DEC 14 1973

Docket No. 50-219

Jersey Central Power & Light Company
ATTN: Mr. I. R. Finfrock, Jr.
Vice President - Generation
Madison Avenue at Punch Bowl Road
Morristown, New Jersey 07960

Change No. 18
License No. DPR-16

Gentlemen:

Your letter dated December 14, 1973, proposed changes to the Technical Specifications of Facility License No. DPR-16 for the Oyster Creek Nuclear Generating Station that would increase the maximum average planar linear heat generation rate (MAPLHGR). These changes in the MAPLHGR are the result of changes in the fuel densification models by the General Electric Company as reported in NEDO-20181, "GEGAP III A Model for Prediction of Pellet-Clad Thermal Conductance in BWR Fuel Rods" (Proprietary) dated November 1973 and by EXXON Nuclear Company as reported in XN-174, November 1973. Modifications to the proposed models were made by the Regulatory staff and transmitted to you by letters dated December 5, 1973, and December 13, 1973. The changes in the fuel densification models provide for an exposure dependent gap conductance, and time-dependent fuel densification.

The attached Safety Evaluations entitled "Supplement 1 to the Technical Report on Densification of General Electric Reactor Fuels" and "United States Atomic Energy Commission, Safety Evaluation by the Directorate of Licensing, Docket No. 50-219, Jersey Central Power & Light Company, Proposed Changes to the Technical Specifications, Effects of Changing the Pellet-Clad Thermal Conductance, December 14, 1973, reflect the Regulatory staff's position that the MAPLHGR may be increased in a manner similar to that indicated in your letter of December 14, 1973.

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On December 13, 1973, Friends of the Earth filed a "Request for Decision" with respect to its petition for derating nine BWRs including Oyster Creek Nuclear Generating Station. Pending resolution of this matter by the Commission, no change in the technical specifications should be effected.

Sincerely,

Original signed by
Donald J. Skovholt

Donald J. Skovholt
Assistant Director
for Operating Reactors
Directorate of Licensing

Enclosures:
1. Supplement 1 to Technical Report
2. Safety Evaluation

cc w/enclosures:

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910 - 17th Street, N. W.
Washington, D. C. 20006

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UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

December 14, 1973

Docket No. 50-219

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ATTN: Mr. I. R. Finfrock, Jr.
Vice President - Generation
Madison Avenue at Punch Bowl Road
Morristown, New Jersey 07960

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UNITED STATES ATOMIC ENERGY COMMISSION

SAFETY EVALUATION BY THE DIRECTORATE OF LICENSING

DOCKET NO. 50-219

JERSEY CENTRAL POWER & LIGHT COMPANY

PROPOSED CHANGES TO THE TECHNICAL SPECIFICATIONS

EFFECTS OF CHANGING THE PELLET-CLAD THERMAL CONDUCTANCE

DECEMBER 14, 1973

On August 24, 1973, Change No. 16 to the Technical Specifications, Appendix A of the Provisional Operating License DPR-16 for Oyster Creek Nuclear Generating Station was issued to account for the effects of fuel densification in boiling water reactor fuel. The background analyses and references pertinent to that change were included in the AEC Regulatory staff report, "Technical Report on Densification of General Electric Reactor Fuels," dated August 23, 1973, "Technical Report on Densification of EXXON Nuclear BWR Fuels", dated September 4, 1973, and the AEC Regulatory staff report, "Safety Evaluation of the Fuel Densification Effects on the Oyster Creek Nuclear Generating Station", dated August 24, 1973.

On November 16, 1973, Change No. 17 to the Technical Specifications, Appendix A of the Provisional Operating License DPR-16 for Oyster Creek Nuclear Generating Station was issued. This change resulted from the removal of a 100°F penalty that we had applied to the peak cladding temperature for the EXXON Type III E fuel. This penalty was removed based on our evaluation of the licensee's submittals dated September 7, and November 5, 1973.

Subsequently, General Electric (GE) submitted a report NEDO-20181, "GEGAP III A Model for the Prediction of Pellet-Clad Thermal Conductance in BWR Fuel Rods", November 1973, with related proprietary information provided in NEDC-20181 Supplement I (Proprietary), November 1973, and EXXON submitted a report XN-174, "Densification Effects on EXXON Nuclear Boiling Water Reactor Fuel", November 1973. The AEC Regulatory staff has reviewed the GEGAP III model and has issued the report entitled

"Supplement 1 to the Technical Report on Densification of General Electric Reactor Fuels" dated December 14, 1973. The AEC Regulatory staff has reviewed the GAPEXX model submitted as part of XN-174 and will issue a report entitled "Supplement 1 to the Technical Report on Densification of EXXON Nuclear BWR Fuels" on December 17, 1973. On December 5 and 13, 1973, letters were sent requesting that Jersey Central Power & Light Company provide the necessary analyses and other relevant data needed to determine the consequences of densification and its effect on normal operation, transients, and accidents using the enclosures, "Modified GE Model for Fuel Densification" and "Modified EXXON Model for Fuel Densification". The licensee provided an analysis of the effect of densification on normal operations, transients, and accidents for the Oyster Creek Nuclear Generating Station in their letter of December 14, 1973.

The "Modified GE Model for Fuel Densification" and the "Modified EXXON Model for Fuel Densification" result in an increase in the pellet-clad thermal conductance. This increase results in a decrease in the stored energy of the fuel rods. The pellet-clad thermal conductance value lies between the value used in the FSAR and the value used in the staff evaluation of August 23, 1973. The results of using the gap conductance from the modified versions of GEGAP III and GAPEXX in the analysis of normal operation and transients is to produce results between those evaluated in the FSAR and those used in the staff evaluation of August 23, 1973. Therefore, it is concluded that the change has essentially no effect on normal operation and improves the margins to pressure and minimum critical heat flux ratio limits for overpressurization and core flow reduction transients.

The increase in pellet-clad thermal conductance would reduce the consequences of the design basis loss-of-coolant accident assuming a constant linear heat generation rate. The reduction would occur during the heatup phase of the accident as a result of the decreased initial stored energy. However, the stored energy is also dependent on the linear heat generation rate of the fuel. A reduction in stored energy then allows a compensating increase in linear heat generation rate, such that operating flexibility is increased while compliance with the Interim Acceptance Criteria is still maintained. The limit curves for MAPLHGR specified in this change represent the most limiting of three limits: MCHFR, cladding strain, and peak clad temperature following LOCA. The staff concludes that the limitations of the average linear heat generation rate of all rods in any fuel assembly at any axial location to the values of the curves on the revised Figure 3.10.1 of the licensee's proposed changes to the Technical Specifications combined with the linear heat generation rate limitations of current technical specifications will assure that the calculated peak clad temperatures will not exceed 2300°F.

Based on the above, it is concluded that there is a reasonable assurance that the proposed changes to the maximum average planar linear heat generation rates for Oyster Creek can be made without endangering the health and safety of the public.

* * *

SUPPLEMENT 1

TO THE

TECHNICAL REPORT ON

DENSIFICATION OF GENERAL ELECTRIC REACTOR FUELS

December 14, 1973

REGULATORY STAFF

U.S. ATOMIC ENERGY COMMISSION

TABLE OF CONTENTS

1.0 INTRODUCTION

Since the first observation of collapsed fuel rods at the Ginna Plant in 1972, the Staff has performed an intensive study of the cause of axial gap formation in reactor fuel rods and of the effects of fuel densification on reactor operations. The results of the study were published on November 14, 1972, in a generic review entitled, "Technical Report on Densification of Light Water Reactor Fuels,"[1] Based on these findings, the Staff requested on November 20, 1972, that applicants for licenses and licensees of light water reactors (both PWRs and BWRs) provide analyses of the effects of fuel densification on normal operation, transients and accidents. On January 17, 1973, the General Electric Company (GE) filed a generic report[2]: "Densification Considerations in BWR Fuel Design and Performance," NEDM-10735, which was applicable to all GE BWRs. The staff review of this report and the first supplement to this report resulted in two sets of questions which were mailed to GE on March 14, 1973 and April 27, 1973. The GE responses to the Staff requests are documented in five proprietary supplements to NEDM-10735 (see references 3 to 7). The supplements were filed in April, May, June, and July, 1973. respectively.

After an in-depth review of the above submittals, the Staff issued a report, "Technical Report on Densification of General Electric Reactor Fuels," on August 1973[8]. The Staff concluded in the report that the model proposed by GE failed to represent the time dependency of fuel densification and gap conductance and reflected a general lack of controlled test data to describe the densification mechanism. Because of these difficulties the Staff required that a conservative model be used to evaluate the effects of fuel densification.

The required assumptions in the conservative model were described in detail in the staff report[8] . In that model the instantaneous geometric densification to 96.5% of theoretical density was assumed to occur. In addition, due to the lack of data submitted by GE on the irradiation growth of their zircaloy cladding, the use of a conservative value of 0.4% for the amount of irradiation growth was required. Both of these requirements were in conformance with the model defined in the November 14, 1972 AEC report on densification (reference 1). Also at that time GE did not have the capability of calculating the fuel-cladding gap conductance as a function of burnup (time) and therefore was required to use a single value for gap conductance obtained from a curve based on available experimental data that predicted gap conductance vs linear heat generation rate (LHGR) with 95 percent confidence that 90 percent of future events would exceed the predictions. This value was selected to ensure that it would be sufficiently conservative throughout fuel exposure lifetime so that gap conductance as a function of burnup would not be of safety concern.

Since August 1973, GE has accumulated data on the time dependence and the amount of densification likely to occur in their fuel, and on the amount of irradiation growth experienced by their cladding; and has developed a computer code to evaluate fuel rod thermal performance. The computer code ("GEGAP-III: A Model for the Prediction of Pellet-Cladding Thermal Conductance in BWR Fuel Rods") was formally submitted to the staff for review on December 3, 1973.[9] Table 1.1 presents a list of the significant milestones which occurred in the staff's review of the GE experimental data and analytical models upon which calculations of GE fuel densification are based. In the new report on GEGAP-III, General Electric presented a model which provides an exposure-dependent gap conductance. The new model incorporates time-dependent fuel densification, time-dependent gap closure, and gap closure effects due to cladding creepdown.

GEGAP-III calculates the steady-state thermal performance of a fuel rod. This information is used as input for calculations of peak cladding temperature during loss-of-coolant accidents. The staff has reviewed this new model and has concluded that although certain changes are required, the basic model could be substituted for items required in reference 1. GE incorporated the required changes in the code and submitted calculations of plant behavior using the modified code in a supplement[10] to the AEC on December 12, 1973.

This report presents the Staff's evaluations, conclusions, and recommendations of the GEGAP-III report and its supplement. The results presented in this report are applicable to all current design GE BWRs. It is intended to be self contained even though it is issued as a supplement to the original staff report.[8] The output of the thermal performance code is an input to transient and accident calculations. Since changes were proposed in the transient and accident analysis models, they are not addressed in this report.

TABLE 1.1

CHRONOLOGY OF EVENTS IN THE STAFF REVIEW OF THE GE FUEL DENSIFICATION MODEL

DATE	MILESTONE
1. 8/30/73	Planning Meeting at Bethesda for Fuel Densification Model Development and review
2. 9/7/73	GE-AEC Technical Discussion at Bethesda
3. 9/19/73	Densification discussion with GE and AEC consultant at MIT, Boston, Mass.
4. 10/2/73	Letter GE Hinds to AEC Stello. Receipt of Additional Material on cladding collapse.
5. 10/2-10/3/73	Densification-thermal performance meeting at GE in San Jose, Calif.
6. 10/15/73	Meeting at San Jose, Calif. to discuss BUCKLE and GE Creep Collapse Model.
7. 11/9/73	Meeting at Bethesda to discuss current status of GE Densification program.
8. 11/15/73	Letter to GE requesting sample calculations for cladding creep-down.
9. 11/21/73	Staff observed resintering test and calibration of input to GEGAP-III, San Jose, Calif.
10. 12/3/73	Receipt of GEGAP-III, Supplement 1, NEDC-20181, by Staff.
11. 12/12/73	Letter GE Hinds to AEC Moore, Plant Evaluation for GEGAP-III, December 12, 1973.

2.0 THE GENERAL ELECTRIC FUEL DENSIFICATION MODEL

2.1 General

Fuel densification in reactor fuel rods causes the fuel rods to contain more stored energy, increases linear heat generation rates in the fuel rods, decreases the heat transfer capability of the fuel rods, and creates the potential (if axial gaps are formed in the fuel column) for local power spikes and for cladding collapse. In safety evaluations of power reactors, it is necessary to consider these effects of fuel densification in the analyses made for all modes of reactor operation. These include normal operation, operation during various transient conditions, and postulated accident situations, including the postulated loss-of-coolant accident (LOCA).

In Section 2.2, a linear heat generation model of densified fuel is discussed. Fuel column gap formation and its effect on the power spike model is discussed in Section 2.3.

Calculational methods for the cladding creepdown and collapse are covered in Section 2.4. In section 2.5, GEGAP-III and its supplement are described and evaluated. This section includes fuel densification and pellet relocation models, gap conductance changes and presents comparisons of GEGAP-III calculations with experimental data. Section 3.0 discusses the effects of fuel densification on BWR safety analyses. Finally, the Staff conclusions and recommendations are given in Section 4.0.

2.2 Linear Heat Generation Rate Model

The linear heat generation rate model to accommodate dual densification is the same as previously described in reference 8.

2.3 Power Spike Model

The General Electric Power Spike Model is unchanged from the model presently used by General Electric and described in reference 8 except that the irradiation growth of the cladding was decreased from the staff value of 0.4% used in reference 1 to 0.25%.

The new irradiation growth factor of 0.25% is based on data presented in reference 30. It is based on measurements on 32-mil and 40-mil-thick BWR cladding from Big Rock Point, Humboldt Bay and Dresden 2 reactors. The staff has examined this data and concluded that a value of 0.25% is justified for use in calculating gap size.

2.4 Mechanical Integrity of Cladding

2.4.1 General

Cladding creepdown and creep-collapse are two phenomena that affect the mechanical behavior of the fuel assembly. Although both phenomena involve creep mechanisms, their effect on fuel behavior and the manner in which they are analyzed differ significantly.

2.4.2 Creepdown

Clad creepdown is tha term used to indicate a phenomenon that affects the size of the radial gap between the fuel pellets and the cladding.

Clad creepdown is a relatively slow inward motion of the clad toward the fuel pellet such that there is a reduction in the gap with a resulting increased gap conductance.

The form of the GE model is based upon theoretical considerations from the open literature which are generally accepted. The form has been compared both with the open literature and with GE proprietary data to determine the magnitude of various constants. The resultant model is an empirical expression for the time-dependent plastic strain of the fuel cladding.

The staff has reviewed the GE creep expression as applied to calculating gap closure in thermal conductance predictions. The staff concludes that the form of the expression is satisfactory. However, the differences between the predicted and the measured creep in the data (reference 29) require that a factor be applied to the predicted creepdown. Therefore, it is required that the predicted creep values be multiplied by 0.31 when applied to calculate gap closure. The use of this factor lowers the difference between predicted and measured creep value such that about 95% of the data would be underpredicted. This may be compared with the unmodified creep expression, for which 17% of the data would be underpredicted. It is expected that with submittal of more data and continued evaluation this factor may be modified to be less restrictive.

2.4.3 Creep Collapse

A description of the cladding creep model and its implication to the safety are discussed in Reference 8. Also in the same reference, the experience of the BWR fuel is discussed and it is concluded that the BWR cladding is not likely to collapse into a fuel gap caused by fuel densification, especially early in life. The Staff concluded that even though collapse later in life does not appear to be a problem, an analytic model should be developed to show that no collapse will occur. At present, GE is developing a collapse model and will submit it for review at a later date. Therefore, no review on the subject is included in this report. Each applicant is required to submit justification for the effects of creep collapse on each plant analyzed until such a model is approved by the staff.

2.5 FUEL CLADDING GAP CONDUCTANCE

2.5.1 General

Gap conductance is a measure of the resistance to the flow of heat from the fuel pellet to the fuel rod cladding, and thence to the coolant. It has an important effect on the temperature, and therefore on the stored energy of the fuel. The stored energy is important in both steady-state and transient reactor analyses but is primarily of concern in the postulated loss-of-coolant accident analyses discussed in Section 3. since stored energy has a large effect on the cladding temperature reached during this postulated accident.

Densification of the fuel increases the radial gap between the fuel pellet and the cladding. This causes a decrease in the gap conductance and a corresponding increase in the stored energy of the fuel.

The previous General Electric model for calculating gap conductance was based on a curve of gap conductance as a function of linear heat generation rate. It was derived from a curve fit through experimental gap conductance data such that the predicted gap conductance was below 95% of the experimental data points 90% of the time. The model was independent of exposure (burnup).

General Electric has proposed to calculate the gap conductance and fuel pellet stored energy by means of a fuel rod thermal performance computer program, GEGAP-III. By means of this program, the thermal performance of a BWR fuel rod can be followed for all power levels and burnups of interest. To do this the calculations must include fuel and cladding thermal expansion, fuel irradiation swelling, fission and sorbed gas release from the fuel, and flux depression effects in the fuel.

In addition to these effects, GEGAP-III also includes mathematical models to account for both the kinetics and extent of fuel densification and fuel pellet relocation.

2.5.2 Densification of Uranium Dioxide

In the GE model approved previously it was assumed that[8] densification of all fuel occurs instantaneously, increasing the geometric fuel density to 96.5% of theoretical density (TD) in accordance with the earlier AEC guidelines.[1] In the present GE model, GEGAP-III,[9] time-dependent densification kinetics are obtained from a theoretical model,[11] which is verified by comparison with recent in-reactor experimental results.

The theoretical densification kinetics model used in GEGAP-III was reported earlier by Marlowe.[11] In the original report,[11] and also in Appendix D of the GEGAP-III report, both densification and fuel swelling are included. However, in the GEGAP-III program, the fuel swelling component is handled separately as described in section 3.1.4.3 of reference 9. Therefore, the densification portion in section 3.2 "Densification Kinetics", is used, and the discussions here will be directed toward that portion of the model.

The densification model is based on a modified form of Coble's thermally-activated-sintering model, which in the modified form can be represented as

$$\Delta\rho = - (M/A) \ln (1 + ADt/G_o^3). \qquad (1)$$

In Equation (1), $\Delta\rho$ is the density change that occurs in time t, D is the applicable diffusion coefficient, G_o is the initial grain size, and M and A (defined below) are rate parameters for representative fuel obtained from measurements on archive or production fuel material. Equation (1) is converted for in-reactor application by replacing the thermal diffusion coefficient D with a radiation-induced diffusion coefficient $D_{irr} = D^{\circ}_{irr} \dot{F}$, where $\dot{F}$ is the fission rate and D°_{irr} is a constant.

The form of Equation (1) is not universally accepted, however, and justification for its use is stated by Marlowe to be that the form of the equation fits many reported sintering data within experimental uncertainty.[12,13] With respect to the appropriateness of using Equation (1) in a predictive model, the accuracy or conservative nature of a first-principles calculation depends on the accuracy of parameters that are used in the model. The rate constants M and A are measured in out-of-reactor thermal tests on the fuel pellets of interest (see ref. 11) in order to characterize the fuel material for the analysis.

The rate constant A is defined as

$$A = (G^3 - G_\circ^3)/Dt, \qquad (2)$$

where G is the grain size after a thermal simulation anneal for time t. The rate constant M is defined as

$$M = A\ \Delta\rho/\ln(1 + ADt/G_\circ^3). \qquad (3)$$

The accuracy of M and A depends on the ability to measure grain sizes and densities. In addition, M and A will depend on the actual densification and grain-growth kinetics if they are different from the assumed forms (it is assumed that densification has a logarithmic time dependence and that grain growth proceeds as $t^{1/3}$).

Figure 2.5.1 shows a measured densification curve for alumina, which is given as an example of a typical ceramic. This figure is from reference 13, which was used by Marlowe to justify the logarithmic time dependence in Equation (1). The curve is linear below about 90% T.D., but above 90% T.D. it is decidedly curved. Assuming that the same behavior is found in UO_2, M will not be uniquely defined above about 90% T.D., the region of current interest, and the value of M determined from a resintering anneal will depend on the resintering time. Similar comments may apply to grain growth curves.

It is further seen that the value of A depends directly on the diffusion coefficient D that has been chosen to represent fuels to which the model is applied. The uranium diffusion coefficient for UO_2 depends strongly on the stoichiometry and structural properties of the material, and measured values vary over several orders of magnitude from one investigator to another.[14,15] It therefore seems inappropriate to presume that a single value for the diffusion coefficient is known and will suffice for all fuels.

In addition to indirectly containing D, the GE model explicitly contains D°_{irr}, an irradiation-induced diffusion constant. Only two measurements of this quantity are known,[16,17] and these values differ by approximately 20%. In view of the large variance usually obtained in out-of-reactor diffusion measurements, this apparently-good in-reactor agreement should not be relied on for confirmation of an absolute value for the diffusivity of uranium.

If the GE densification equation is examined carefully, however, it is found that in the only place where the diffusion coefficients appear, they appear as the ratio D°_{irr}/D. Since these coefficients may depend on materials properties in a similar manner, their ratio may be insensitive to many materials variables. It is likely that the model will be well behaved, but values for the diffusion-coefficient ratio are treated with uncertainty, along with M and A, and subject to calibration.

To qualify the densification model for predictive use, GE has compared recent in-reactor data from the Halden reactor to predictions of the model. Most of the Halden data have been published separately[18], and additional information from Halden was submitted in reference 9. The fact that GE calculates good agreement with most of the Halden data without adjusting any parameters gives substantial credibility to the model. It must be pointed out, though, that the GE model does not correctly or conservatively predict the small density changes that occurred in the 92% and 95% TD "stable" fuels, which are presumably similar to the GE production fuels. A remedy for this is described below.

In view of the small discrepancy in the predicted densification of high density "stable" fuels and the inherent difficulties in obtaining accurate values of M, A, D, and $D°_{irr}$, as discussed above, two provisions are to be applied to the GE densification-kinetics model:

1. The model should be adjusted such that the predicted maximum density, including sintering and swelling, occurs no later than 4,000 MWd/tU.
2. The model should be adjusted such that the maximum predicted density, including sintering and swelling, is no smaller than the resintered density achieved at 1700°C for 24 hours, as measured on a statistically significant sampling of archive pellets.

Justification of Provision 1

In-reactor sintering (or porosity elimination) and in-reactor swelling of fuel pellets are concurrent and competing processes. For a given swelling rate, the slower that densification proceeds, the lower will be the pellet density at any time. Thus slower densification is less conservative, from a reactor safety standpoint, than faster densification.

The rate of densification can be gauged by the burnup (time) at which the maximum density occurs as determined by these two competing processes.

The burnup at which the predicted peak density occurs can be seen[9,11,19,20] to depend on the magnitude of the rate constants M and A in the GE model. Since information is available from operating reactor experience on burnup at which the peak density actually occurs, it is desirable to conservatively limit the prediction of the peak according to observed values.

Some of the Halden data[18], against which the G. E. model was tested, are shown in Figure 2.5.2. These curves generally indicate a peak density (maximum reduction in length) at about 4,000 MWd/tU, although one of the curves indicates an even lower burnup. In addition to the Halden data, non-proprietary Westinghouse data[21] indicate a maximum density at an exposure between 4,000 and 10,000 MWd/tU, and these data are shown in Figure 2.5.3 While no statistical analysis has been performed by us on these data, it is clear that a predicted maximum density that occurred significantly later than 4,000 MWd/tU would be neither realistic nor conservative. We believe that rate constants similar to the ones currently being used by G.E.[9] will produce density maxima at about 4,000 MWd/tU and that a 4,000 MWd/tU restriction will have little or no effect. However, if smaller rates constants are found that are similar to earlier values used by G.E.[11], the 4,000 MWd/tU restriction may affect the result significantly and in a conservative manner.

Justification of Provision 2

The extent of densification predicted by the G.E. model will be affected by uncertainties or errors in the rate constants that are used. For check on the prediction, we have found that an appropriate out-of-reactor resintering test correlates well with in-reactor densification at its maximum value, which occurs around 4,000 MWd/tU.

The appropriate resintering test to be used is an anneal at 1700°C for 24 hours. In order to make the data comparison, resintering data have been adjusted to 1700°C for 24 hours using an assumed activation energy of 82 kcal/mole. This is the same activation energy used by Marlowe[11].

Figure 2.5.4 exhibits excellent correlation between resintering pellet-length for 24 hours. The original resintering data were taken at 1625 C for 5 hours. The extrapolation also utilized sintering curves supplied by G.E.[22].

Figure 4 exhibits excellent correlation between resintering pellet-length changes and in-reactor pellet-length changes around 4,000 MWd/tU. Points below the 45° equivalence line indicate greater out-of-reactor densification and are thus conservative. Since out-of-reactor dimensional changes are isotropic and in-reactor dimensional changes are anisotropic[11], all points will be moved downward. If $\Delta L/L$ is taken as $1/2\ \Delta V/V$, a factor of 2/3 would apply to the in-reactor values, moving all data points below the equivalence line and implying that in-reactor densification is less than densification produced out-of-reactor at 1700°C for 24 hours.

In a recent paper Brucklacher and Dienst[23] compare out-of-reactor sintering to in-reactor densification. They claim that sintering at 1250°C gives equivalent densification to low temperature irradiation with a fission rate of 6 to 8 x 10^{12} f/cm^3 sec. Their crack-width measurement are a less sensitive means of obtaining densities than immersion-density measurements and the large extrapolation to 1700°C (using again 82 kcal/mole) is uncertain; nevertheless, going through the exercise yields an equivalent burnup of 10,400 MWd/tU for an anneal at 1700°C for 24 hours. While little confidence can be placed in this result alone, it is consistent with the other data and indicates conservatively the use of the resintering test.

Based on theoretical considerations, the G.E. model[11] discusses explicitly the equivalence between in-reactor densification and out-of-reactor sintering. From Figure 11 of reference[11] it is seen that sintering at 1700°C for 24 hours is predicted to be equivalent to a burnup of 5,000 MWd/tU. Thus the G.E. model itself predicts the validity of the resintering restriction almost exactly as it is being applied, although our confidence in the use of such a test is derived primarily from the experimental data. Because of the compatability of the resintering test with the G.E. model, it is believed that the imposition of the resintering test as a restraint will not significantly alter the performance of the G.E. model when its predictions are realistic.

Rather than rely solely on the theoretical G.E. model, we have thus required that restraints be placed on the model to protect against possible unrealistic predictions due to uncertainties in several input parameters. The two provisions we have required are empirically derived from a rather broad data base. The provisions are also compatible with the G.E. model and should provide no serious handicap to the model when it is predicting densification realistically.

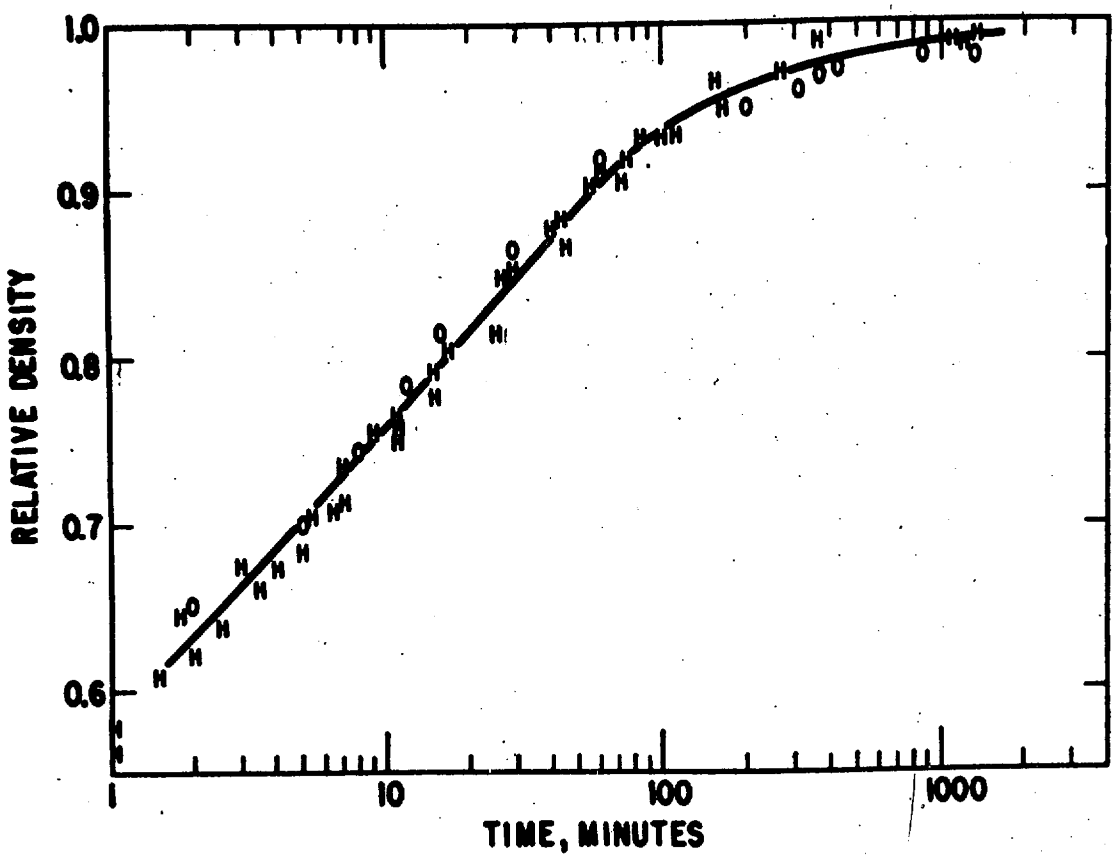


Figure 2.5.1. Densification of several alumina compacts heated in oxygen (O) and hydrogen (H), respectively; from Coble, reference 13.

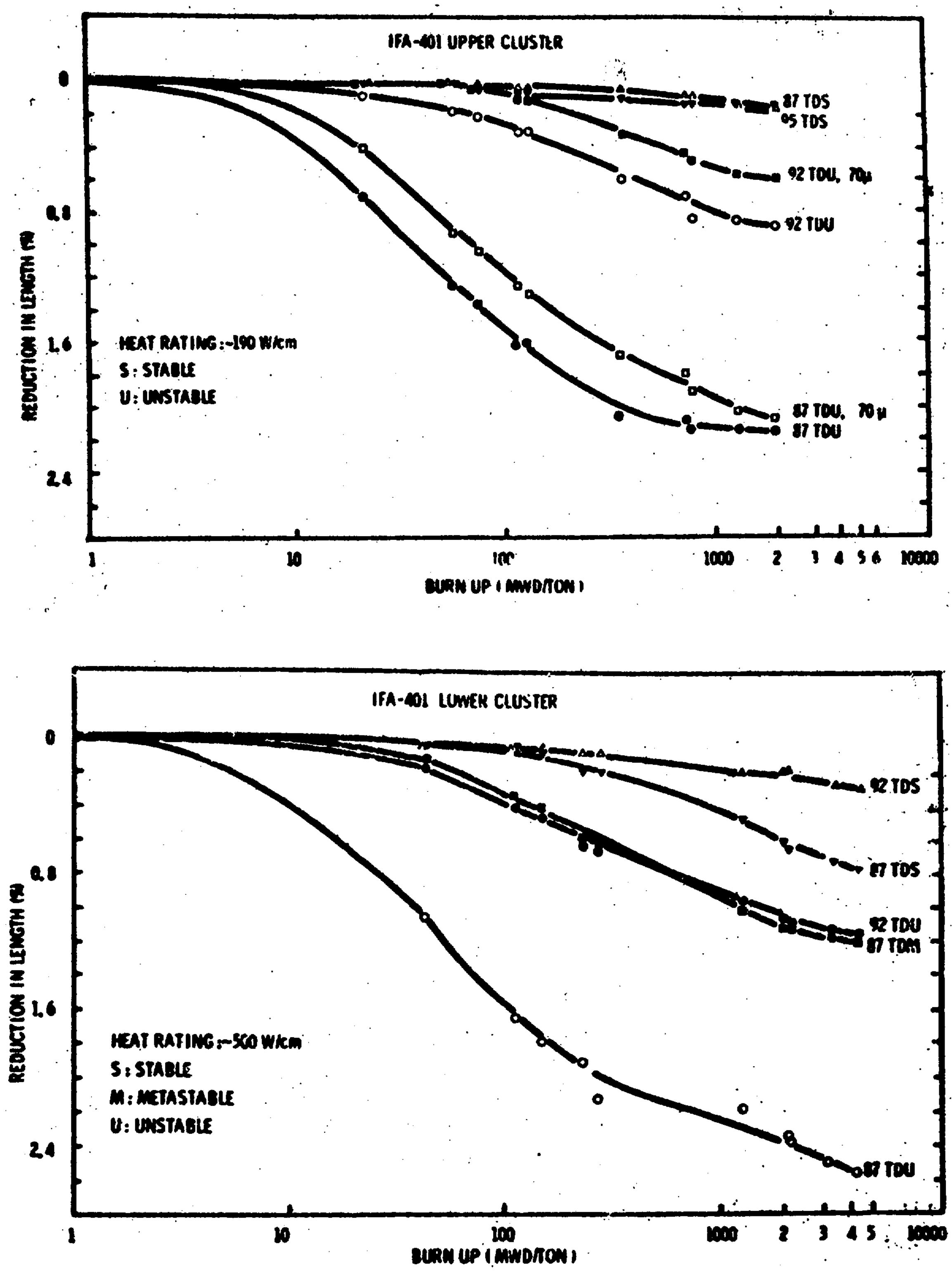


Figure 2.5.2. Reduction in stack length as a function of burnup; from Hanevik et al. (Halden), reference 18.

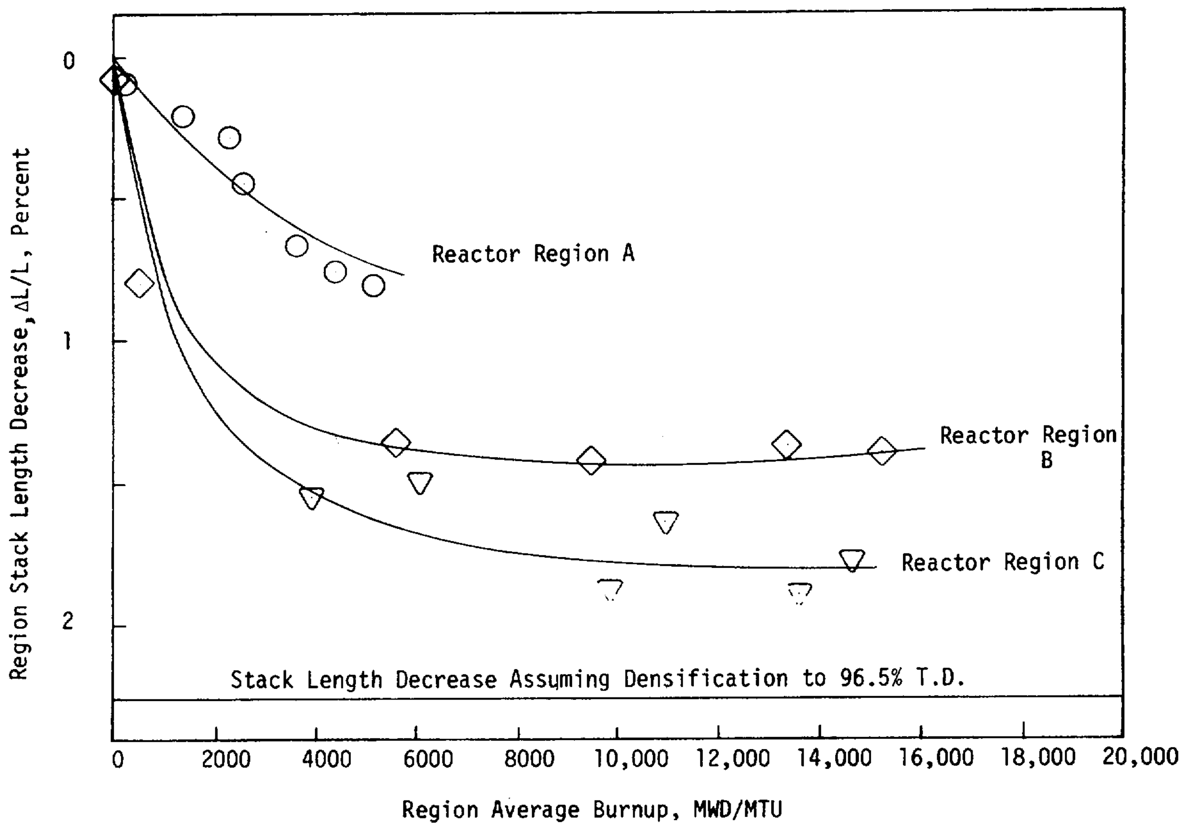


Figure 2.5.3. Neutron detector measurement of stack length changes for 92% T.D. UO_2; from Hellman et al. (Westinghouse), reference 21.

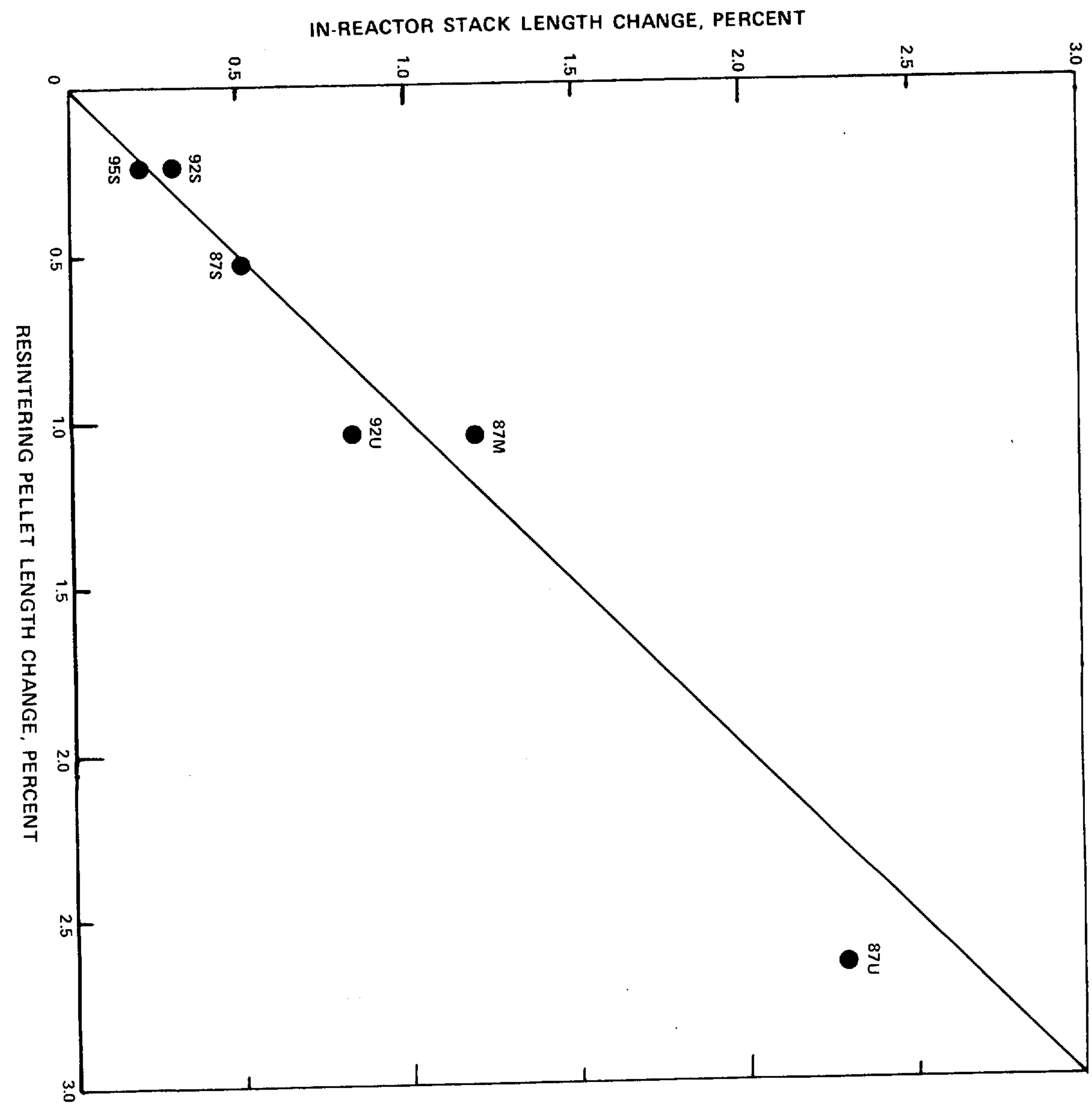


Figure 2.5.4. In-reactor stack length changes compared to out-of-reactor resintering length changes adjusted to correspond to resintering at 1700°C for 24 hours.

2.5.3 Fuel-Cladding Gap Closure Due to Pellet Cracking and Relocation of Pellet Fragments

Thermal expansion, fuel fission product swelling, radial and circumferential cracking of the fuel, and subsequent mismatch of the crack surfaces are held to be contributing factors in causing fuel pellet diametral increases. This increase in pellet diameter results in a corresponding decrease in the fuel-cladding gap, but the fuel-cladding gap dimension at any time is a function of many variables including the initial (as-built) gap, initial pellet diameter, power level (LHGR), cladding elastic deflection and creep, thermal expansion of fuel and cladding, and densification, cracking, and swelling. Because of the complexity of the phenomena, it is not possible to calculate or predict the amount of gap closure from first principles. Instead, pellet cracking and relocation models are usually based upon attempts to fit mathematical expressions to experimental observations and measurements of residual cold gaps. These measurements are made on cross sections of irradiated fuel pins and typically cannot separate the fission product swelling contribution from the pellet-cracking contribution to pellet diametral expansion, nor are the fuel densification, clad creep-down contributions to gap change usually taken into account.

The G.E. correlation for pellet relocation was obtained by fitting an equation to 204 data points which included observations reported by HEDL and Belgonucleaire as well as GE-data generated from test and production fuel rods.

In the G.E. relocation model the effective hot gap is equal to the current cold gap, minus the pellet expansion, minus the clad inward deflection. By assembling the data and developing their correlation, G.E. further corrected the data for the effects of fuel densification cladding creepdown (BWR fuels) and cladding swelling (fast reactor cladding) using best estimates of these effects. The final measured gap was corrected by subtracting the estimated values of these effects, so that the resulting changes in the gap reflected only the contribution from pellet relocation.

The G.E. fuel relocation model, based on these data, is put in terms of an analytic expression which conservatively bounds 80% of the data. When data were selected from the most prototypic BWR fuel rods and tested for correlation to the GE analytic expression, the resulting correlation coefficient was 92.9%.

As a further conservatism, no credit is taken in the gap conductance calculation for interfacial pressure which might result from gap closure, unless interference is achieved without the benefit of relocation.

The staff has examined the GE pellet relocation model and the data on which it is based and has also examined some nonproprietary gap closure data[24]. Based on this detailed review of the data, and the conservatism in the analytic expression discussed above, the staff considers the GE fuel relocation model to be acceptable for use in licensing calculations considering densified fuel.

2.5.4 Gap Conductance Calculations

GEGAP-III is a fuel thermal performance computer program used by General Electric to predict the behavior of BWR fuel rods as a function of fuel rod power and burnup.

To predict the overall thermal performance of a fuel rod, GEGAP-III predicts the thermal expansion and irradiation swelling of the fuel, the amount of fission gas released by the fuel and the amount of deformation of the cladding, both from elastic deflection and creepdown.

The staff has examined each of these models in GEGAP=III for various phenomena that occur in the fuel by comparing calculations with available data. The material properties used by General Electric in GEGAP-III were also evaluated by the staff. In addition to this evaluation of the individual components of GEGAP, GEGAP-III calculations were compared with available fuel temperature and gap conductance data. In addition to GEGAP-III calculations, the staff also used its own thermal performance computer program, GAPCON-THERMAL-I to perform sensitivity calculations to check the effects of the relocation and densification models used by General Electric.

GEGAP-III includes the General Electric fuel densification model, modified as described in Section 2.5.2. This modification provides an added conservatism to the GEGAP-III calculations which the staff has verified by examinations of comparisons of GEGAP-III predictions with experimental data.

The staff modification for densification added approximately a 7% conservatism to the difference between the predicted and measured gap conductances.

GEGAP-III calculates thermal expansion by assuming that the fuel is completely cracked and there is no restraint to movement of the fuel. This gives a relatively large effect compared with other methods of calculating thermal expansion but is considered acceptable since it is based on acceptable assumptions.

GEGAP-III allows no external changes in dimensions of the fuel to occur due to fuel swelling until all porosity has been filled, including the effects of densification. The change in volume due to fuel swelling is 0.4% $\frac{\Delta V}{V}$ per 10^{20} fissions/cm^3. The delay in changes in the external dimensions and the relatively low swelling rate mean that swelling has no effect on the fuel until after a considerable burnup. The staff considers the GEGAP-III swelling model to be acceptable.

GEGAP-III uses Lyons' UO_2 thermal conductivity data which has a conductivity from 0° to 2800°C of 93 w/cm. This value is the same as used in the staff's thermal performance computer program GAPCON-THERMAL-I and is acceptable to the staff.

GEGAP-III includes the Ross and Stoute thermal contact conductance model[25] but contact is assumed only for the purpose of experimental data comparisons where small gap fuel rods were included. For calculations of stored energy in G.E. BWR fuel rods, the interfacial pressure due to pellet-cladding contact is conservatively assumed to be zero.

The fuel relocation model discussed in section 2.5.3 produces a large increase in the gap conductance as calculated in GEGAP-III. However, gap closure due to fuel cracking is a well recognized phenomenon and General Electric, as described in Section 2.5.3 has supplied a sufficient amount of data for typical BWR fuel and treated these data in a conservative manner, so that the staff is confident that the model conservatively calculates the average calculated fuel temperature.

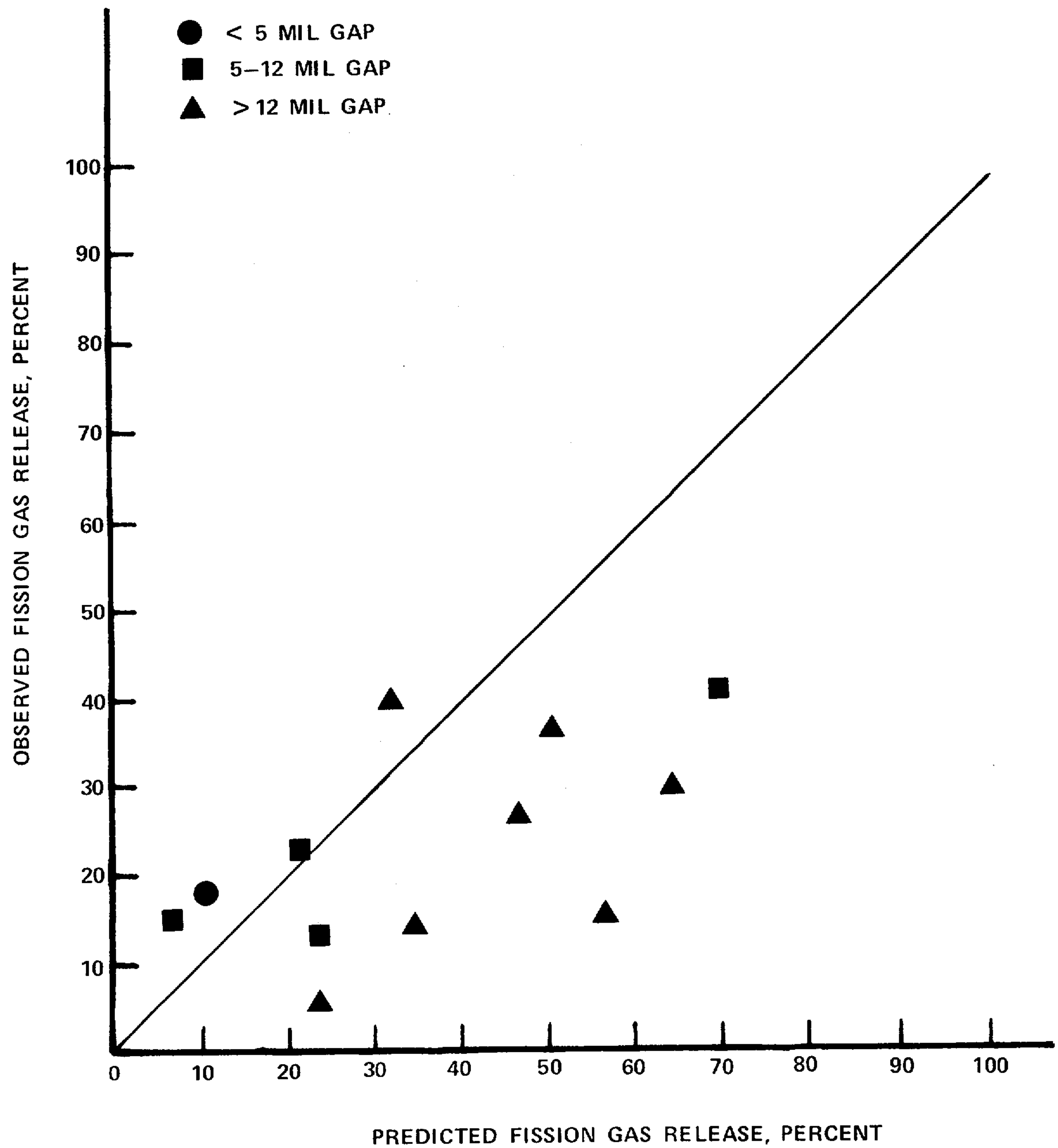
GEGAP-III considers the effects of sorbed gas released from the fuel. The mixture of sorbed gases is assumed to be released completely at beginning of life and to be completely absorbed at a later time. Calculations performed by the staff using GAPCON-THERMAL-I, along with test data submitted to the staff by GE show that this method of accounting for sorbed gas is reasonable. The staff therefore considers the GEGAP-III sorbed gas model to be acceptable.

Fission gas release has an important effect on the gap conductance of a fuel rod because it changes the thermal conductivity of the fill gas which is the heat transfer medium both before and after contact in GEGAP-III, (because solid contact is neglected). GEGAP-III uses a fission gas release model based on the data of Hoffman & Coplin[27]. This model is also used by the staff in GAPCON-THERMAL-I. Figure 2.5.5 shows a plot of the GEGAP-III calculations for fission gas release compared with experimental data. These results show that the fission gas release model is, in general, conservative and is therefore acceptable to the staff.

As part of the evaluation of GEGAP-III the staff requested that GEGAP-III be used to predict the behavior of certain fuel rods for which experimental results were available. These were in addition to the experimental comparisons submitted by General Electric. Three of the fuel rods were irradiated for a period of between one and two months at various power levels. In these three rods the gap conductance was determined from the equiaxed grain growth radius measured after irradiation. Since this radius was the measured parameter, its prediction by GEGAP-III is a better indication of code verification than the gap conductance or fuel temperature calculated by the experimenter. Table 2.1 shows the results of a comparison of predicted and measured equiaxed grain growth radii for these three fuel rods. The agreement is very good.

FIGURE 2.5.5

PREDICTED VS OBSERVED FISSION GAS RELEASE, PERCENT



These three fuel rods were selected based on three criteria:

1. Similarity in gap to BWR rods
2. No Melting
3. Complete characterization of all parameters needed for the calculation including physical dimensions and power histories

TABLE 2.1

Comparision of Equiaxed Grain Growth Radii calculated by GEGAP-III with Reported Values

Experimental Rod	$\frac{(r_{gg})\text{reported} - (r_{gg}*)\text{predicted}}{(r_{gg}*)\text{predicted}}$
1	3%
2	-7%
3	-5.5%

* The radius for predicted equiaxed grain growth was chosen to represent the highest power of the fuel rod during its irradiation.

2.5.5 Summary of Fuel-Cladding Conductance Evaluations

The staff finds the GEGAP-III fuel thermal performance computer program to be acceptable for licensing calculations for General Electric Boiling Water Reactor Fuel rods. The staff has evaluated GEGAP-III and found it to be conservative in the following ways:

1. The relocation model is conservative in that the model is fit to the data so that 80 percent of the data relocated more than predicted by the model.
2. The fuel swelling due to irradiation is all accomodated internally until all porosity is filled, thus taking no credit for external swelling until late in life.
3. No credit is taken for the improved heat transfer which would result from the interfacial pressure of the fuel pellet pressing on the cladding after contact. Unless the contact occurs without the contribution to gap closure due to fuel pellet relocation.
4. For several well characterized gap conductance experiments, GEGAP-III predicts the measured experimental parameter (equiaxed grain growth radius) conservatively.
5. The densification model as modified in Section 2.5.2 employs contraints that conservatively limit the kinetics such that the maximum density occurs at a burnup no greater than 4,000 MWd/tU. The predicted maximum density is required to be as large as the density produced during a 1700°C, 24-hour resintering anneal, which has been found to predict conservatively the maximum observed extent of in-reactor densification.

3.0 THE EFFECTS OF FUEL DENSIFICATION ON BWR SAFETY ANALYSIS

The occurrence of fuel densification in reactor fuel rods causes the fuel rods to contain more stored energy, increases linear heat generation rates in the fuel rods, decreases the heat transfer capability of the fuel rods, and creates the potential (if axial gaps are formed in the fuel column) for local power spikes and for cladding collapse. In safety evaluations of power reactors it is necessary to consider these effects of fuel densification in the analyses made for all modes of reactor operation. These include normal operation, operation during various transient conditions, and postulated accident situations including the postulated loss-of-coolant accident (LOCA).

The new GE fuel densification model, incorporated into GEGAP-III as described in Section 2, results in a lower value of stored energy than the previous GE AEC gap conductance model for all values of linear heat generation rate. Therefore, the results of all predictions of transients and accidents will be less severe with the new GE fuel densification model. Since this review did not include the models used to calculate the results of these accidents and transients, they will not be discussed further here.

4.0 SUMMARY AND CONCLUSIONS

The General Electric fuel densification model is described in NEDC-20181, NEDM-10735 and Supplements, 1, 2, 3, 4, and 5 to NEDM-10735 (see references 2 through 6). The model includes provisions for time dependent densification effects and provides a description of the gap conductance of individual fuel rods a function of burnup (time). The model, when modified as described below and in reference 31, is considered to be suitably conservative for the evaluation of densification effects in BWR fuel.

The possible effects of fuel densification are: (1) power spikes due to axial gap formation; (2) increase in LHGR because of pellet length shortening; (3) creep collapse of the cladding due to axial gap formation; and (4) changes in stored energy due to increased radial gap size. Similarly, the GE model for fuel densification consists of four parts: power spike model, linear heat generation model, clad creep collapse model and stored energy model. The required modifications to each of these models are listed below.

4.1 Power Spike Model

The GE power spike model is acceptable as it is described in NEDM-10735 and supplement 1 to NEDM-10735 and modified in Supplement 5 of NEDM-10735 as long as it is used in conjuction with a maximum axial gap size given by the following equation:

$$\Delta L = \left(\frac{0.965 - \rho i}{2} - 0.0025\right) L$$

where ΔL = maximum axial gap length

L = fuel column length

ρi = mean value of measured initial pellet density (geometric)

0.0025 = allowance for irradiation induced cladding growth and axial strain caused by fuel-clad mechanical interaction.

4.2 Linear Heat Generation Model

The following expression should be used to calculate the decrease in fuel column length in determinations of the linear heat generation rate:

$$\Delta L = \left(\frac{0.965 - \rho i}{2}\right) L$$

where: ΔL = decrease in fuel column length

L = fuel column length

ρi = mean value of measured initial pellet density (geometric)

Credit can be taken for fuel column length increase due to thermal expansion, and for the actual measured length of the fuel column.

4.3 Clad Creep Collapse Model

Examination of exposed BWR fuel rods (ref. 5) and Regulatory staff calculations show that clad collapse will not occur in typical BWR fuel during the first cycle of operation. Consequently, no additional creep collapse calculations are required for the first cycle of typical BWR fuel.

For reactors in subsequent cycles of operation the GE creep collapse model described in NEDO-10735 should be used with the following modifications:

1. The equation used to calculate the change in ovality due to the increasing creep strain should account for the ovality change due to change in curvature as well as for the ovality change due to change in rod circumference.
2. A conservative value should be used for the clad temperature. Axial temperature variations in the vicinity of a fuel gap as affected by thermal radiation from the ends of the pellets and by axial heat conduction should be taken into account. Effects from any buildup of oxide and crud on the clad surfaces should also be considered.
3. The calculations should be made for the fuel rod having the worst combination of fast neutron flux and clad temperature.
4. No credit should be taken for fission gas pressure buildup.
5. No credit should be taken for end effects. An infinitely long, unsupported length of cladding should be assumed.
6. Conservative values for clad wall thickness and initial ovality should be used. An acceptable approach is to use the two standard deviation limit as fabrication dimensions.

4.4 Densification

The densification-kinetics expression as described in NEDC-20181 is acceptable subject to the restriction that the rate constants (M,A, and $D°_{irr}$) are adjusted such that a specified density increase occurs at a burnup no greater than 4,000 MWd/tU. The specified density increase will correspond to the density increase experienced by like fuel during an out-of-reactor resintering anneal at 1700°C for 24 hours. This density increase may be considered to give the maximum density in the model, and no further density increase need be predicted.

Resintering tests already performed by G.E. and reported in NEDC-20181 on archive and current production pellets may be used as a basis for obtaining the 24 hour resintering data. A linear interpolation to 24 hours will be acceptable on a semi-logarithmic plot of density increase vs time between the measured points at 4 hours and 100 hours. The 4-hour and 100-hour points will correspond to the 95 percentile values on the measured density-increase distributions for the resintered pellets at each time period.

4.5 For purposes of calculating the densification effect on gap conductance and stored energy, the change in fuel pellet radius should be calculated from the density change in (4.4) above and from the assumption that shrinkage is isotropic, i.e.

$$\frac{\Delta r}{r} = 1/3 \frac{\Delta \rho}{\rho} \text{ where}$$

$\Delta \rho$ = change in density from densification-kinetics expression described in NEDC-20181

r = radius

4.6 Creep

Clad creepdown as it effects gap conductance may be calculated with the CREEP-1 code, as described in NEDC-20181, provided that the resultant creep strains are multiplied by 0.31.

4.7 Since the assembly average stored energy is one of the most important inputs to BWR LOCA evaluation, a Technical Specification limit should be imposed on maximum permitted assembly power.

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