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

A. INTRODUCTION

Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," 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. This guide provides an analytical model and related assumptions and procedures that are acceptable to the NRC staff for predicting the effects of fuel densification in light-water-cooled nuclear power reactors. The guide also describes statistical methods related to product sampling that will provide assurance that this and other approved analytical models will adequately describe the effects of densification for each initial core and reload fuel quantity produced.

* The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position.

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 pellet-length decreases 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 taken into account in applying analytical models.

The NRC staff has reviewed the available information concerning fuel densification, and the technical basis for the regulatory position of this guide is given in Reference 1. 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 <10,000 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 $\Delta\rho_{sntr}$ that would occur outside the reactor in the same pellet during resintering at 1700°C for 24 hours.

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

* Lines indicate substantive changes from previous issue.

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

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Comments and suggestions for improvements in these guides are encouraged at all times, and guides will be revised, as appropriate, to accommodate comments and to reflect new information or experience. This guide was revised as a result of substantive comments received from the public and additional staff review.

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2. Densification Kinetics

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

$$\Delta\rho = 0 \quad \text{(for BU} \leq 20 \text{ MWd/t);} \tag{1a}$$

$$\Delta\rho = m \log(BU) + b \quad \text{(for } 20 < BU < 2000 \text{ MWd/t);} \tag{1b}$$

and

$$\Delta\rho = \Delta\rho_{sntr} \quad \text{(for BU} \geq 2000 \text{ MWd/t),} \tag{1c}$$

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% TD, the in-reactor density change as a function burnup may be taken as

$$\Delta\rho = 0 \quad \text{(for BU} \leq 5 \text{ MWd/t);} \tag{2a}$$

$$\Delta\rho = m \log(BU) + b \quad \text{(for } 5 < BU < 500 \text{ MWd/t);} \tag{2b}$$

and

$$\Delta\rho = \Delta\rho_{sntr} \quad \text{(for BU} \geq 500 \text{ MWd/t),} \tag{2c}$$

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 Equations 1 and 2, $\Delta\rho_{sntr}$ 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 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.

a. 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% of the population $\Delta\rho_{sntr}$ values with 95% 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. 2) demonstrates nonnormality at the 1% 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.

(1) *Normal Distribution*. In this case, $\Delta\rho^{**}_{sntr}$ is given by

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

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. 3).

† Symbols are defined in the List of Symbols at the back of this guide.

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

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

(2) *Nonnormal Distribution*. In this case $\Delta\rho^{**}_{sntr}$ is given by

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

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. 4).

Note that a minimum of 60 observations is required to produce a meaningful result by this method.

b. Multiple-Pellet Effects

Fuel-column-length changes, which can result in axial gaps in the pellet stack, are determined by average pellet behavior. 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% confidence. Thus $\Delta\rho^{*}_{sntr}$ is the upper one-sided 95% confidence limit on the mean density change and can be obtained from the sample values using the expression:

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

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

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. 3).

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 so maintained that specimen temperatures are no lower than the desired test temperature (1700°C in the model above) after temperature measurement errors have been taken into account.

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

Fuel stoichiometry (O/M ≈ 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 ~1800°C.

5. Isotrophy Assumptions

In order 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 $\Delta L/L = \Delta\rho/2\rho$.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

This guide reflects a refinement in NRC practice and supersedes the previously accepted assumption that all fuels densify to a maximum density of 96.5% of their theoretical density as measured geometrically. Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein should be used in submittals for construction permit, operating license, and reload applications until this guide is revised as a result of suggestions from the public or additional staff review.

REFERENCES

1. R. O. Meyer, "The Analysis of Fuel Densification," USNRC Report NUREG–0085, July 1976.

2. "American National Standard Assessment of the Assumption of Normality (Employing Individual Observed Values)," ANSI Standard N15.15–1974.

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

4. P. N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits," Ann. Math., Stat. 29, 599 (1958).

LIST OF SYMBOLS

The major symbols used in Sections C.1 through C.5 are identified below:

BU	Burnup, MWd/t.
D	Nominal initial pellet diameter, cm.
L	Nominal initial pellet length, cm.
TD	Theoretical density, g/cm^3.
ΔD	In-reactor pellet diameter change (function of burnup), cm.
ΔD_{sntr}	Measured diameter change of a pellet due to ex-reactor resintering, cm.
ΔL	In-reactor pellet 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 due to ex-reactor resintering, g/cm^3.
$\Delta\rho^{*}_{sntr}$	One-sided 95% 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.