U.S. NUCLEAR REGULATORY COMMISSION

March 1977

REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 1.126

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.

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/tU). 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.

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**

*The model presented in this guide is applicable only to UO_2 fuel pellets.

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

$$\Delta\rho = 0 \quad \text{(1a)}$$

(for BU $\leqslant$ 20 MWd/tU);

$$\Delta\rho = m \log(BU) + b \quad \text{(1b)}$$

(for 20 < BU < 2000 MWd/tU);

and $$\Delta\rho = \Delta\rho_{sntr} \quad \text{(1c)}$$

(for BU $\geqslant$ 2000 MWd/tU),

where the coefficients m and b are given by

$$0 = m \log(20) + b \text{ and}$$

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

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

$$\Delta\rho = 0 \quad \text{(2a)}$$

(for BU $\leqslant$ 5 MWd/tU);

$$\Delta\rho = m \log(BU) + b \quad \text{(2b)}$$

(for 5 < BU < 500 MWd/tU);

and $$\Delta\rho = \Delta\rho_{sntr} \quad \text{(2c)}$$

(for BU $\geqslant$ 500 MWd/tU),

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/tU in the above expressions is megawatt days per metric ton of heavy metal (uranium).

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 must 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.

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 interest is the initial core loading or reload quantity of fuel for which the safety analysis, and hence the densification analysis, is being performed. If the distribution of $\Delta\rho_{sntr}$ values is normal, methods of evaluating normally distributed data may be used. If the "W" test (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).

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 m^{th} 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).

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

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 pellet lot within that quantity that exhibits the largest mean of the $\Delta\rho_{sntr}$ values from the sample. A pellet lot is defined as a group of pellets made from a single UO_2 powder source that has been processed under the same conditions. The distribution of $\Delta\rho_{sntr}$ values for the selected pellet lot is 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 pellet lot 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:

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

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

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 laboratory-quality 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 black-body conditions. Furnace temperatures should be so maintained that true 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.

Fuel stoichiometry (O/M ≈ 2.00) should be maintained by using dry tank hydrogen or dry gas mixtures (e.g., N_2-H_2) and avoiding temperatures in excess of ~1800°C.

5. Isotropy 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 will be used in the evaluation of submittals for construction permit, operating license, and reload applications docketed after November 1, 1977, unless this guide is revised as a result of suggestions from the public or additional staff review. If for any reason the effects of fuel densification are reanalyzed for fuel covered in an application docketed on or before November 1, 1977, the method described in this guide would *not* be necessary and previously approved assumptions would be allowed for that fuel.

If an applicant wishes to use this regulatory guide in developing submittals for applications docketed on or before November 1, 1977, the pertinent portions of the application will be evaluated on the basis of this guide.

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. 115 (1970).

4. P. N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits," Ann. Math. Stat. 29, 559 (1958).

LIST OF SYMBOLS

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

BU	Burnup, MWd/tU.
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 lot, 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.