: Reissue Unmodified Regulatory Guide 1.126

Under this alternative, the NRC would reissue Regulatory Guide 1.126, with consideration of more recent information on in-reactor densification but without substantive changes in the existing technical guidance. This alternative would reformat the regulatory guide document and reconfirm the existing regulatory approach to this issue. The cost of reissuing a reformatted document is expected to be relatively small. Applicants and existing licensees would incur little or no additional cost because the technical requirements would remain unchanged.

3.3 Alternative 3: Update Regulatory Guide 1.126

Under this alternative, the NRC would update and reissue Regulatory Guide 1.126, with consideration of recent information, particularly about the manner in which other parts of the safety analysis use resintering data. One benefit of this action is that it would enhance reactor safety by ensuring regulatory consistency. However, the cost to licensees would be significant because it would involve reanalysis using revised methods. The impact to the NRC would be the significant costs associated with preparing and issuing the revised regulatory guide. The impact to the public would be the voluntary costs associated with reviewing and providing comments to NRC during the public comment period.

4. Conclusion

Based on the review described previously, the staff recommends Alternative 2, the NRC reissue of the reformatted but technically unmodified Regulatory Guide 1.126. The staff concludes that the proposed action would maintain the existing level of reactor safety. This alternative would result in no additional costs to the industry because the technical requirements would remain unchanged.

TERMS USED IN EQUATIONS

The following identifies the major symbols used in Section C:

BU burn up unit expressed in megawatt days per metric ton of heavy metal (MWd/t)

c, c' population parameters in Tables 1 and 3

D nominal initial pellet diameter, centimeters (cm)

L nominal fuel column length, cm

m population parameter from Table 2

s standard deviation of the sample data

s' standard deviation of the sample data from the selected material population

TD theoretical density, grams per cubic centimeter (g/cm^3)

ΔD in-reactor pellet diameter change (function of burnup), cm

ΔD_{sntr} measured diameter change of a pellet resulting from ex-reactor resintering, cm

ΔL in-reactor fuel column length change (function of burnup), cm

$\Delta \rho$ in-reactor pellet density change (function of burnup), g/cm^3

$\Delta \rho_{sntr}$ measured density change of a pellet resulting from ex-reactor resintering, g/cm^3

$\overline{\Delta \rho}_{sntr}$ mean of the measured density change data, $\Delta \rho_{sntr}$, g/cm^3

$\overline{\Delta \rho}'_{sntr}$ mean of a selected material population of the measured density data, $\Delta \rho_{sntr}$, g/cm^3

$\Delta \rho^{*}_{sntr}$ one-sided 95-percent upper confidence limit on the mean of the $\Delta \rho_{sntr}$ values from the selected material population, g/cm^3

$\Delta \rho^{**}_{sntr}$ one-sided 95/95 upper tolerance limit for the total population of $\Delta \rho_{sntr}$ values, g/cm^3

ρ nominal initial pellet density, g/cm^3

REFERENCES

1. 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," U.S. Nuclear Regulatory Commission, Washington, DC.

2. NUREG-0085, "The Analysis of Fuel Densification," R.0. Meyer, U.S. Nuclear Regulatory Commission, Washington, DC, July 1976.

3. ANSI Standard N15.15-1974, "Assessment of the Assumption of Normality (Employing Individual Observed Values)," American National Standards Institute.

4. G.J. Hahn, "Statistical Intervals for a Normal Population, Part I. Tables, Examples and Applications," J. Quality Technol. 2, 115, 1970.

5. P.N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits," Ann. Math. Stat. 29, pp. 599–601, 1958.

6. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.126, "An Acceptable Model and Related Statistical Methods for the Analysis of Fuel Densification," Washington, DC.

7. W.G. Luscher (PNNL) letter to J.C. Voglewede (NRC) on "Densification in MOX Fuel," January 7, 2008.