Westinghouse
Electric Company

Box 355
Pittsburgh Pennsylvania 15230-0355

July 21, 2000
NSBU-NRC-00-5975

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: J. S. Wermiel, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," WCAP-15063-P-A, Revision 1, with Errata (Proprietary) and WCAP-15064-NP-A, Revision 1, with Errata (Non-Proprietary).

Dear Mr. Wermiel:

Enclosed are 15 copies of the Proprietary and Non-Proprietary versions of the topical report "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," WCAP-15063-P-A, Revision 1, with Errata (Proprietary) and WCAP-15064-NP-A, Revision 1, with Errata (Non-Proprietary).

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-00-1409 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-00-1409.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.17(a)(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Add: J.S. Wermiel Ltr 1 Encl 1
T008 - WCAP-15064-NP-A Rev
1/15

Correspondence with respect to any Application for Withholding should reference AW-00-1409 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Copy to:
M. S. Chatterton, NRR
S. L. Wu, NRR
R. Caruso, NRR
S. Bloom, NRR

Westinghouse
Electric Company

Box 355
Pittsburgh Pennsylvania 15230-0355

July 21, 2000
AW-00-1409

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: J. S. Wermiel, Chief,
Reactor Systems Branch
Division of Systems Safety and Analysis

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," WCAP-15063-P-A, Revision 1, with Errata (Proprietary) and WCAP-15064-NP-A, Revision 1, with Errata (Non-Proprietary).

Reference: Letter from H. A. Sepp to J. S. Wermiel, NSBU-NRC-00-5975, dated July 21, 2000

Dear Mr. Wermiel:

The application for withholding is submitted by Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse"), pursuant to the provisions of paragraph (b)(1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-00-1409 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-00-1409 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Copyright Notice

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 21st day
of July, 2000.

Lorraine M. Piplica
Notary Public

Notarial Seal
Lorraine M. Piplica, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Dec. 14, 2003
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Business Unit, of the Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Electric Company.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Electric Company in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," WCAP-15063-P-A, Revision 1, with Errata (Proprietary) and WCAP-15064-NP-A, Revision 1, with Errata (Non-Proprietary), July 21, 2000, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSBU-NRC-00-5975) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of J. S. Wermiel, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information is the approved version of the topical report as required by the SER and NUREG-0390.

This information is part of that which will enable Westinghouse to:

(a) Ensure proper fuel performance of fuel operating in reactors.

(b) Assist customers to obtain license changes resulting from fuel performance modeling.

Further this information has substantial commercial value as follows:

(a) Westinghouse can use this fuel performance modeling capability to further enhance their licensing position over their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Westinghouse Non-Proprietary Class 3

WCAP-15064-NP-A
Revision 1, with
Errata

Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)

Westinghouse Electric Company LLC
Nuclear Fuel

WCAP-15064-NP-A
Revision 1, with Errata

Westinghouse Non-Proprietary Class 3

Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)

June 1998 original
November 1999 revision
July 2000 approved

Authors:
J. P. Foster
S. Sidener

Edited by:
W. H. Slagle

APPROVED: A. L. Casadei, Manager
Core Engineering
Nuclear Fuel

APPROVED: D. Colburn, Manager
Materials and Fuel Rod Design
Nuclear Fuel

Westinghouse Electric Company
Nuclear Fuel
P. O. Box 355
Pittsburgh, Pennsylvania 15230

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K Letter from H. A. Sepp (Westinghouse) to T. E. Collins (NRC), "Notification of 'Errata for WCAP-15063-P, "Westinghouse In-Reactor Creep Model",'," NSD-NRC-99-5825, February 5, 1999.

L Letter from H. A. Sepp (Westinghouse) to J. S. Wermiel (NRC), "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0), WCAP-15063-P, Revision 1 (Proprietary)," NSBU-NRC-99-5956, November 18, 1999.

M Letter from H. A. Sepp (Westinghouse) to J. S. Wermiel (NRC), "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0), WCAP-15063-P, Revision 1 (Proprietary), Revisions to RAI #9," NSBU-NRC-00-5965, February 25, 2000.

SECTION A

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

April 24, 2000

Mr. Henry A. Sepp, Manager
Regulatory and Licensing Engineering
Nuclear Services Division
Westinghouse Electric Corporation
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355

SUBJECT: SAFETY EVALUATION RELATED TO TOPICAL REPORT WCAP-15063, REVISION 1, "WESTINGHOUSE IMPROVED PERFORMANCE ANALYSIS AND DESIGN MODEL (PAD 4.0)" (TAC NO. MA2086)

Dear Mr. Sepp:

By letter dated June 9, 1998, Westinghouse Electric Company LLC, submitted Topical Report WCAP-15063, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)" for NRC staff review. This report describes the improved models for the Westinghouse fuel performance code PAD. In a letter dated November 18, 1999, Westinghouse submitted a revision to the subject topical report.

The Westinghouse PAD model is a best estimate fuel rod performance model used for both fuel rod performance analysis and safety analysis input. The PAD code consists of several fuel rod performance models integrated to predict fuel temperature, rod pressure, fission gas release, cladding elastic and plastic behavior, cladding growth, cladding corrosion, fuel densification, and fuel swelling as a function of linear power and time. Subsequent to the original model introduction, two specific revisions have been submitted for review and approval (PAD 3.3 and PAD 3.4). With respect to the creep model used in PAD, the original model form remains in effect except for a revision to the irradiation enhanced creep portion of the model in PAD 3.4. The thermal creep portion of the model has remained the same since the model's inception in 1972.

This topical report introduces a new creep model to be used in the overall PAD fuel rod performance model. The new creep model accounts for advances in the understanding of in-reactor creep that have occurred between 1972 and 1998, and represents a description of in-reactor creep relative to the information and data that are available in 1998. This model enhancement is projected to restore rod internal pressure limit margin to the fuel rod design criterion.

The NRC staff's review of the topical report was initiated by your letter dated June 9, 1998, followed by a September 15, 1998, meeting between the staff and representatives of Westinghouse to discuss the issues related to the revised PAD code. During the meeting, questions were raised that, along with a request for additional information from the NRC dated September 10, 1998, were answered in letters dated November 13, 1998, January 5, 1999, and

February 25, 2000. Westinghouse also submitted supplemental information in letters dated September 11 and 29, 1998, as well as an errata in a letter dated February 5, 1999. Westinghouse submitted WCAP-15063, Revision 1, by letter dated November 18, 1999. The staff has reviewed the topical report and the additional information provided, and finds that the topical report is acceptable for referencing. Our safety evaluation does not include any new staff positions and is provided as an enclosure to this letter.

The expected results from the improved PAD 4.0 model are more consistent with in-reactor experience using a mechanistic approach. Westinghouse states that for some fuel already in an operating reactor core or fuel that exists in the spent fuel pool that may be reinserted in later cycles, it may be possible that the new PAD 4.0 model might still predict some gap reopening. If analyses were to indicate that this situation could occur, Westinghouse would demonstrate that the affected fuel assemblies will continue to meet all safety limits as well as 10 CFR 50.46 oxidation limits for operating as well as future cycles, using the methodology that has already been presented to the NRC for gap reopening analysis. The staff agrees that this is an appropriate way to proceed.

Further, it is planned that the implementation of the new PAD 4.0 model will be made on a "forward-fit basis" (e.g., currently analyzed or operating cycles will not require reanalysis using the PAD 4.0 model). All plant specific reload analyses will be analyzed with the new PAD 4.0 in the year 2000 on a schedule consistent with an implementation plan being developed with the Westinghouse Owners Group. This implementation schedule is based on establishing appropriate documentation and training. The staff finds that this implementation schedule and analysis approach is acceptable.

Pursuant to 10 CFR 2.790, we have determined that the enclosed safety evaluation does not contain proprietary information. However, we will delay placing the safety evaluation in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

We do not intend to repeat our review of the matters described in the report and found acceptable when the report is referenced in licensing actions except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that Westinghouse publish accepted versions of this report, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions should incorporate this letter and the appropriate evaluation between the title page and the abstract. The accepted versions shall include an -A (designating accepted) following the report identification symbol.

Should our acceptance criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, Westinghouse and/or the applicant referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the topical report without revision of the respective documentation.

Sincerely,

Stuart Richards, Director
Project Directorate IV & Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 694

Enclosure: Safety Evaluation

cc w/encl:
Mr. Andrew Drake, Project Manager
Westinghouse Owners Group
Westinghouse Electric Corporation
Mail Stop ECE 5-16
P.O. Box 355
Pittsburgh, PA 15230-0355

Mr. Jack Bastin, Director
Regulatory Affairs
Westinghouse Electric Corporation
11921 Rockville Pike
Suite 107
Rockville, MD 20852

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

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-15063-P, REVISION 1

"WESTINGHOUSE IMPROVED PERFORMANCE ANALYSIS AND DESIGN

MODEL (PAD 4.0)"

WESTINGHOUSE ELECTRIC COMPANY LLC

1.0 INTRODUCTION

Westinghouse Electric Company (Westinghouse) has submitted to the U.S. Nuclear Regulatory Commission (NRC) Topical Report WCAP-15063-P (Reference 1) entitled, "Westinghouse In-Reactor Creep Model," for review and approval. This report documents changes to their Zr-4, improved Zr-4 and ZIRLO cladding creep models employed in the PAD fuel performance code. The creep model is also used to determine the internal rod pressure limits at extended burnups. An errata to this submittal was provided in Reference 2. Westinghouse informed the NRC in References 3 and 4 of their intent to change the original submittal and provided preliminary information on the changes that were to be incorporated in the topical report. As requested by NRC, a revision to Topical Report, WCAP-15063-P, Revision 1, was provided in Reference 5 that also changed the title to "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)." This revised submittal made five additional model changes to the PAD fuel performance code and these are discussed in Section 2.0 of this report along with the change in the creep model. Westinghouse responses to the last RAI (RAI # 9) were also provided in References 5 and 10.

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC in this review. In a meeting on September 15, 1998 with PNNL and NRC, Westinghouse demonstrated the effects the creep model changes were going to have on the PAD code and also informed the NRC that they were going to make several other changes to the code at the same time and re-calibrate the code against thermal and fission gas release (FGR) data. The NRC staff informed Westinghouse that they would have to address several questions and issues before approval of the new revised PAD code and model changes could be granted. These issues were documented in the minutes of this meeting (Reference 6) and a follow-on meeting on June 23, 1999. Westinghouse provided partial responses to the questions and issues identified in the September 15, 1998, meeting in References 7, 8 and 9. The Westinghouse revised responses to RAI # 9 provided an example of PAD 4.0 licensing analyses for NRC audit comparisons as well as errata to their previous responses. These are provided in Reference 10.

As a result of several changes to PAD, Westinghouse has had to re-calibrate their thermal (gap conductance) and fission gas release models. The overall ability of the PAD 4.0 code to predict fuel temperatures, fission gas release, and rod pressures as well as the uncertainties in these predictions based on comparisons to data is discussed in Section 3.0 of this report.

The PAD 4.0 fuel performance code will be used by Westinghouse for stored energy and rod pressure inputs to LOCA, determining maximum rod internal pressures and rod pressure limits, and fuel melting analyses. Audit calculations have been made with the NRC developed FRAPCON-3 fuel performance code for comparison to PAD 4.0 calculations for maximum rod internal pressure, LOCA temperatures and pressures, and temperatures for the fuel melting analyses. These audit results will be discussed in Section 4.0. The conclusions are presented in Section 5.0.

2.0 PAD MODEL CHANGES

The original Westinghouse submittal (Reference 1) only applied to changes to the Zr-4, improved Zr-4, and ZIRLO cladding creep models. Westinghouse has made several model changes to the PAD 4.0 code (Reference 5) compared to the previous version, PAD 3.4 (Reference 11). These model changes are to the cladding creep, cladding irradiation growth, Zr-4 and ZIRLO clad thermal conductivity, Zr-oxide thermal conductivity, equation of state (EOS) gas pressure, the oxide-metal ratio, and Zr-4 clad gas absorption models. While the form of the gap conductance and fission gas release (FGR) models have not changed, the coefficients and uncertainties for these models have changed.

2.1 Cladding Creep Model

Westinghouse has made significant changes to their PAD 4.0 creep models for standard Zr-4, improved (low tin) Zr-4 and ZIRLO cladding materials. However, they have relied on essentially the same creep data base presented in their previously approved Westinghouse topical reports (References 11, 12 and 13) for previous creep models for these cladding materials. The amount of creep data for the standard Zr-4 is quite large with measurements from over 70 rods and 130 cycles of operation from 5 different plants. The improved Zr-4 data base is much smaller with measurements from fewer than 10 rods and the ZIRLO data base is even smaller. In order to accurately model cladding creep, creep data is needed from several different fuel batches and from different plants. These data are also needed to estimate the uncertainties in creep that are introduced from fabrication differences between different batches and from uncertainties in determining cladding temperatures for different plants. Westinghouse originally proposed to use only the improved Zr-4 data and only the ZIRLO data in determining improved Zr-4 creep and ZIRLO creep uncertainties, respectively. Westinghouse used nearly a hundred cladding diameter measurements per rod for the improved Zr-4 and ZIRLO cladding types to make their uncertainties appear low although they are only based on a very small number of rods. Use of this data suggested that the newer cladding types had much lower uncertainty than the standard Zr-4 creep. However, it was noted that the improved Zr-4 and ZIRLO data bases were much too small for a valid estimate of uncertainty. Westinghouse has revised their estimate of the improved Zr-4 and ZIRLO creep uncertainties (Reference 5) based on the standard Zr-4 data plus their respective data of Zr-4 and ZIRLO.

Westinghouse has assumed that the basic creep model is applicable for all three cladding types and has only adjusted the creep with a multiplication factor for each of the three types. Westinghouse assumes that the activation energy and stress dependencies in their creep model are applicable to all three cladding types. It is anticipated that the improved Zr-4 is most closely applicable because there was only a small change in tin content, but the ZIRLO cladding had larger changes in its metallurgy. These changes could introduce changes in the activation energy and stress dependencies different than for ZIRLO. Westinghouse intends to collect additional in-reactor creep data for ZIRLO to verify the activation energy and stress dependence for ZIRLO.

Westinghouse was also questioned about an apparent difference between tensile and compressive (stress state) creep rates for their cladding materials because different creep rates have been observed for zircaloy by other investigators (References 14 and 15) such that tensile creep rates are higher than compressive creep rates. An increase in tensile creep over compressive creep will reduce the margin to the rod pressure limit. Westinghouse responded (Reference 9) that the in-reactor experimental data from Reference 14 had several problems that made this data suspect. For example, Westinghouse claims that the reported steady state creep rates were unreasonably high compared to other in-reactor measurements of similar cladding, the creep measurements were not taken at steady-state creep because the time for the measurements was too short (still in transient or primary creep), and Zn crud formation from coolant chemistry could be altering the creep measurements. These are valid comments suggesting that this data may not be an accurate assessment of creep differences between tensile and compressive stress states.

Westinghouse has also reevaluated (Reference 9) the creep data in Reference 16 and claims that while there does appear to be a small difference in creep rate for the two stress states that it is within the uncertainty of this data and, therefore, there is little or no difference in creep rate between these two stress states. The staff has examined the Westinghouse reevaluation of the Reference 16 data and does not completely agree with Westinghouse's evaluation. One part of Westinghouse's re-analysis (Reference 9) is a linear fit to the compressive and tensile data as a function of hoop stress in the experimental samples to help substantiate the claim that there is little or no difference in the two creep states. The Westinghouse linear fit makes an implicit assumption in the analysis that there is no difference between tensile and compressive creep which does not appear to be valid proof that only small differences exist between the two stress states.

Westinghouse has also offered another alternative approach (Reference 9) to the analysis of the data by Garzarolli et al (Reference 15). Because there is a very small strain (creep) component in zircaloy cladding during irradiation at zero stress, Garzarolli has included a test capsule with zero stress to measure this component of strain. Garzarolli has subtracted this strain component from the compressive and tensile data in his analysis of this data as is appropriate for his analysis of creep differences. For Westinghouse's analysis of this same data, they have elected to average the zero stress data to Garzarolli data with a small level of tensile stress to estimate their zero stress component. The staff agrees that there is considerable scatter in creep data in general and that there is very little compressive to tensile data offered in either References 14 or 15 to accurately estimate the differences and uncertainty in creep rate for these two stress states. The staff contends that there may be a smaller difference between tensile versus compressive creep rates than previously estimated.

Westinghouse has initiated an experimental program to examine in-reactor creep for ZIRLO cladding and intends to measure creep under both compressive and tensile stresses to provide a more accurate estimate of creep differences in these two stress states. Westinghouse was requested to provide a list of the conservatisms in their rod pressure analyses to determine if there was ample conservatism in other parts of this analysis to compensate for the potential lack of conservatism in tensile creep in the revised Westinghouse creep model.

Westinghouse has provided the conservative margins used in their rod pressure analyses as contributed by each uncertainty component such as from creep, densification/swelling, fission gas release (FGR), and other uncertainties such as helium absorption/solubility, helium release, and fabrication. These uncertainties demonstrate that the fission gas release model contributes the greatest uncertainty. In addition, PAD 4.0 also provides a conservative prediction on rod pressures with their best estimate model (see Sections 3.2 and 4.1).

The staff has examined the impact of the possibility of tensile creep being greater than compressive creep on Westinghouse's rod pressure analysis. The staff has also examined the conservatism in the PAD 4.0 prediction of rod pressures as well as the FGR uncertainties to determine if there is adequate conservatism in this part of the Westinghouse rod pressure analysis to compensate for a possible lack in conservatism due to tensile creep. The staff has concluded that it appears that the conservatism in the PAD 4.0 predictions of rod pressure are adequate to compensate the decrease in rod pressure margin due to higher tensile creep.

Based on the adequate conservatism of rod pressure, the staff concludes that the PAD 4.0 creep models for Zr-4, improved Zr-4 and ZIRLO and associated uncertainties are acceptable.

2.2 Cladding Irradiation Growth Model

Westinghouse has retained the irradiation growth dependence for their Zr-4 and ZIRLO cladding but has also added a temperature dependence to these models above a particular temperature. This growth dependence has no impact on most of Westinghouse fuel licensing applications and only a very small impact on some rods in plants with high coolant outlet temperatures.

From an examination of the zircaloy growth data, the Westinghouse correlation of temperature dependence appears to be a best estimate representation of the temperature dependence in the growth data although there appears a large scatter in the data suggesting that there is considerable uncertainty in this temperature dependence.

Based on the results produced by the PAD model, the staff concludes that the Westinghouse modification of a temperature dependence to the Zr-4 and ZIRLO irradiation growth model is acceptable.

2.3 Zr-4 and ZIRLO Clad Thermal Conductivity Model

Westinghouse presents new correlations for Zr-4 and ZIRLO thermal conductivity based on ex-reactor measurements. The ZIRLO conductivity is slightly higher than the Zr-4, but the dependence (slope) versus temperature is identical. Based on the presentation and documentation of sufficient data, the staff has determined that these models are acceptable.

2.4 Zr-Oxide Thermal Conductivity Values

Westinghouse presents a range of oxide conductivity values derived from EPRI-sponsored Halden in-pile experiments. In these experiments, the oxide conductivity was deduced by comparison of cladding expansion between oxidized and non-oxidized fuel rodlets. The proprietary EPRI presentations on these measurements available to the NRC generally support Westinghouse's conclusions. Westinghouse proposes to increase their value for the oxide thermal conductivity based on the mean of this new data. The staff concludes that this change is appropriate for the best estimate PAD 4.0 code.

2.5 Equation of State Gas Pressure Model

PAD 4.0 uses an equation of state (EOS) that accounts for the non-ideal behavior of the gases found in the fuel rod internal void volume. It uses a modified version of the Peng-Robinson equation of state. In form, this EOS is similar to the more familiar Van der Waals EOS. Westinghouse has modified the Peng-Robinson calculated pressure values by a factor that adjusts the values upward slightly to match their data base of pressure-temperature data for a variety of gas mixtures.

To evaluate the PAD 4.0 EOS, the staff compared its pressure predictions to those of Van der Waals for pure gases at representative fuel rod operating gas temperatures and gas pressures. The modified Peng-Robinson model was found to predict lower pressures than the Van der Waals EOS slightly, but provided a better fit to the referenced data base used by Westinghouse. In order to verify that the relatively complex parameter and mixing rule equations used by Westinghouse, Westinghouse has supplied an example calculation with the Peng-Robinson EOS for a defined gas mixture and condition. An audit calculation was performed and agreed with the Westinghouse example. The staff concludes that the Westinghouse application of the Peng-Robinson EOS is acceptable because it correlates well with an extensive and applicable data base for gas mixtures at high pressures.

2.6 O-M Ratio Model

The oxygen-to-metal (O-M) ratio is often referred to as the Pilling-Bedworth ratio which is a measure of the volume of the oxide formed to the volume of the metal consumed during the ZrO_2 reaction. The theoretical ratio for zirconium oxide, ZrO_2, to zirconium is 1.56 which means that the oxide volume is a factor of 1.56 greater than the volume of the metal consumed. It is known that porosity, defects and cracks exist in the in-reactor zircaloy oxide layer such that the actual O-M ratio is sometimes greater than the theoretical value of 1.56. It is also observed that as the oxide thickness becomes larger in irradiated cladding, more cladding cracking is observed in the oxide layers and for some cladding with thick oxide layers the oxide begins to spall off the cladding. One of the uses of the O-M ratio for fuel performance calculations is in determining the cladding thinning due to oxide metal consumption for the calculation of cladding stresses. This generally only impacts high burnup cladding with oxide thicknesses between 3 to 4 mils. The other use is for determining the metal wastage factor due to cladding oxidation during a LOCA analysis for which 10 CFR 50.46 (Reference 16) imposes a limit on total calculated cladding oxidation not to consume more than 0.17 times the total cladding thickness

before oxidation. Westinghouse has stated that the new best-estimate O-M ratio model will not be used for evaluating the 17 percent cladding wastage oxide limit used for LOCA in 10 CFR 50.46.

Westinghouse has metallographically measured the O-M ratio from several irradiated fuel rods by measuring the oxide thickness and the remaining metal thickness. The O-M ratios measured by Westinghouse are typical for high burnup cladding. Westinghouse has proposed a best estimate fit to this data that is a function of oxide thickness. The Westinghouse O-M ratio model does appear to go through the median of the data but there is a very large scatter in the data that is on the order of the difference between the theoretical value and that predicted with their model. The impact on cladding stress is small, however, and is much smaller than the uncertainty in the overall PAD 4.0 stress prediction.

Based on the sufficient data collected, the staff concludes that the Westinghouse O-M ratio model is acceptable for use in best estimate calculations for PAD 4.0.

2.7 Zr-4 Clad Gas Absorption Model

The Westinghouse application of the earlier PAD 3.4 code used ambient air in their fuel rods for their licensing analyses. The existence of ambient air in their rods had two impacts on fuel performance. It increased rod pressures slightly and increased fuel temperatures because nitrogen and oxygen have lower gas conductivities than the helium fill gas which decreases the fuel-cladding gap conductance. Westinghouse has proposed in their revised submittal (Reference 5) that while the air exists in their fuel rods following fabrication, it reacts quickly with the zircaloy and ZIRLO cladding when charged into the reactor and brought up to hot coolant conditions and operating powers. Based on the Westinghouse analyses the zircaloy has a strong affinity for oxygen and it will react first to form ZrO_2. According to Westinghouse the reaction of the nitrogen takes only a few hours to react with zircaloy. Therefore, Westinghouse proposes that the oxygen and nitrogen will have reacted with the cladding by the time the fuel rods achieve full power operation.

An independent analysis has been performed in Reference 17 on the reaction of gaseous impurities in fuel rods. Using these reaction rates it is calculated that it takes only a few minutes for the oxygen to react with zircaloy cladding but approximately 2 days for the nitrogen to react in a Westinghouse Zr-4 clad fuel rod. The reaction rates from Reference 17 were measured from zircaloy and Zirconium that had been abraded to reduce the oxide thickness. The Westinghouse coating will have a thicker oxide layer particularly after the oxygen reaction (from the air) is complete. Therefore, if we conservatively assume that the reaction rate decreases by a factor of 3 due to the extra oxide thickness it takes approximately 6 days for the nitrogen to react in a Westinghouse Zr-4 clad fuel rod. It is noted that the oxide reaction rates for ZIRLO in water and steam are approximately a factor of 2 less than for Zr-4. Assuming that the reaction rates of ZIRLO with nitrogen decrease a similar amount, the nitrogen will take up to 12 days to react with ZIRLO clad rods.

The Westinghouse PAD 4.0 analysis that is primarily impacted by the assumption of nitrogen in a fuel rod is in the initial conditions for LOCA and resulting PCT. For Westinghouse LOCA analyses the reaction of nitrogen decreases the initial rod internal pressures and decreases fuel average temperatures which have opposing effects on PCT. For example, lower rod pressures

increase PCT while lower average fuel temperatures decrease PCTs. Westinghouse has performed a preliminary evaluation to determine the impact of nitrogen reacting immediately with the cladding on LOCA initial conditions and resulting PCT, i.e., the rod pressure and average fuel temperature decrease. This preliminary evaluation suggested that assuming the nitrogen reacts immediately in the rod (nitrogen does not exist during operation at full power) may result in slightly higher fuel PCTs for LOCA analyses than assuming the nitrogen exists in the fuel rod. This evaluation is based on previous Westinghouse sensitivity analyses of the impact of rod internal pressure and average fuel temperatures on PCT as well as the PAD 4.0 results on these two parameters.

Based on these conservative results, the staff concludes that the clad gas absorption model is acceptable for PAD 4.0.

3.0 PAD 4.0 COMPARISON TO THERMAL AND FISSION GAS RELEASE DATA

3.1 Comparison to Thermal Data

As noted in the Introduction (Section 1.0), the only thermal models in PAD 4.0 that have been changed are the Zr-4, ZIRLO cladding and ZrO_2 oxide thermal conductivities. However, the coefficients to the gap conductance model have also been changed. These changes in the cladding and oxide thermal conductivities reduce the predicted fuel temperatures in PAD compared to the previous results.

The primary licensing analyses that use PAD 4.0 thermal predictions are the loss-of-coolant accident (LOCA) and fuel melting analyses. The PAD 4.0 code is used to provide initial thermal conditions (fuel centerline and volume average temperatures) and rod pressures for the start of the LOCA analysis. The fuel volume average temperature is the primary PAD input that impacts the calculation of maximum peak cladding temperatures (PCTs) to verify that Westinghouse meets the 10 CFR 50.46 requirement of PCT not exceeding 2200°F. Traditionally, the NRC has required that a best estimate code such as PAD 4.0 maintain a 95 percent bounding estimate of centerline and volume average temperatures at a 95 percent confidence level for input to LOCA analyses.

The change in coefficient to the gap conductance model can make significant impact on thermal predictions. Therefore, it is important to evaluate the PAD 4.0 predictions against measured in-reactor temperatures. Westinghouse has elected to calibrate, validate and estimate code predictive uncertainties using the same experimental test rods from the Halden Reactor as used for PAD 3.4 even though there are a large number of additional rods at lower and higher burnups currently available (both from Halden and other experimental reactors) for code comparisons that were not available previously. In addition, the code uncertainties have been estimated from data at very low burnups because the LOCA and fuel melting analyses to which these thermal predictive uncertainties are applied are always limiting near beginning-of-life (BOL). From the example LOCA calculation provided by Westinghouse, the maximum fuel temperatures (generally corresponds to maximum PCTs) calculated by PAD 4.0 are consistent with the FRAPCON-3 code (Reference 18 and 19) results.

Westinghouse was questioned about the lower conservatism of PAD 4.0 compared to those data with a much more conservative 95 percent bounding at a 95 percent confidence level. Westinghouse responded that the initial conditions for their base (best estimate) PAD 4.0 calculation for LOCA are really not performed using best estimate input, but instead used conservative input values for fuel density, fuel sintering temperature, inlet coolant temperatures, coolant flow, and cladding creep. These additional conservatisms will further bound and remove the concern of the less conservatism in the uncertainty analysis.

PNNL has performed a calculation of the additional conservatism introduced in the Westinghouse PAD 4.0 best estimate input for LOCA on calculated fuel temperatures. Westinghouse has provided the uncertainty introduced by their root mean square (RMS) analysis of fabrication and additional model uncertainties not considered in PAD 4.0. Adding these uncertainties to those proposed by Westinghouse to bound fuel centerline temperatures for LOCA analyses results in an uncertainty value that appears to bound the data at a 95/95 level of conservatism.

Based on the conservative results produced by the PAD model, the staff concludes that the PAD 4.0 thermal predictions and uncertainties to thermal data are acceptable for PAD 4.0.

3.2 Comparison to FGR Data

The coefficients to the PAD low and high temperature FGR models as well as the transient FGR model have all been changed to provide a best estimate fit to their calibration data for these respective models. The PAD FGR models are also strongly temperature dependent such that the coefficients for the thermal and FGR modeling are interrelated.

The steady-state high temperature FGR data used by Westinghouse are from fuel with high burnups. A significant portion of this steady-state FGR data utilized by Westinghouse is primarily older FGR data from fuel manufactured by Westinghouse in the late 1960s to early 1970s, and typically has greater fuel densification than fuel fabricated today. The staff has observed that fuel with a greater degree of densification will show a larger amount of FGR and greater variation (uncertainty) among the data compared to fuel with a lesser degree of densification. Also, a significant amount of the transient FGR data used by Westinghouse is from another vendor that is also relatively older fuel with different fuel micro-structure and greater densification than fuel fabricated today. This fuel also tends to result in greater FGR than fuel fabricated today. Therefore, the use of this data to calibrate and verify the PAD 4.0 code should result in the code providing conservative predictions of FGR for today's fabricated fuel.

Examination of the Westinghouse PAD 4.0 code comparisons to the high temperature steady-state and transient FGR data reveals a best-estimate prediction of this data with a large uncertainty. Because as noted above, Westinghouse has used FGR data from older fabricated fuel that the PAD 4.0 code would predict higher FGR than more state-of-the-art codes such as FRAPCON-3 (References 18 and 19). However, the FRAPCON-3 audit calculation of FGR and rod pressures shows similar results and uncertainties are generated between PAD and FRAPCON-3 codes. This is expected given that the FRAPCON-3 code has been calibrated against both steady-state and transient FGR data from modern fuel with several data points near rod average burnups of 62 GWd/MTU, and one data point at 74 GWd/MTU (Reference

19). Based on the acceptable similar results between PAD and FRAPCON-3 codes, the staff concludes that the FGR model and rod pressure analysis are thus acceptable for PAD 4.0.

4.0 PAD 4.0 LICENSING CALCULATIONS

The NRC requested that Westinghouse provide examples of licensing analyses for which the PAD 4.0 code will be applied, so that audit calculations could be performed with the NRC developed FRAPCON-3 code (References 18 and 19) for comparison to the examples provided in PAD 4.0 licensing analyses. Subsection 4.1 addresses the maximum rod pressure limit analysis, Subsection 4.2 addresses the temperature and rod pressure input supplied to LOCA analyses, and Subsection 4.3 addresses the centerline temperatures for the fuel melting analyses.

4.1 Audit of Rod Pressure Analysis

A maximum rod internal pressure limit is imposed on in-reactor operating fuel in order to prevent the rods from being over-pressurized to the point where the cladding swells or balloons due to normal operation and normal operating transients. Ballooning of the fuel rod could result in other adjacent rods going into departure from nucleate boiling (DNB) which could cause this rod to balloon and fail resulting in its neighboring rods to go through DNB. This could result in significant local flow blockages and further failures. Currently, NRC allows fuel rods to balloon during certain transients and accidents but requires vendors to account for and not underestimate the flow blockage and dose consequences. However, cladding ballooning and flow blockage is not allowed as a result of normal operation. In order to prevent this scenario the NRC Standard Review Plan, Section 4.2, (Reference 20) has conservatively limited rod pressures to below reactor system pressure. In the last 15 years vendors have requested and NRC has approved a rod pressure limit above system pressure such that the cladding creep rate does not exceed the fuel swelling during normal operation using the lower bound (95 percent) fuel swelling rate and the upper bound cladding creep rate. In addition, the NRC has required that vendor calculations of rod pressures be bounding at the 95 percent level. This approval of rod internal pressure above system pressure has been granted to Westinghouse (Reference 21).

As requested, Westinghouse provided an example of rod pressure (best estimate and bounding) analysis results using the PAD 4.0 code to calculate rod pressures for a UO_2 fuel rod near the Westinghouse pressure limit (Appendix A of Reference 10). The example rod pressure input and analysis provided by Westinghouse for the audit calculation was modified from a typical Westinghouse UO_2 fuel rod in order to calculate rod pressures that are typical of a peak integrated fuel burnable absorber (IFBA) rod. The IFBA rods almost always provide the more limiting rod pressures rather than UO_2 rods.

The FRAPCON-3 code was used to perform a rod pressure audit analysis using the same input as used for the PAD 4.0 code. The FRAPCON-3 code was developed to be a best estimate code similar to PAD 4.0 and has been compared to a large amount of high burnup data up to a rod average burnup of 62 GWd/MTU with a small amount of thermal data up to 100 GWd/MTU. The primary fuel performance parameter that impacts the internal rod pressure analysis is FGR. The FRAPCON-3 calculated results of rod pressure and FGR were similar to those calculated by Westinghouse PAD 4.0 taking into account the effects in different models. Based on the

similar results produced by the PAD and FRAPCON-3 code, the staff concludes that the rod internal pressure prediction is acceptable for PAD 4.0 code.

4.2 Audit of LOCA Input

Westinghouse provided an example of PAD 4.0 analyses with best estimate fuel temperatures and rod pressures that are used for initialization of LOCA analyses (Appendix B of Reference 10). For Westinghouse analyses of LOCA, higher predicted fuel average temperatures and lower predicted rod internal pressures result in higher (more conservative) PCTs. Therefore, for LOCA analyses, Westinghouse uses PAD 4.0 best estimate predicted temperatures plus several uncertainties to provide upper bound initial fuel average temperatures. In order to provide a lower bound rod pressure for LOCA, Westinghouse uses PAD 4.0 best estimate rod pressures for the average operating (low power) rod in the core minus uncertainties in the rod pressure calculation.

FRAPCON-3 audit analyses were also performed using the same input used in PAD 4.0 to calculate best estimate fuel temperatures and rod pressures. A comparison of the FRAPCON-3 calculated centerline and average fuel temperatures to those from PAD 4.0 at LHGRs typical for LOCA initialization demonstrates that PAD 4.0 predicts higher temperatures very early in core life. This difference is reduced with increasing burnups such that the PAD 4.0 code prediction is similar at moderate burnups, and PAD predicts lower fuel temperatures than FRAPCON-3 at high burnups. The reason why the PAD 4.0 code thermal predictions are lower at high burnups is because the FRAPCON-3 code has a fuel thermal conductivity model that is burnup dependent (lower fuel conductivity with increasing burnup) while the PAD 4.0 code has a thermal conductivity model with no burnup dependence. A burnup dependence on thermal conductivity was first proposed by the Halden reactor staff (Reference 22) and has since been verified by several Halden experiments involving both in-reactor (Reference 23) and ex-reactor measurements of the thermal conductivity of high burnup fuel (References 24 and 25). The scatter in ex-reactor measurements have been proposed to be due to differences in irradiation temperatures of the ex-reactor samples (Reference 26).

Westinghouse was questioned about the lower conservatism in the PAD 4.0 thermal calculations at moderate to high burnup levels. Westinghouse responded that LOCA limiting conditions are currently limiting at early in life based on a recent Westinghouse justification for continued operation (JCO) analysis (Reference 27) that accounted for thermal conductivity degradation with burnups. This analysis also made some very conservative assumptions such as no burnout of the fissile material occurs in the fuel with burnup. The staff therefore believes that the PAD 4.0 prediction of LOCA temperatures are acceptable for licensing analysis.

The FRAPCON-3 predicted rod pressures for LOCA were slightly lower than those predicted with PAD 4.0. As noted above, the limiting rod pressure that results in the most conservative PCTs is a lower bound rod pressure. For this reason Westinghouse uses lower bound inputs and uncertainties for PAD 4.0 predictions of rod pressures for LOCA initial conditions. The difference between the FRAPCON-3 and PAD 4.0 code predictions of rod pressure is within the lower uncertainty bounds that Westinghouse applies to their PAD 4.0 predictions of rod pressure for LOCA. Therefore, the Westinghouse rod pressure input for LOCA are conservative and acceptable.

Based on the conservative results produced by the input described by Westinghouse, the staff concludes that the PAD 4.0 code is acceptable for LOCA analysis.

4.3 Audit of Fuel Melting Analysis

Westinghouse also provided an example of PAD 4.0 input and analysis results of best estimate fuel centerline temperatures that are used for the fuel melting analysis (Appendix B of Reference 10). FRAPCON-3 calculations were also made at various LHGRs to establish best estimate predicted fuel centerline temperatures near the fuel melting temperature using the same input as PAD 4.0. A comparison of the FRAPCON-3 and PAD 4.0 results demonstrated that PAD 4.0 predicted higher fuel centerline temperatures than FRAPCON-3 at BOL. Similar to the LOCA audit comparisons, the temperature differences decreased with increasing burnup such that PAD 4.0-predicted centerline temperatures became lower than those predicted by FRAPCON-3. Westinghouse has also claimed that the fuel melting analysis is limiting at BOL temperatures. PNNL analysis of fuel melting using FRAPCON-3 confirms that BOL predicted temperatures are limiting even with thermal conductivity degradation and the additional uncertainty in degradation considered.

Based on the conservative results produced by the PAD model, the staff concludes that the PAD 4.0 code is acceptable for fuel melting analysis.

5.0 CONCLUSIONS

The staff has reviewed the Westinghouse improved fuel performance code PAD 4.0 as described in WCAP-15063-P, Revision 1, and concludes that PAD 4.0 is acceptable for fuel licensing applications up to rod average burnup 62,000 MWd/MTU.

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Principal Contributor: S. Wu

Date: April 24, 2000

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Westinghouse Improved Performance Analysis and Design Model
(PAD 4.0)
Executive Overview

This revised topical report addresses all model changes made to the Westinghouse Performance Analysis and Design (PAD) model. The original topical report, submitted to the NRC in June 1998, addressed only changes made to the creep model used in the PAD model, but as the model development progressed, additional changes were identified. These additional changes were formally presented to the NRC in September 1998. Since all of these changes have been formally reviewed by the NRC, it has been requested by the NRC that the originally submitted topical report be revised to encompass all the model changes made to PAD. Therefore, the revised topical report has been divided into two sections: Section 1 (the originally submitted in-reactor creep model), and Section 2 (other model changes made to PAD and submitted to the NRC in September 1998).

PAD is a best estimate fuel rod performance model used for both fuel rod performance and safety analysis inputs. The last version of PAD that was reviewed by the NRCwas PAD 3.4. The changes made to PAD 4.0 will be related to changes made from this previously licensed version (i.e., PAD 3.4).

Section 1

Westinghouse In-Reactor Creep Model

Westinghouse In-Reactor Creep Model

1.0 Introduction & Background

The Westinghouse Performance Analysis and Design (PAD) model is a best estimate fuel rod performance model used for both fuel rod performance analysis and safety analysis inputs. The PAD code consists of several fuel rod performance models integrated to predict fuel temperature, rod pressure, fission gas release, cladding elastic and plastic behavior, cladding growth, cladding corrosion, fuel densification, and fuel swelling as a function of linear power and time. Many of the fuel rod performance models were first introduced to the NRC (then AEC) in the 1972-1973 time frame[(1)(2)(3)(4)]. Subsequent to the original model introduction, two specific revisions have been submitted for review and approval (i.e., PAD 3.3[(5)] and PAD 3.4[(6)]). With respect to the creep model used in PAD, the original model form remains in effect except for a revision that occurred to the irradiation enhanced creep portion of the model in PAD 3.4. The thermal creep portion of the model has remained the same since the model's inception in 1972.

1.1 Purpose

The purpose of this section is to introduce the new creep model to be used in the overall PAD fuel rod performance model. The new creep model accounts for advances in the understanding of in-reactor creep that have occurred between 1972 and 1998, and represents a description of in-reactor creep relative to the information and data that are available in 1998. This model enhancement is projected to restore rod internal pressure limit margin to the fuel rod design criterion.

1.2 Discussion of the Current PAD Creep Model (PAD 3.4)

The total in-reactor creep rate, de/dt, in PAD 3.4 is evaluated as the sum of the out-of-reactor (laboratory) thermal creep rate, de/dt(out-rx tc), plus the irradiation enhanced creep rate, de/dt(ic).

$$de/dt = de/dt(out\text{-}rx\ tc) + de/dt(ic) \qquad (1)$$

The out-of-reactor (laboratory) thermal creep rate, de/dt(out-rx tc), is a function of clad temperature, clad equivalent or effective stress and time. [

]^{a,c}.

The irradiation enhanced creep rate, de/dt(ic), is a function of neutron flux and fluence. [

]^{a,c}.

1.3 Evaluation of PAD 3.4 Creep Model - Need for Change

With the current generationof fuel and the enhanced operational performance requirements placed on the fuel (i.e., increased cycle lengths, higher operating system temperatures, higher operating power levels, higher peaking factors, and higher burnup levels), enhanced modeling and prediction capabilities are necessary to demonstrate the continued acceptable performance of thefuel to the original fuel rod design criteria. As such, new post-irradiation examination (PIE) data needs to be accounted for and incorporated into the fuel rod performance models. This new PIE data has already demonstrated a need to revise the fuel rod corrosion model in PAD[7]. In addition, other material property characteristics exist that previously had not been accounted for, either due to the lack of available data or the level of sophistication of the mechanics. With new data now available and the level of sophistication of the mechanics reaching closer to the phenomenological level, significant improvements to the fuel rod performance models can be achieved.

A review of current in-reactor creep models and methods was performed by Westinghouse relative to the state-of-the art mechanics of fuel rod behavior. This involved a detailedreview of work performed by AECL and reported in 1996 by Christodoulou et al.[8]. The subsequent work performed at AECL, reported by Christodoulou, has demonstrated that the PAD 3.4 in-reactor creep model is overly conservative and needs to be revised. Christodoulou presented the formulation and results of a fundamental-empirical model describing the in-reactor creep of cold-worked (CW) Zr-2.5Nb for pressure tube application. Some of the many models proposed to describe the in-reactor creep of zirconium alloys are described in References 8, 9 and 10. The Christodoulou model is considered to be the most fundamental model that is also based on the largest in-reactor data set to date. The model includes the effects of texture, grain shape, anisotropy and the relative contributions of prismatic, basal and pyramidal planes to dislocation climb assisted glide. This in-reactor model includes data from creep measurements of pressure tubes in power reactors, pressure tubes in test reactors, small pressurized tubes in test reactors and beam stress relaxation samples in test reactors. The test data includes samples with thermal creepstrain. In addition, the test data includes textures typical of both pressure and fuel-cladding tubes. As a result, the framework of this model was selected by Westinghouse to formulate a new in-reactor creep model for fuel rod application.

According to the Christodouloumodel, the in-reactor creep rate is the sum of the in-reactor thermal creep rate, de/dt(tc), and the irradiation enhanced creep rate, de/dt(ic).

$$de/dt = de/dt(tc) + de/dt(ic) \quad (2)$$

[

]^{a,c}. As a result, the predicted total creep rate from the current PAD model (Equation (1)) is higher than that derived from Equation (2) and is therefore conservative. This effect will be discussed in subsequent sections.

The PAD creep model needs to be revised dueto the demonstrated fact that the original PAD 3.4 creep model is conservative; therefore, there is a need to account for new PIE data and material property behavior. Specifically, the PAD 3.4 in-reactor creep model is being replaced for the following reasons:

- [ ]a,c

- [ ]a,c

- [ ]a,c

  Out-of-reactor and in-reactor creep behavior is dependent on fabrication process parameters such as final area reduction, intermediate anneal temperature, final anneal temperature and time and post-extrusion anneal temperature.

- [ ]a,c

- [ ]a,c

2.0 New PAD In-Reactor Creep Model

The new in-reactor creep model developed for fuel rod application in PAD is based on [

] a, c. According to Christodoulou, the total in reactor creep rate is the sum of the in-reactor thermal creep rate, de/dt(tc), and the irradiation enhanced creep rate, de/dt(ic)

$$de/dt = de/dt(tc) + de/dt(ic) \tag{2}$$

[ ] a, c.

The new in-reactor creep model was developed to describe Westinghouse cold-worked stress relieved (CWSR) tubing. The specific material behavior of the new PAD model is based on Westinghouse cladding. [

] a, c the new creep model describe Westinghouse cladding.

2.1 In-Reactor Thermal Creep Overview

The new in-reactor creep model was developed to describe Westinghouse cold-worked stress relieved (CWSR) improved (IMP) Zr-4 (low tin Zr-4) tubing. The model is based on [

] a, c. The in-reactor thermal creep is given by the out-of-reactor (laboratory) thermal creep corrected for in-reactor irradiation hardening. This behavior is described by:

[ ] a, c (3)

where [

] a, c. The equation [

] a, c. The equation for [ ] a, c is given by:

[ ] a, c (11)

where [ ]^{a,c}. The thermal creep strain given by [ ]^{a,c} IMP Zr-4 thermal creep tests [ ]^{a,c} according to:

[ ]^{a,c} (4)

The expression for IH is:

[ ]^{a,c} (5)

where [ ]^{a,c}. Equation (5) provides a smooth transition with increasing fluence from no irradiation hardening [ ]^{a,c} to complete irradiation hardening [ ]^{a,c}. The irradiation hardening [ ]^{a,c}. The application of the [ ]^{a,c}.

Since both [ ]^{a,c}. Thus:

[ ]^{a,c} (6)

The derivative of the numerator is given by:

[ ]^{a,c} (35)

The derivative of the denominator is given by:

[ ]^{a,c} (36)

and the expression for de/dt(tc) is:

[

]^{a,c} (37)

2.2 Irradiation Enhanced Creep Overview

The new irradiation enhanced creep component was developed using [ ]^{a,c}. The irradiation creep behavior [ ]^{a,c}. Since the [ ]^{a,c}. The irradiation enhanced creep rate equation is given by:

[ ]^{a,c} (7)

where [ ]^{a,c}. The [ ]^{a,c} creep rate equation is given by:

[ ]^{a,c} (8)

where [ ]^{a,c}. The [ ]^{a,c}. The equation was [ ]^{a,c} out-of-reactor (laboratory) thermal creep rates [ ]^{a,c}. The calculation was performed for typical fuel rod parameters. The parameters used were [ ]^{a,c}. C_3 was evaluated according to:

[ ]^{a,c} (9)

The results of the analysis are listed in Table 7.

The [ ]^{a,c} measurements were performed at PWR reactor coolant temperature. Irradiation enhanced creep increases with increasing temperature. The [

]^{a,c} in:

[ ]^{a,c} (10)

where [

]^{a,c}. Hence, Equation (10) gives the [

]^{a,c}.

A more detailed evaluation of each component of the PAD model is provided in the subsequent sections.

3.0 Creep Model Detailed Justification

As stated in the previous section, a more detailed justification for the equations and coefficients follows below for a more thorough understanding of Westinghouse's model development.

3.1 Out-of-Reactor (Laboratory) Thermal Creep

The out-of-reactor (laboratory) creep behavior of CWSR Zr-4 tubing fabricated by Westinghouse was established for [ ] a, c. Internal pressure creep tests were conducted using [

] a, c. The test samples in each test condition were strained into the secondary creep region. The internal pressure and diametral strain were converted to mid-wall hoop stress and strain. The mid-wall hoop strain data were analyzed by separating the total strain into primary and secondary components. The following equations resulted:

- Total creep strain, e (fraction):

[ ] a, c (11)

where t is the time (hour).

- Secondary creep rate, $(de/dt)_s$ (fraction/hour):

[ ] a, c (12)

where [

] a, c.

- Elastic modulus, E_E (psi):

[ ] a, c (13)

where TF is the temperature in (°F).

- Saturated primary strain, e_p (fraction):

[ ] a, c (14)

- Time coefficient, K:

[ ]$^{a, c}$ (15)

The PAD code calculates [

]$^{a, c}$ is:

[ ]$^{a, c}$ (16)

The coefficient [

]$^{a, c}$ is therefore given by:

[ ]$^{a, c}$ (17)

3.2 In-Reactor Thermal Creep

3.2.1 Irradiation Hardening

3.2.1.1 Model Development

The determination of the in-reactor creep components may be illustrated by the CW Zr-2.5Nb pressure tube reported by Fidleris[11] as shown in Figure 2. The tube was irradiated for 27,550 hours in the Whiteshell WR-1 test reactor. At the outlet end of the tube the temperature is 650K (711 °F) and the hoop stress is 43 MPa (6.2 ksi), [ ] a, c. These temperatures are considerably higher than normal CANDU pressure tube service operation temperatures, because the Whiteshell test reactor used organic coolant.

[

] a, c. This clearly shows that irradiation reduces the out-of-reactor (laboratory) thermal creep strain, i.e., that irradiation hardening of out-of-reactor (laboratory) thermal creep occurs.

The irradiation hardening of out-of-reactor (laboratory) thermal creep is further illustrated by [

] a, c. This clearly shows that irradiation decreases (or "hardens") the out-of-reactor (laboratory) thermal creep. [

]^{a,c}.

The irradiation hardening effect on the out-of-reactor (laboratory) thermal creep is even noticeable[

]^{a,c}.

The irradiation enhanced component is [ ]^{a,c}.

[ ]^{a,c} (18)

This is shown in Figure 3 as the irradiation enhanced component.

The irradiation hardening [

]^{a,c} may be described by an equation of the form:

[ ]^{a,c} (19)

where Φ is the fluence in n/cm^2 (E>1 MeV). Equation (19) provides a smooth transition with increasing fluence from no irradiation hardening [

]^{a,c} to complete irradiation hardening [ ]^{a,c}.

3.2.1.2 Model Evaluation

The irradiation hardening factor, [

]a,c. This shows that the Zircaloy-2.5Nb data are applicable to Zircaloy-4. [

]a,c. The results were:

[ ]a,c (20)

[ ]a,c

The [

]a,c.

The result was:

[ ]a,c (21)

These results indicate that the in-reactor irradiation hardening of thermal creep is [

]a,c.

Limback and Andersson[10] reported a model that describes the in-reactor creep behavior of CWSR Zr-4 cladding. The [

]a,c. The equations are:

[ ]a,c (22)

where [ ]a,c, and:

[ ]a,c (23)

where [

]a,c Equation (23) becomes:

[ ]a,c (23a)

The calculated IH factors using Equation (23a) are presented in Figure 6 as a dashed line. Figure 6 shows that the calculated [

]a,c.

3.2.2 Irradiation Creep

3.2.2.1 Modeling of the B&W/EPRI Data

The determination of the irradiation enhanced creep component was performed using the reported B&W/EPRI Oconee-2 creepdown data[15]. The tabulation presented by Franklin[20] is the [

]a,c. The hoop strain, $\Delta D/D$, was described by an equation of the form:

[ ]^{a,c} (24)

where [

]^{a,c}:

[ ]^{a,c} (25)

[ ]^{a,c}

Figure 12 shows that this fit is in excellent agreement with the data.

[

]^{a,c}.

The steady state irradiation creep component is [

]^{a,c}.

The [

]^{a,c}.

3.2.2.2 Normalization of B&W/EPRI Irradiation Creep to Westinghouse Behavior

The out-of-reactor (laboratory) thermal creep rates are directly related to the in-reactor irradiation creep rates for a given zirconium alloy. This relationship [

]a,c.

In the case of the [

]a,c.

The B&W/EPRI in-reactor creep data [

]a,c.

The out-of-reactor (laboratory) thermal creep rates may be [

] a,c.

The irradiation enhanced creep behavior [

] a,c according to Equation (26):

[ ] a,c (26)

[

] a,c:

[ ] a,c (27)

Equation (27) may be written as:

[ ] a,c (28)

For [ ] a,c.

Equation (28) becomes,

[ ][a,c] (29)

which is the form of Equation (26). Hence, Equations (26) and (27) are related by the relationships, [

][a,c]. The conversion factors are:

[ ][a,c] (30)

[ ][a,c]

and the resulting equation for [ ][a,c] is:

[ ][a,c] (31)

where [

][a,c]:

[ ][a,c] (32)

The average value for C_3 was

[ ][a,c] (33)

This factor was [ ][a,c].

3.2.2.3 Irradiation Creep Temperature Dependence

The irradiation creep temperature dependence was [

]^{a,c}. The data may be described by a function:

$$[\qquad]^{a,c} \tag{34}$$

where [ ]^{a,c}.

3.3 In-Reactor Creep Model

The behavior of the in-reactor creep model is illustrated in Figure 17. The calculation of the creep rates were performed for typical fuel rod parameters. The parameters were [ ]^{a,c}. The out-of-reactor thermal and in-reactor thermal creep components are also shown.

4.0 Application to ZIRLO™

The in-reactor creep model developed above to describe CWSR IMP Zr-4 may be applied to ZIRLO™. This application may be accomplished using the Westinghouse IMP Zr-4 and ZIRLO™ fuel rod creepdown data. Generally, after 1-cycle, the cladding is freestanding (i.e., fuel pellet contact has not occurred). [

]^{a,c}.

The irradiation creep behavior exhibited by Westinghouse IMP Zr-4 and ZIRLO™ fuel rods is considered to be consistent with in-reactor irradiation creep data. [

]^{a,c}.

Higher burnup Westinghouse IMP Zr-4 and ZIRLO™ fuel rods are available. Table 6B [

]^{a,c}. As a result of this ZIRLO™ creep discussion, a multiplier will be used to account for ZIRLO™ creep as compared to IMP Zr-4 creep.

5.0 Summary and Conclusions

In summary, the discussion above presented a new in-reactor creep model. The model was developed based on the best available zirconium alloy in-reactor creep models and data available to date. The model is consistent with fundamental descriptions of in-reactor creep. As a result of the mechanistic approach, the model is expected to be much more consistent with in-reactor creep behavior. The model describes the behavior of Westinghouse CWSR tubing. The total in-reactor creep rate is composed of irradiation enhanced and in-rector thermal components. The irradiation enhanced component is dependent on the stress, flux (and fluence) and temperature. The in-reactor thermal component is dependent on the stress, time, temperature and fluence.

6.0 References

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Table 1
IMP Zr-4 Out-of-Reactor (Laboratory) Thermal Creep Data

a, c

Table 2A

Calculated STD Zr-4 Out-of-Reactor Creep Rate Values as a Function of Time

[ ] a, c

Table 2B

Out-of-Reactor Creep Rate Normalization Factor for IMP Zr-4 Data Relative to STD

[ ] a, c

Table 3

Irradiation Hardening Reduction Factors Evaluated by Strain Ratio and Strain Rate Ratio Analysis

	[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]		[redacted]
[redacted]	[redacted]		[redacted]
[redacted]	[redacted]		
[redacted]	[redacted]		

Table 4
Comparison of Oconee-2 In-Reactor and
Out-of-Reactor (Laboratory) Creep Rates.

[ ] a, c

Table 5
Average Diameter Creepdown of IMP Zr-4 and ZIRLO™ Fuel Rods
in the High Power Region of North Anna Advanced Material Demonstration Assemblies

[ ] a, c

Table 6A

Westinghouse 1-Cycle Fuel Rods

[ ] a, c

Table 6B

Westinghouse High Burnup Fuel Rods

[ ] a, c

Table 7

Calculated Values of the Coefficient C_3

a, c

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Table 8

ZIRLO™ North Anna In-Reactor Creepdown

and Out-of-Reactor Thermal Creepout

a, c

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]			[redacted]
[redacted]					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]		[redacted]	[redacted]
[redacted]					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
				[redacted]	[redacted]

Figure 1

Out-of-Reactor Thermal Creep Steady State Rate - Tin Dependence

a, c

[ ]

Figure 2

CW Zr-2.5Nb Pressure Tube Diameter Data (the flux data are not accurate)

Figure 8 of Reference 11

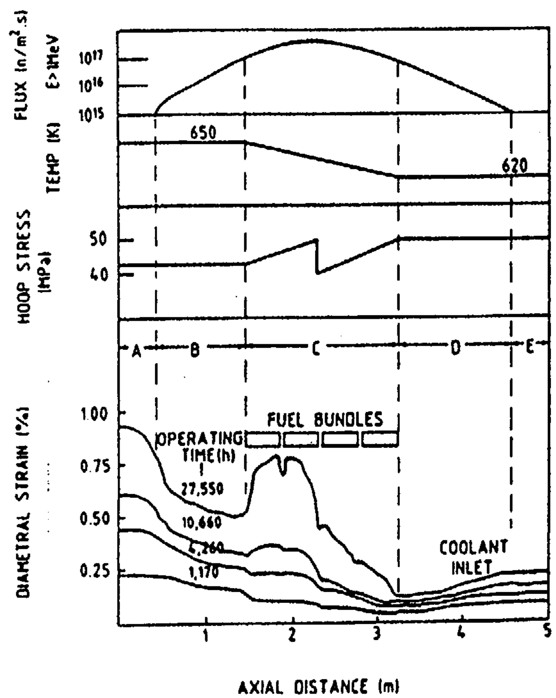


Fig. 8. Diametral creep of cold-worked Zr-2.5Nb loop tube in WR-1 reactor.

Figure 3

Creep Components - CW Zr-2.5Nb Pressure Tube

650 K, 43 MPa Hoop Stress

a, c

Figure 4

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 4 of Reference 13

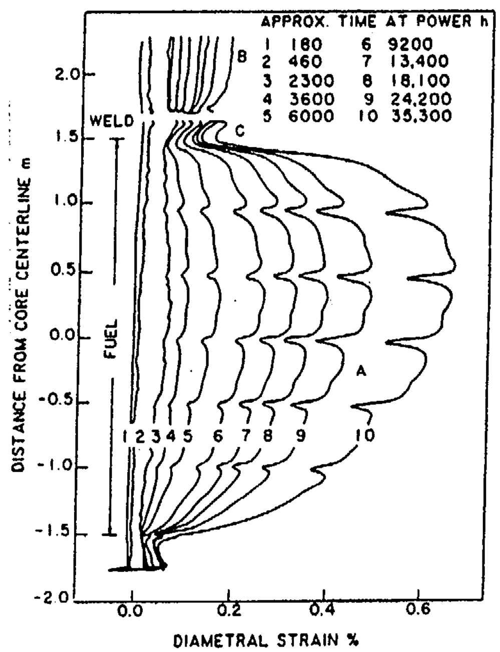


FIGURE 4 Diametral strain of cold-worked Zr-2.5 wt% Nb pressure tube vs axial location in NRU. Illustrating

A approximate cosine distribution of strain in fueled zone
B creep in upper extension, and
C suppression of creep near edge of core.

Figure 5

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 7 of Reference 14

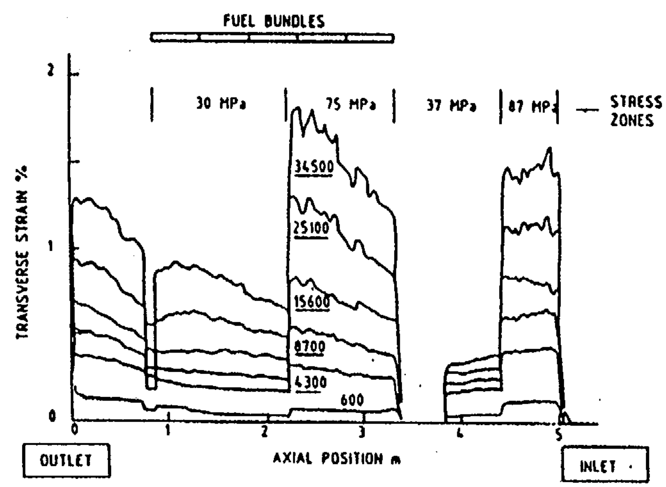


FIG. 7—*Transverse strain profiles of a pressure tube in WR1.*

Reprinted from Influence of Radiation on Material Properties: 13th International Symposium (Part II), ASTM STP 956, A. R. Causey, V. Fidleris, S. R. MacEwen and C. W. Schulte, "In-Reactor Deformation of Zr-2.5 wt% Nb Pressure Tubes", pp 54-68, Copyright 1987, with permission from ASTM.

Figure 6

Saturated Out-of-Reactor (Laboratory) Thermal Creep Reduction Factor

a, c

Figure 7

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 69 MPa

a, c

Figure 8

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 86 MPa

a, c

Figure 9

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 103 MPa

a, c

Figure 10

CWSR Zr-4 Saturated Transient Component, B&W/EPRI, Lot S-1, 577-578 K

a, c

Figure 11

CWSR Zr-4 Steady State Component, B&W/EPRI, Lot S-1, 577-578 K

a, c

Figure 12

Comparison of Measured and Calculated Strain for CWSR Zr-4

Lot S-1, B&W/EPRI, 577-578 K

a, c

Figure 13

CWSR Zr-4, Lot S-1, B&W/EPRI, 581-582 K, 103 MPa

a, c

Figure 14

CWSR Zr-4 Apparent Temperature Dependence

Lot S-1, B&W/EPRI, 103 MPa

a, c

Figure 15

Comparison of In-Reactor and Out-of-Reactor Creep Rates

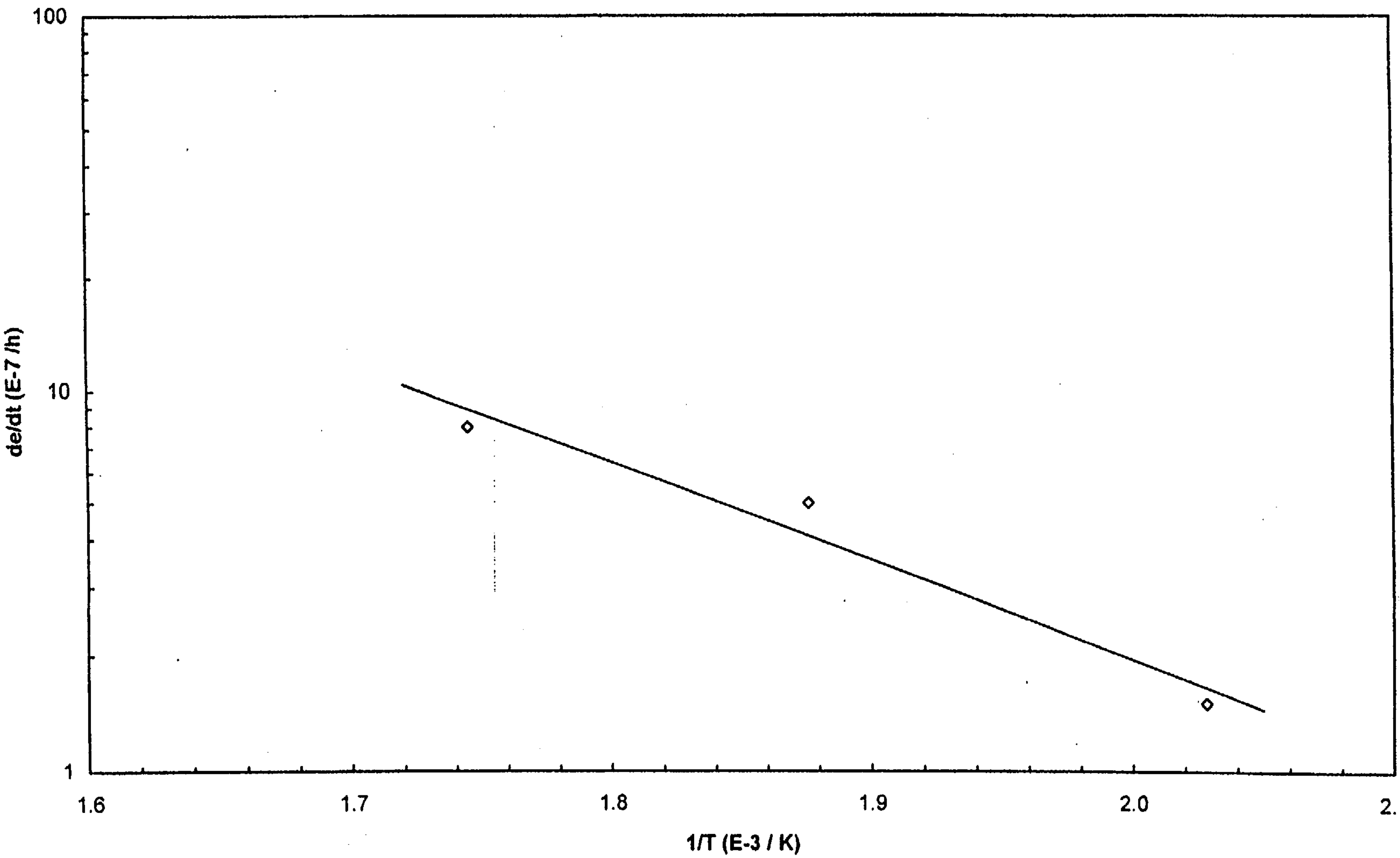
B&W/EPRI, 86 MPa

a, c

Figure 16

CW Zr-2 Irradiation Creep Temperature Dependence, 207 MPa

From Reference 16



Graphical representation of data from Reference 16

This figure was not included in Reference 16

Figure 17

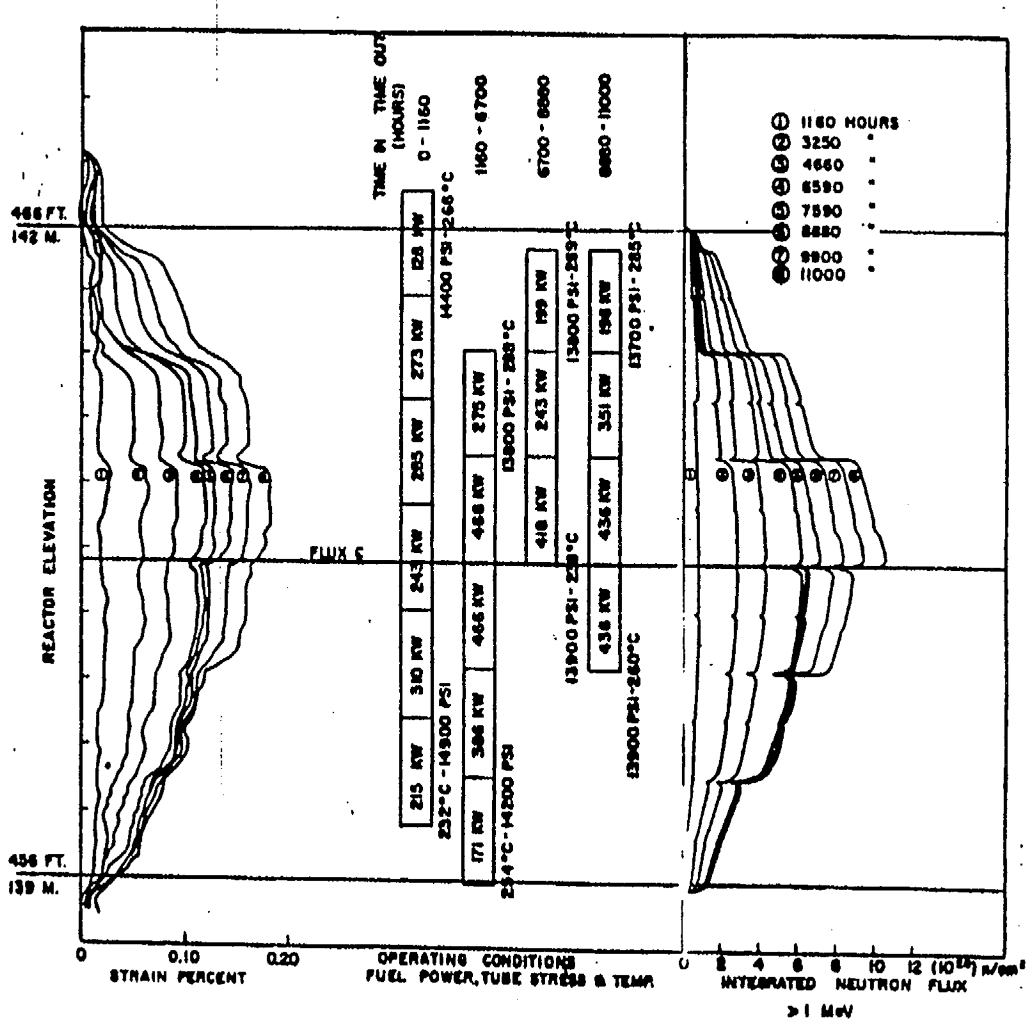
CWSR IMP Zr-4 In-Reactor Creep

1.08×10^{22} n/cm^2 (E > 1 MeV), 41 MPa (6.0 ksi) Hoop Stress

a, c

Figure 18

Operating Conditions Fuel Power, Tube Stress & Strain versus Reactor Elevation



Reprinted from P. A. Ross-Ross and C. E. L. Hunt, "The In-Reactor Creep of Cold-Worked Zircaloy-2 and Zirconium-2.5 wt % Niobium Pressure Tubes," Journal of Nuclear Materials, Volume 26, 1968, pages 2 through 17, with permission from Elsevier Science

Figure 19

Westinghouse BR-3 Fuel Rod Profilometry (Creepdown)

ZIRLO™ 15x15 Cladding

a, c

Figure 20

Out-of-Reactor Thermal Creep (Creepout)

658 K (725 °F), 108 MPa (15.6 ksi) Equivalent Stress

a, c

Figure 21

Comparison of In-Reactor and Out-of-Reactor Creep Rates

Westinghouse ZIRLO™

a, c

Section 2
Other PAD Model Changes

1.0 Revised PAD Code Summary of Changes

The following changes have been incorporated into the revised PAD code:

1) Revised Creep Model (described in Section 1 of this report),
2) Revised Rod Irradiation Growth Model,
3) Updated Zr-4 and ZIRLO™ Clad Thermal Conductivity Values,
4) Updated Zr-oxide Thermal Conductivity Value,
5) Updated Equation of State (EOS) Model,
6) Variable Oxide-Metal Ratio Model (as discussed during the Westinghouse/NRC meeting on May 5, 1998), and
7) Gas Absorption in Cladding Effect.

Item 1 was submitted in the original version of WCAP-15063-P. Items 2 through 7 were presented to the NRC as additional model changes that were being incorporated into the PAD model during a meeting with the NRC and Battelle Northwest Labs (reviewer of the WCAP). These latter items were requested to be incorporated into WCAP-15063-P by the NRC since that had been reviewed along with the revised creep model and would be the basis for the new PAD 4.0 model.

1.1 Revised Creep Model

Description: Refer to WCAP-15063-P for creep model details. This is a substantial improvement in the creep model, which is an important model with wide-reaching impacts for all of the subsequent calculations in the revised PAD code.

Why Change?: The revised creep model is fundamentally sound and has a much more rigorous in-reactor data base to support the mechanistic understanding of in-reactor creep. The new model incorporates temperature-dependent irradiation creep and irradiation hardening.

Effect of change: The overall impact of the revised creep model in the revised PAD code on rod internal pressure predictions is favorable.

1.2 Revised Rod Irradiation Growth Model

Description: The current PAD model (WCAP 10851-P-A) does not have a temperature dependence for irradiation growth of zirconium alloys. The revised PAD model incorporates this temperature dependence.

Why change?: This change is based on work reported by the industry which has been demonstrated at EBR-II and DIDO that irradiation growth is a strong function of temperature, particularly for temperatures above 660 K (728 °F).

Effect of change: This is a relatively small change which will only effect rod growth when high temperatures are present in the cladding.

1.3 Updated Zr-4 and ZIRLO™ Clad Thermal Conductivity Values

Description: PAD (WCAP-10851-P-A) currently uses conductivity values from open literature for Zircaloy-4 and Zircaloy-2, for Westinghouse Zr-4 and ZIRLO™. The revised PAD code uses measured values on Westinghouse fuel products; for both ZIRLO™ and Zr-4.

Why change?: Experimental work was conducted specifically to update the database for Westinghouse product, and when incorporated will substantially improve thermal model accuracy.

Effect of Change: This update has a positive impact on rod internal pressure by slightly lowering clad temperatures for a given power level.

1.4 Updated Zr-oxide Thermal Conductivity Values

Description: PAD (WCAP-10851-P-A) currently uses a value for zirconium-oxide thermal conductivity based on work done in 1979 on theoretically-dense zirconium-oxide in a vacuum. Recent EPRI-sponsored work shows that the oxide thermal conductivity is higher than that currently included in PAD. Oxide thermal conductivity has been revised in the new version of PAD based on this work.

Why Change?: Recent in-pile tests indicate that a more conductive thermal oxide layer is formed in PWR environments, which enhances the oxide thermal conductivity. This change will enable more accurate assessments of the rod thermal response characteristics consistent with industry understanding of zr-oxide properties.

Effect of Change: This change yields a small reduction in clad average temperature and thus a reduction in fuel centerline temperature.

1.5 Equation of State (EOS) Gas Model

Description: PAD (WCAP-10851-P-A) currently uses the ideal gas law for calculating the pressure inside the fuel rods. A review of the available state-of-the art gas laws, show that a new equation of state (EOS) model is more accurate. The revised PAD code uses the Peng-Robinson EOS model for the calculation of fuel rod internal pressure.

Why change?: Changing the PAD gas model from the ideal gas law to the Peng-Robinson EOS will more accurately represent the internal gas pressure of Westinghouse fuel rods.

Effect of Change: This model causes the predicted rod pressure to increase for a given burnup higher than the current ideal gas law and has a small negative effect on rod internal pressure.

1.6 Variable Oxide-Metal Ratio Model

Description: PAD (WCAP-10851-P-A) currently uses a constant theoretical oxide-metal ratio 1.56 to calculate metal wastage. Westinghouse previously identified to the NRC (May 1998) that we would be using a value of [

]^{a,c}.

Why change?: The change in oxide characteristics as the thickness increases has been documented in public literature and measured on archive hot cell photomicrographs.

Effect of Change: This change allows for accurate calculation of remaining wall thickness as oxide is generated and thus improves accuracy of the clad stress and creep calculations.

1.7 Gas Absorption in Cladding Effect

Description: PAD (WCAP-10851-P-A) currently models that air can contribute to the internal pressure of the fuel rod throughout life. Air is rapidly absorbed into the cladding by forming hydrides, oxides and nitrides of zirconium and is eliminated from gas pressure calculations in the revised PAD code.

Why change?: Published literature on diffusion/reaction rates for gases in zirconium alloys, confirms a rapid consumption of any air or reactive gases is expected at operating fuel temperatures. [

]^{a,c}.

Effect of Change: This change will result in a small reduction in rod internal pressure.

2.0 Revised Rod Irradiation Growth Model

2.1 Model Background and Justification

Extensive in-reactor testing has been performed in EBR-II (fast neutron spectrum) and DIDO (thermal spectrum). One set of tests reported by Rogerson determined the irradiation growth in DIDO and EBR-II with the same material (RXA Zr-2)[1]. Theresult shows that the growth strain exhibited by the EBR-II sample is within the sample-to-sample scatter exhibited by the DIDO data. This result shows that irradiation growth data measured in a fast neutron spectrum (specifically EBR-II) is applicable to thermal neutron spectra. Therefore, the EBR-II data may be applied to PWRs.

The available CW irradiation growth data covers an extensive parameter range. The temperatures are in the range of 353 to 687 K (176 to 777°F), and the fluences extend up to values similar or higher than typical end-of-life PWR fuel rods (1.7×10^{22} n/cm^2, E > 1 MeV). In the case of the EBR-II tests, large growth strains were observed (strains as large as 2.5%)[2]. At high fluences (> 0.5×10^{22} n/cm^2, E > 1 MeV) and temperatures > 650 K, the irradiation growth strain and strain rate is the same for CW and RXA material. Figures from Reference 2 for 20% CWSR Zr-2 slab material show that this behavior is not texture or temperature dependent (for temperatures > 650 K).

2.2 PAD Revision

The revised PAD irradiation growth equation was modified using the irradiation growth rate temperature dependence reported by Fidleris et. al.[3]. At temperatures > 660 K, the irradiation growth rate increases rapidly with increasing temperature. The high temperature effect (for temperatures > 660 K), was modeled by [

] a,c (see Figure 2-1):

[ ]a, c

[

] a,c.

Figure 2-1

G/G_o versus Temperature

a, c

3.0 Updated Zr-4 and ZIRLO™ Clad Thermal Conductivity Values

3.1 Model Background and Justification

Table 3-1 summarizes the thermal conductivity values calculated as a function of temperature, based on the tests conducted by the "Properties Research Laboratory" in West Lafayette, Indiana, on Westinghouse Zircaloy-4 and ZIRLO™ cladding. [

] a, b, c.

A linear fit of the data presented in Table 3-1 yields the following best estimate model for Zircaloy-4, in the temperature range of [ ] a, b, c.

[ ] a, b, c (1)

where, k = Thermal Conductivity in $Wcm^{-1}K^{-1}$
T = Temperature in °C

In the case of ZIRLO™, a linear fit of the data presented in Table 3-1 yields the following best estimate model in the temperature range of [ ] a, b, c.

[ ] a, b, c (2)

where, k = Thermal Conductivity in $Wcm^{-1}K^{-1}$, and
T = Temperature in °C

Figure 3-1 represents the linear plots of thermal conductivity versus temperature forZircaloy-4 and ZIRLO™ as represented by Equations 1 and 2 respectively.

3.2 PAD Revision

In view of the fact that the maximum allowable clad design temperature for steady state operation for Zircaloy-4 is [ ] a, c and for ZIRLO™ is [ ] a, c respectively, and for Condition II transients is [ ] a, c for Zircaloy-4 and [ ] a, c for ZIRLO™, models represented by Equation (1) for Zircaloy-4 and Equation (2) for ZIRLO™ clad will be used for thermal conductivity predictions as a function of temperature for Westinghouse fuel clad in the revised PAD code.

Table 3-1

Thermal Conductivity as a function of temperature

[ ] a, c

Figure 3-1

Thermal Conductivity as a Function of Temperature

for Zircaloy-4 and ZIRLO™

(1st Order Fit)

a, c

4.0 Updated Zr-Oxide Thermal Conductivity Value

4.1 Model Background and Justification

A best estimate value of [ ]^{a,b,c} has been used in PAD (WCAP-8720) for Zr-4 oxide layers, based on data from Reference 4. Since that time, additional data have become available (References 5 and 6) which indicates that the oxide layer thermal conductivity has a higher value. The purpose of this update is to use the appropriate data from References 5 and 6 to establish a revised best-estimate average value of the Zr oxide layer thermal conductivity.

The first set of new ramp tests (Reference 5) consisted of a set of 12 ramps on four rods with oxide layer thicknesses of 30, 54, 66 and 82 microns. Thermal conductivity values ranged from 1.4 to 3.7 W/mK with an average value of 2.4 W/mK.

The second set of ramp tests, Reference 6, was run because there was no clear dependence of oxide thermal conductivity on oxide layer thickness, and it seemed that crud could have been present on two of the rods and that could have affected the results. The two fuel rods were brushed and the tests were repeated.

During the second set of ramps, it was noted that the rod elongation during up-ramps was greater than contraction during down-ramps. It was postulated that pellet-cladding mechanical interaction could be occurring during the up-ramps, and it was recommended that only the down-ramps be used for thermal conductivity measurements. The oxide layers were re-measured, and it was found that the thickness of the 26 micron layer was actually 30 microns.

A total of six down ramps were measured during the second set of experiments. The resulting thermal conductivity values are given in Table 3-2 of Reference 6. A summary of the thermal conductivities from the first set of ramps is given in Table 4-1.

Table 4-1

Summary of Conductivity Values From First Set of Ramps

[ ] a, b, c

These data were combined with data from the second set of ramps given in Table 3-1 of Reference 6. The combined data are given in Table 4-2. The variables are the TEST series, 1 or 2, the RAMP number, UP1D2 = 1 for up ramps and 2 for down ramps, t = the oxide thickness, and K = the thermal conductivity.

Table 4-2

Summary of Conductivity Data

[ ] a, b, c

Table 4-2 (cont.)
Summary of Conductivity Data

a, b, c

Table 4-2 (cont.)
Summary of Conductivity Data

[ ]a, b, c

The results of a statistical analysis of the Table 4-2 data for the down ramps are given below:

[ ]a,c
[ ]a,c
[ ]a,c

Tests were performed to determine if the conductivity values are normally distributed. [ ]a,c.

4.2 PAD Revision

In conclusion, the NFIR conductivity data can be characterized and included in the revised PAD code as follows:

[ ]a,c

for evaluating cladding temperatures with oxide layers present.

5.0 Updated Equation of State Model (EOS)

5.1 Model Background and Justification

The relationship between pressure, temperature, and mass for a fission gas in PAD (WCAP-10851-P-A) is based on the Ideal Gas Law,

$$PV = NRT \tag{3}$$

where *P* and *T* and the pressure and temperature of the gas respectively, *V* is the volume occupied by the gas, and *N* is the number of moles of gas. The universal gas constant is *R*. Equation (1) is equivalent to:

$$Pv = RT \tag{4}$$

where *v* is the specific volume and *R* is a (particular) gas constant.

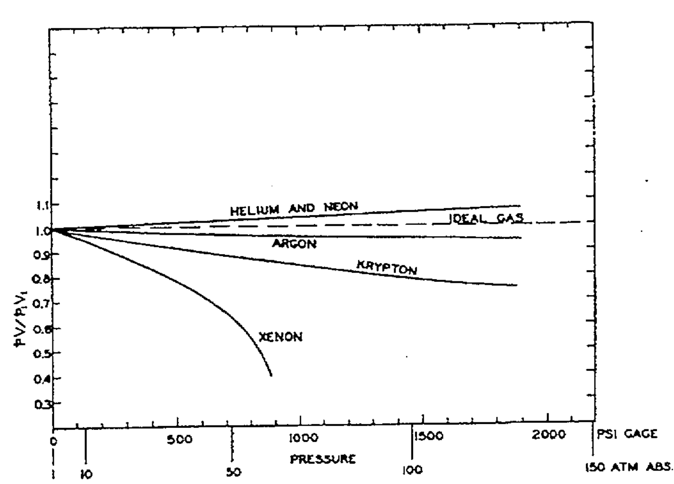
The Ideal Gas Law relationship is valid for many gases near room temperature and pressure, and is good for noble gases such as helium, neon, and argon up to moderate pressures (400 - 500 psia). At high pressures (P > 500 psia) however, the Ideal Gas Law becomes increasingly inaccurate. Figure 5.0, taken from Reference 8, shows the compressibility of several gases at high pressure, where compressibility Z is defined as:

$$Z = \frac{Pv}{RT} \tag{5}$$

For an ideal gas, the compressibility Z = 1.0. Deviation from 1.0 is an indication of non-ideal behavior, and that the use of the Ideal Gas Law will lead to inaccurate results.

Figure 5.0 shows that above about 500 psia, inert gases do not exhibit ideal behavior.

Figure 5-0
Compressibility of Inert Gas at 21 °C



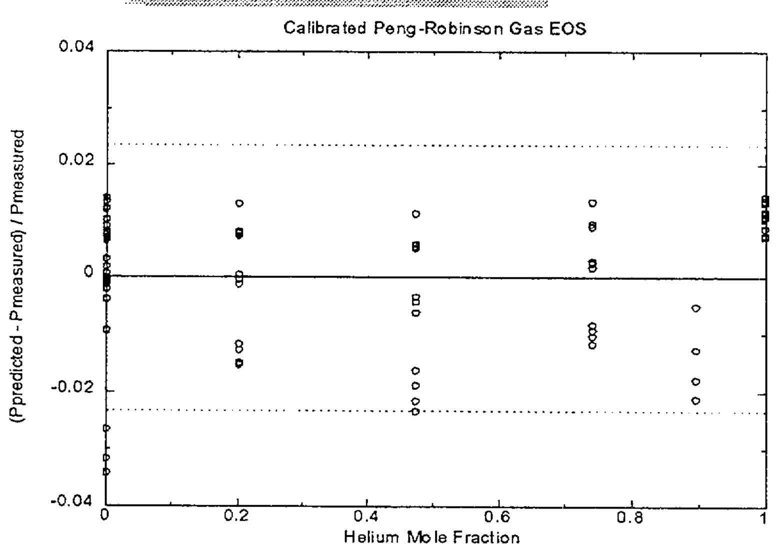
At end of life, when the rod internal pressure can exceed 2000 psia, none of these gases will exhibit ideal behavior. Therefore, use of the Ideal Gas Law to estimate rod pressure given the temperature and specific volume will be inaccurate. Since helium makes up the majority of the gas, and the compressibility of helium is greater than 1.0, the Ideal Gas Law will underpredict the actual rod pressure.

A survey was conducted to determine the most appropriate gas EOS. It was determined that the Peng-Robinson equation, Reference 9, gave the most accurate predictions for the range of interest. However, this EOS consistently under predicts the measurements over the whole range of helium mole fraction. A positive aspect of this EOS is that the prediction error is insensitive to the helium concentration, thus leading to the following (calibrated) gas EOS:

$$P^c = \alpha x P \qquad (6)$$

where P^c is the Corrected or Calibrated Peng-Robinson gas EOS, P is the original Peng-Robinson gas EOS and [ ]^{a,c} is a correction factor determined from the data depicted in Figure 5-2. Figures 5-2 show the graph for the Corrected Peng-Robinson EOS. The prediction errors are very balanced and range between -2% and 2%.

Figure 5-2
Calibrated Peng-Robinson Equation of State
ΔP/P versus Helium Mole Fraction



For fission gas mixtures even at end of life, helium has the highest mole fraction. To check the EOS for high

He mole fraction, the results were plotted as ΔP/P versus helium mole fraction. These results are shown in Figure 5-2. Measured data was obtained from References 10 through 14, for the various gas matrix evaluations.

Note that ΔP/P is defined as:

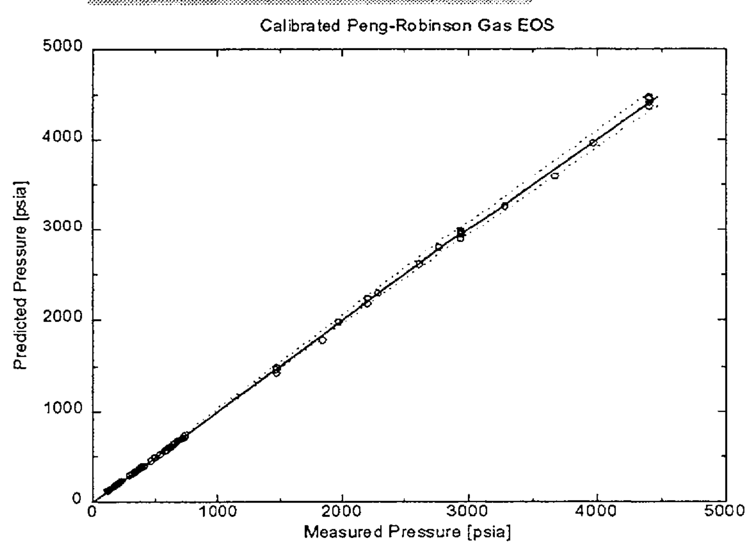
$$\frac{\Delta P}{P} = \frac{P_{prediction} - P_{measured}}{P_{measured}} \qquad (7)$$

This quantity is positive when the pressure is over predicted, and negative when under predicted.

From Figure 5-0 it becomes clear that for gas compositions rich in helium, the Ideal Gas Law may under predict the actual pressures, in some cases by more than 10%.

The Calibrated Peng-Robinson EOS performs well at high He composition. For any mole fraction, it predicts the pressure within +/- 2%. Figure 5-3 shows Calibrated the Peng-Robinson Predicted vs. Measured plot results for various pressures.

Figure 5-3
Calibrated Peng-Robinson Equation of State
Measured versus Predicted Pressure



5.2 Summary

The Ideal Gas Law was found to potentially under predict pressure for compositions with high helium mole fraction. The more complex cubic Equations of State (Redlich-Kwong, Soave, and Peng-Robinson) were more accurate at high helium mole fraction, and tended to over predict the pressure slightly. Of these three, the Peng-Robinson EOS was found to be slightly better than the other two.

5.3 Pad Revision

PAD revision investigations of several Equations of State applicable to gas mixtures when compared to available data over a range of pressure, temperature, and composition shows the Calibrated Peng-Robinson EOS is most accurate and will be used in the revised PAD code.

The pressure-temperature-volume relationship for a pure fluid is often represented by a cubic Equation of State, which has the general form:

$$P = \frac{RT}{v - b} - \frac{a}{v^2 + ubv + wb^2} \tag{8}$$

where P is the pressure, T is temperature, v is specific volume, and R is the Universal Gas constant.

For the Peng-Robinson equation of state, $u = 2, w = -1$ with

$$b = \frac{0.07780 T_c}{P_c} \tag{9}$$

and

$$a = \frac{0.45724 r^2 T_c^2}{P_c} [1 + f\omega (1 - T^{0.5}{}_r)]^2 \tag{10}$$

where,

$$f\omega = 0.37464 + 1.54226\,\omega - 0.26992\,\omega^2 \tag{11}$$

In Equations (7) and (8), the subscript "c" denotes properties at the critical point. The *reduced* temperature is defined as

$$T_r = \frac{T}{T_c} \tag{12}$$

The function for $f\omega$ given by Equation (9) uses the eccentric factor ω, which is a parameter that represents the complexity of a molecule with respect to geometry and polarity. For mono-atomic gases, ω is usually zero or very small.

In the revised PAD code up to seven different gases can be present in the gas mixture. The following table lists these components and the properties assigned in the code as taken from Reference 9:

Table 5-1
Pure Gas Component Properties List for PAD

Component	T_c (K)	P_c (bar)	ω
Helium	5.19	2.27	-0.365
Xenon	289.7	58.4	+0.008
Krypton	209.4	55.0	+0.005
Argon	150.8	48.7	+0.001
Nitrogen	126.2	33.9	+0.039
Water Vapor	647.3	221.2	+0.344
Hydrogen	33.2	13.0	-0.218
Oxygen	154.6	50.4	+0.025

For gas mixtures, the attraction and repulsion between molecules of different components causes non-linear variation of some properties with composition. To account for this in Equation (6), a set of mixing rules can be defined to this non-linearity. The values of "a" and "b" in Equation (6) are re-defined. Based on the recommendations in Reference 9, the following mixing rules are used in the revised PAD code.

$$a_m = \sum_i \sum_j y_i y_j (a_i a_j)^{0.5} (1 - k_{ij}) \tag{13}$$

$$b_m = \sum_i y_i b_i \tag{14}$$

The b_i and a_i for each pure component are given by Equations (7) and (8) respectively. The term k_{ij} is used for some binary pairs to adjust for strong interactions and is determined from experimental data. In the revised PAD code $k_{ij} = 0$, is assumed for all binary combinations.

6.0 Variable O-M Ratio Model

6.1 Model Background and Justification

In order to accurately model fuel rod clad temperatures and stresses in a fuel performance models as well as 17% metal wastage calculations, an accurate model of Zircaloy-4 oxide to metal ratio is needed for use in design. Due to the differences in densities of the oxide and the base metal, there is a volumetric change from the metal consumed to the oxide formation. This volumetric difference results in a thicker oxide than the metal that was consumed. The ratio of the volumes is characterized by the oxide-to-metal ratio (O/M). The theoretical oxide-to-metal ratio is referred to as the Pilling-Bedworth ratio, and for Zirconium based alloys the value of 1.56 is commonly used. However, during the in-reactor generation of ZrO_2, different mechanisms occur that cause the oxide density to be less than theoretical resulting in higher O/M ratios at increasing oxide thicknesses. Westinghouse metallographic O/M measurements from fuel rod hot cell programs were evaluated and a predictive model was generated which relates O/M with oxide thickness. [

]^{a,c}. This model was first presented to the NRC by presentation on May 5, 1998.

6.2 Variable O/M Ratio Model Details

As the oxide grows, it transitions from a protective to a non-protective structure. The non-protective oxide contains cracks and pores and this transition occurs when the oxide is about [ ]^{a,c}. In generating a model which predicts O/M ratio as a function of oxide thickness, the first [ ]^{a,c} of oxide should result in a constant theoretical value of O/M ratio. At higher oxide thicknesses, the data presented in the previous section is used to develop the relationship of O/M ratio with increasing oxide thickness.

The equations governing the O/M ratio as a function of oxide thickness are as follows:

$$\frac{O}{M} = \frac{O}{M_{Th}}, \quad t < [\quad]^{a,c} \tag{1}$$

$$\frac{O}{M} = [\qquad]^{a,c} \tag{2}$$

where: O/M_{th} = theoretical value of O/M ratio = 1.56
a = fitting coefficient, [ ]^{a,c}
b = fitting coefficient
t = oxide thickness (mils)

Equations 1 and 2 are combined and plotted against the sorted data from O/M measurements in Figure 6-1.

Figure 6-1
Best Estimate O/M Ratio Model

a, b, c

7.0 Gas Absorption in Cladding Effect

7.1 Model Background and Justification

The fuel rod internal gas mixture includes: (1) the fission gasses produced during operation, (2) gas from the pellets including the gas from the IFBA coating if present, (3) the gas from the rod pre-pressurization, and (4) the [ ]^{a,c}. When the rod is pre-pressurized and sealed during fabrication, the rod [ ]^{a,c}. Both IFBA and non-IFBA rods contain this equivalent volume[ ]^{a,c}. Zirconium alloys are known to react with [ ]^{a,c}.

For example, assuming a plenum volume of about [ ]^{a,c} and a gas mixture of [ ]^{a,c}.

With about [ ]^{a,c} the corresponding weight gain for total [ ]^{a,c}. Based on reaction rates in Reference 16, [ ]^{a,c} will occur within [ ]^{a,c}; thus, all of the [ ]^{a,c}.

Zirconium preferentially reacts with [ ]^{a,c} are present. The reaction rate with [ ]$^{a,c(2)}$. When the [ ]^{a,c}. The absorption rate of [ ]^{a,c}. Based upon the weight of[ ]^{a,c}. Thus, it will take about[ ]^{a,c}. This may be a lower than actual rate since rate is temperature dependent. [ ]^{a,c}.

Irradiated rods were punctured in the hot cell and the gas present in the rod was captured and analyzed. In the 22, [ ]^{a,c} measured and in 7 other rods from [ ]^{a,c} there was [ ]^{a,b,c}. The measurement sensitivity is reported as less than 0.01% by volume. If the[ ]^{a,c} pressurization and a resultant internal rod gas mixture with [ ]^{a,c} by volume. These levels, if present in the rod at end of life, are above the detection limit by a factors of over 100.

7.2 PAD Change

Evaluations indicate that the [ ]^{a,c} the Zirc-4 or ZIRLO™ microstructure and [ ]^{a,c}. Based on this evaluation, the revised PAD code will not use[ ]^{a,c}.

8.0 References

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SECTION C

June 9, 1998
NSD-NRC-98-5709

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: "Westinghouse In-Reactor Creep Model," WCAP-15063-P (Proprietary), WCAP-15064 (Non-Proprietary, June 1998

Dear Mr. Collins:

Enclosed, per commitments made during the May 5, 1998 NRC/Westinghouse meeting, are three copies of the Proprietary version of WCAP-15063-P, "Westinghouse In-Reactor Creep Model" and three copies of the Non-proprietary version (WCAP-15064) of the report.

The Westinghouse In-Reactor Creep Model is one of several sub-routine models incorporated into the Westinghouse Fuel Rod Performance Model (PAD). Due to the nature of PAD, a formal verification and validation process is required that involves both model calibration and uncertainty determination. The verification and validation will be performed with Westinghouse fuel rod data. The creep model will be calibrated using 1-cycle fuel rod diameter creepdown data. The 1-cycle data may be used for this purpose because the cladding is typically freestanding after 1-cycle.

In addition, higher burnup Westinghouse fuel rods will be used for verification and validation of the PAD code. This data will be used to obtain consistency between the PAD code and the fuel rod data. Note that the Westinghouse IMP Zr-4 profilometry creepdown data was not used in the development formulation of the new in-reactor creep model. The Westinghouse IMP Zr-4 profilometry creepdown data will be used to benchmark (or calibrate) the new PAD code creep behavior. High burnup fuel rod data is available for both IMP Zr-4 and ZIRLO™.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-98-1240 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-98-1240.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.5(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1240 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

copy to:
T. E. Collinsn, NRR
P. C. Wen, NRR

June 9, 1998
AW-98-1240

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief,
Reactor Systems Branch
Division of Systems Safety and Analysis

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: "Westinghouse In-Reactor Creep Model," WCAP-15063-P (Proprietary), WCAP-15064 (Non-Proprietary), June 1998

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5709, dated June 9, 1998

Dear Mr. Collins:

The application for withholding is submitted by Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse"), pursuant to the provisions of paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-98-1240 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-98-1240 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

cc: T. Carter / NRC (5E7)

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

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ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 9th day
of June, 1998.

Notary Public

Notarial Seal
Janet A. Schwab, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires May 22, 2000
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Division, of the Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked "Westinghouse In-Reactor Creep Model," (Proprietary), June 1998, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSD-NRC-98-5709) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of T. E. Collins, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information as submitted by Westinghouse Electric Company is to provide information on the revised Westinghouse Creep Model that is used in the Westinghouse Performance Analysis and Design model (PAD). This information is provided for review and approval of this revised creep model.

This information is part of that which will enable Westinghouse to:

(a) Ensure proper fuel performance of fuel operating in reactors.

(b) Assist customers to obtain license changes resulting from fuel performance modeling.

Further this information has substantial commercial value as follows:

(a) Westinghouse can use this fuel performance modeling capability to further enhance their licensing position over their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Westinghouse In-Reactor Creep Model

June 1998

Author:
J. P. Foster

Reviewed by:
N. Christodoulou, AECL

Edited by:
W. H. Slagle

APPROVED: S. Ray, Manager
Core Analysis & Fuel Licensing
Commercial Nuclear Fuel Division

APPROVED: D. Colburn, Manager
Materials and Fuel Rod Design
Commercial Nuclear Fuel Division

Westinghouse Electric Company
Commercial Nuclear Fuel Division
P. O. Box 355
Pittsburgh, Pennsylvania 15230

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Westinghouse In-Reactor Creep Model

Executive Overview

This topical report addresses the changes made to the creep model used in the Westinghouse Performance Analysis and Design (PAD) model. PAD is a best estimate fuel rod performance model used for both fuel rod performance and safety analysis inputs. The last version of PAD that was reviewed by the NRC was PAD 3.4. The changes to the creep model will be related to changes made from this previously licensed version (i.e., PAD 3.4). The new creep model will be incorporated into an overall revision to PAD that is planned to be released later this year.

Westinghouse In-Reactor Creep Model

1.0 Introduction & Background

The Westinghouse Performance Analysis and Design (PAD) model is a best estimate fuel rod performance model used for both fuel rod performance analysis and safety analysis inputs. The PAD code consists of several fuel rod performance models integrated to predict fuel temperature, rod pressure, fission gas release, cladding elastic and plastic behavior, cladding growth, cladding corrosion, fuel densification, and fuel swelling as a function of linear power and time. Many of the fuel rod performance models were first introduced to the NRC (then AEC) in the 1972-1973 time frame[1][2][3][4]. Subsequent to the original model introduction, two specific revisions have been submitted for review and approval (i.e., PAD 3.3[5] and PAD 3.4[6]). With respect to the creep model used in PAD, the original model form remains in effect except for a revision that occurred to the irradiation enhanced creep portion of the model in PAD 3.4. The thermal creep portion of the model has remained the same since the model's inception in 1972.

1.1 Purpose

The purpose of this topical report is to introduce the new creep model to be used in the overall PAD fuel rod performance model. The new creep model accounts for advances in the understanding of in-reactor creep that have occurred between 1972 and 1998, and represents a description of in-reactor creep relative to the information and data that are available in 1998. This model enhancement is projected to restore rod internal pressure limit margin to the fuel rod design criterion.

1.2 Discussion of the Current PAD Creep Model (PAD 3.4)

The total in-reactor creep rate, de/dt, in PAD 3.4 is evaluated as the sum of the out-of-reactor (laboratory) thermal creep rate, de/dt(out-rx tc), plus the irradiation enhanced creep rate, de/dt(ic).

$$de/dt = de/dt(out\text{-}rx\ tc) + de/dt(ic) \tag{1}$$

The out-of-reactor (laboratory) thermal creep rate, de/dt(out-rx tc), is a function of clad temperature, clad equivalent or effective stress and time. [

]^{a,c}.

The irradiation enhanced creep rate, de/dt(ic), is a function of neutron flux and fluence. [

] a, c.

1.3 Evaluation of PAD 3.4 Creep Model - Need for Change

With the current generation of fuel and the enhanced operational performance requirements placed on the fuel (i.e., increased cycle lengths, higher operating system temperatures, higher operating power levels, higher peaking factors, and higher burnup levels), enhanced modeling and prediction capabilities are necessary to demonstrate the continued acceptable performance of the fuel to the original fuel rod design criteria. As such, new post-irradiation examination (PIE) data needs to be accounted for and incorporated into the fuel rod performance models. This new PIE data has already demonstrated a need to revise the fuel rod corrosion model in PAD(7). In addition, other material property characteristics exist that previously had not been accounted for, either due to the lack of available data or the level of sophistication of the mechanics. With new data now available and the level of sophistication of the mechanics reaching closer to the phenomenological level, significant improvements to the fuel rod performance models can be achieved.

A review of current in-reactor creep models and methods was performed by Westinghouse relative to the state-of-the art mechanics of fuel rod behavior. This involved a detailed review of work performed by AECL and reported in 1996 by Christodoulou et al.(8). The subsequent work performed at AECL, reported by Christodoulou, has demonstrated that the PAD 3.4 in-reactor creep model is overly conservative and needs to be revised. Christodoulou presented the formulation and results of a fundamental-empirical model describing the in-reactor creep of cold-worked (CW) Zr-2.5Nb for pressure tube application. Some of the many models proposed to describe the in-reactor creep of zirconium alloys are described in References 8, 9 and 10. The Christodoulou model is considered to be the most fundamental model that is also based on the largest in-reactor data set to date. The model includes the effects of texture, grain shape, anisotropy and the relative contributions of prismatic, basal and pyramidal planes to dislocation climb assisted glide. This in-reactor model includes data from creep measurements of pressure tubes in power reactors, pressure tubes in test reactors, small pressurized tubes in test reactors and beam stress relaxation samples in test reactors. The test data includes samples with thermal creep strain. In addition, the test data includes textures typical of both pressure and fuel-cladding tubes. As a result, the framework of this model was selected by Westinghouse to formulate a new in-reactor creep

model for fuel rod application.

According to the Christodoulou model, the in-reactor creep rate is the sum of the in-reactor thermal creep rate, de/dt(tc), and the irradiation enhanced creep rate, de/dt(ic).

$$de/dt = de/dt(tc) + de/dt(ic) \tag{2}$$

[

] a, c. As a result, the predicted total creep rate from the current PAD model (Equation (1)) is higher than that derived from Equation (2) and is therefore conservative. This effect will be discussed in subsequent sections.

The PAD creep model needs to be revised due to the demonstrated fact that the original PAD 3.4 creep model is conservative; therefore, there is a need to account for new PIE data and material property behavior. Specifically, the PAD 3.4 in-reactor creep model is being replaced for the following reasons:

- [

  ] a, c
- [ ] a, c
- [

  ] a, c Out-of-reactor and in-reactor creep behavior is dependent on fabrication process parameters such as final area reduction, intermediate anneal temperature, final anneal temperature and time and post-extrusion anneal temperature.
- [ ] a, c
- [

  ] a, c

2.0 New PAD In-Reactor Creep Model

The new in-reactor creep model developed for fuel rod application in PAD is based on [

] a, c.

According to Christodoulou, the total in reactor creep rate is the sum of the in-reactor thermal creep rate, de/dt(tc), and the irradiation enhanced creep rate, de/dt(ic)

$$de/dt = de/dt(tc) + de/dt(ic) \tag{2}$$

[ ] a, c.

The new in-reactor creep model was developed to describe Westinghouse cold-worked stress relieved (CWSR) tubing. The specific material behavior of the new PAD model is based on Westinghouse cladding. [

] a, c the new creep model describe Westinghouse cladding.

2.1 In-Reactor Thermal Creep Overview

The in-reactor thermal creep component was developed using Westinghouse cold-worked stress relieved (CWSR) improved (IMP) Zr-4 (low tin Zr-4) tubing. The in-reactor thermal creep is given by the out-of-reactor (laboratory) thermal creep corrected for in-reactor irradiation hardening. This behavior is described by:

[ ] a, c (3)

where [

] a, c. The equation [

] $^{a, c}$. The equation for [ ] $^{a, c}$ is given by:

[ ] $^{a, c}$ (4)

where [ ] $^{a, c}$. The equation was [ ] $^{a, c}$ IMP Zr-4 thermal creep tests [ ] $^{a, c}$ according to:

[ ] $^{a, c}$ (5)

The irradiation hardening [ ] $^{a, c}$. The expression for IH is:

[ ] $^{a, c}$ (6)

where [ ] $^{a, c}$. Equation (6) provides a smooth transition with increasing fluence from no irradiation hardening [ ] $^{a, c}$ to complete irradiation hardening [ ] $^{a, c}$. The application of the [ ] $^{a, c}$ was supported by an evaluation of the creep activation energy (discussed below) and the in-reactor thermal creep hardening model reported by Limback and Andersson[10] for CWSR Zr-4.

2.2 Irradiation Enhanced Creep Overview

The new irradiation enhanced creep component was developed using [ ] $^{a, c}$. The irradiation creep behavior [ ] $^{a, c}$. Since the [ ] $^{a, c}$. The irradiation enhanced creep rate equation is given by:

[ ][a, c] (7)

where [

][a, c]. The [ ][a, c] creep rate equation is given by:

[ ][a, c] (8)

where [

][a, c]. The [

][a, c]. The equation was [ ][a, c] IMP Zr-4 out-of-reactor (laboratory) thermal creep tests [

][a, c] and the out-of-reactor (laboratory) creep rate equation for [ ][a, c] according to:

[ ][a, c] (9)

The [ ][a, c] measurements were performed at PWR reactor coolant temperature. Irradiation enhanced creep increases with increasing temperature. The [

][a, c] in:

[ ][a, c] (10)

where [

][a, c]. Hence, Equation (10) gives the [

][a, c].

A more detailed evaluation of each component of the PAD model is provided in the subsequent sections.

3.0 Creep Model Detailed Justification

As stated in the previous section, a more detailed justification for the equations and coefficients follows below for a more thorough understanding of Westinghouse's model development.

3.1 Out-of-Reactor (Laboratory) Thermal Creep

The out-of-reactor (laboratory) creep behavior of CWSR Zr-4 tubing fabricated by Westinghouse was established for [ ] a, c. Internal pressure creep tests were conducted using [

] a, c. The test samples in each test condition were strained into the secondary creep region. The internal pressure and diametral strain were converted to mid-wall hoop stress and strain. The mid-wall hoop strain data were analyzed by separating the total strain into primary and secondary components. The following equations resulted:

- Total creep strain, e (fraction):

[ ] a, c (11)

where t is the time (hour).

- Secondary creep rate, $(de/dt)_S$ (fraction/hour):

[ ] a, c (12)

where [

] a, c.

- Elastic modulus, E_E (psi):

[ ] a, c (13)

where TF is the temperature in (°F).

- Saturated primary strain, e_p (fraction):

[ ]$^{a, c}$ (14)

- Time coefficient, K:

[ ]$^{a, c}$ (15)

The PAD code calculates [

]$^{a, c}$

is:

[ ]$^{a, c}$ (16)

The coefficient [

]$^{a, c}$ is therefore given by:

[ ]$^{a, c}$ (17)

3.2 In-Reactor Thermal Creep

3.2.1 Irradiation Hardening

3.2.1.1 Model Development

The determination of the in-reactor creep components may be illustrated by the CW Zr-2.5Nb pressure tube reported by Fidleris[11] as shown in Figure 2. The tube was irradiated for 27,550 hours in the Whiteshell WR-1 test reactor. At the outlet end of the tube the temperature is 650K (711 °F) and the hoop stress is 43 MPa (6.2 ksi), [ ] a, c. These temperatures are considerably higher than normal CANDU pressure tube service operation temperatures, because the Whiteshell test reactor used organic coolant.

[

] a, c. This clearly shows that irradiation reduces the out-of-reactor (laboratory) thermal creep strain, i.e., that irradiation hardening of out-of-reactor (laboratory) thermal creep occurs.

The irradiation hardening of out-of-reactor (laboratory) thermal creep is further illustrated by [

] a, c. This clearly shows that irradiation decreases (or "hardens") the out-of-reactor (laboratory) thermal creep. [

] a, c.

The irradiation hardening effect on the out-of-reactor (laboratory) thermal creep is even noticeable [

] a, c.

The irradiation enhanced component is [
] a, c.

[ ] a, c (18)

This is shown in Figure 3 as the irradiation enhanced component.

The irradiation hardening [

] a, c may be described by an equation of the form:

[ ]$^{a, c}$ (19)

where Φ is the fluence in n/cm^2 (E > 1 MeV). Equation (19) provides a smooth transition with increasing fluence from no irradiation hardening [

] $^{a, c}$ to complete irradiation hardening [ ] $^{a, c}$.

3.2.1.2 Model Evaluation

The irradiation hardening factor, [

] $^{a, c}$. The results were:

[ ]$^{a, c}$ (20)

[ ]$^{a, c}$

The [

] $^{a, c}$. The result was:

[ ]$^{a, c}$ (21)

These results indicate that the in-reactor irradiation hardening of thermal creep is [

] $^{a, c}$.

Limback and Andersson[10] reported a model that describes the in-reactor creep behavior of CWSR Zr-4 cladding. The [

] a, c. The equations are:

[ ]a, c (22)

where[ ] a, c, and:

[ ]a, c (23)

where [

] a, c Equation (23) becomes:

[ ]a, c (23a)

The calculated IH factors using Equation (23a) are presented in Figure 6 as a dashed line. Figure 6 shows that the calculated [

] a, c.

3.2.2 Irradiation Creep

3.2.2.1 Modeling of the B&W/EPRI Data

The determination of the irradiation enhanced creep component was performed using the reported B&W/EPRI Oconee-2 creepdown data[15]. The tabulation presented by Franklin[20] is the [

] a, c. The hoop strain, $\Delta D/D$, was described by an equation of the form:

[ ]a, c (24)

where [

] a, c:

[ ]a, c (25)

[ ]a, c

Figure 12 shows that this fit is in excellent agreement with the data.

[

] a, c.

The steady state irradiation creep component is [

] a, c.

The [

]$^{a, c}$.

3.2.2.2 Normalization of B&W/EPRI Irradiation Creep to Westinghouse Behavior

The B&W/EPRI in-reactor creep data [

]$^{a, c}$.

The out-of-reactor (laboratory) thermal creep rates may be [

]$^{a, c}$.

The irradiation enhanced creep behavior [

]$^{a, c}$ according to Equation (26):

[ ]$^{a, c}$ (26)

[

]$^{a, c}$:

[ ]$^{a, c}$ (27)

Equation (27) may be written as:

[ ]$^{a, c}$ (28)

For [

]$^{a, c}$. Equation (28) becomes,

[ ]$^{a, c}$ (29)

which is the form of Equation (26). Hence, Equations (26) and (27) are related by the relationships,

[

]$^{a, c}$. The conversion factors are:

[ ]$^{a, c}$ (30)

[ ]$^{a, c}$

and the resulting equation for [ ]$^{a, c}$ is:

[ ]$^{a, c}$ (31)

where [

] a, c:

[ ]a, c (32)

The average value for C_3 was

[ ]a, c (33)

This factor was [

] a, c.

3.2.2.3 Irradiation Creep Temperature Dependence

The irradiation creep temperature dependence was [

] a, c.

The data may be described by a function:

[ ]a, c (34)

where [ ] a, c.

4.0 Application to ZIRLO™

The in-reactor creep model developed above to describe CWSR IMP Zr-4 may be applied to ZIRLO™. This application may be accomplished using the Westinghouse IMP Zr-4 and ZIRLO™ fuel rod creepdown data. Generally, after 1-cycle, the cladding is freestanding (i.e., fuel pellet contact has not occurred). [

] a, c.

The irradiation creep behavior exhibited by Westinghouse IMP Zr-4 and ZIRLO™ fuel rods is considered to be consistent with in-reactor irradiation creep data. [

] a, c.

Higher burnup Westinghouse IMP Zr-4 and ZIRLO™ fuel rods are available. Table 6B [

] a, c. As a result of this ZIRLO™ creep discussion, a multiplier will be used to account for ZIRLO™ creep as compared to IMP Zr-4 creep.

5.0 Summary and Conclusions

In summary, the discussion above presented a new in-reactor creep model. The model was developed based on the best available zirconium alloy in-reactor creep models and data available to date. The model is consistent with fundamental descriptions of in-reactor creep. As a result of the mechanistic approach, the model is expected to be much more consistent with in-reactor creep behavior. The model describes the behavior of Westinghouse CWSR tubing. The total in-reactor creep rate is composed of irradiation enhanced and in-rector thermal components. The irradiation enhanced component is dependent on the stress, flux (and fluence) and temperature. The in-reactor thermal component is dependent on the stress, time, temperature and fluence.

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Table 1

IMP Zr-4 Out-of-Reactor (Laboratory) Thermal Creep Data

a, c

Table 2A

Calculated STD Zr-4 Out-of-Reactor Creep Rate Values as a Function of Time

[ ] a, c

Table 2B

Out-of-Reactor Creep Rate Normalization Factor for IMP Zr-4 Data Relative to STD

[ ] a, c

Table 3

Evaluation of Zr-2.5Nb Out-of-Reactor Thermal Creep

Irradiation Hardening

a, c

* Minimum diameter near the edge of the fuel.

** Diameter measured about 1 meter from the core edge.

Table 4

Comparison of Oconee-2 In-Reactor and Out-of-Reactor (Laboratory) Creep Rates.

[ ]a, c

Table 5

Average Diameter Creepdown of IMP Zr-4 and ZIRLO™ Fuel Rods in the High Power Region of North Anna Advanced Material Demonstration Assemblies

[ ]a, c

Table 6A

Westinghouse 1-Cycle Fuel Rods

[ ] a,c

Table 6B

Westinghouse High Burnup Fuel Rods

[ ] a, c

Figure 1

Out-of-Reactor Thermal Creep Steady State Rate - Tin Dependence

a, c

Figure 2

CW Zr-2.5Nb Pressure Tube Diameter Data (the flux data are not accurate)

Figure 8 of Reference 11

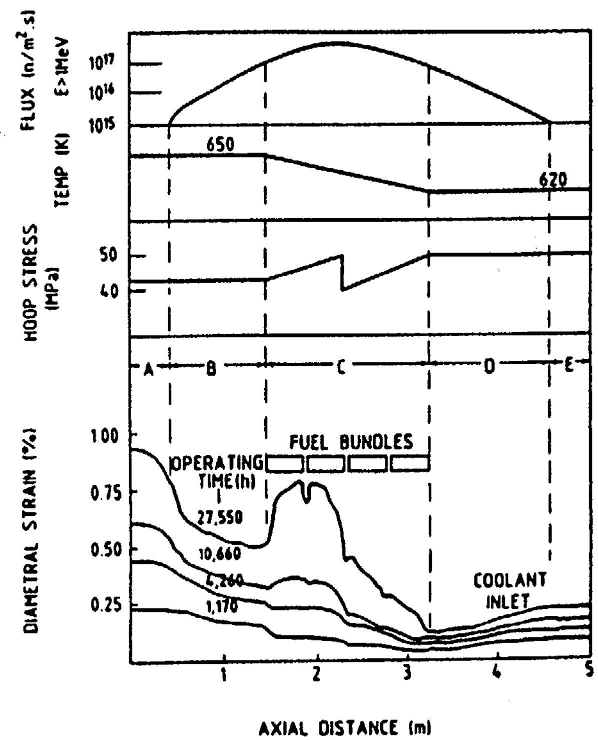


Fig. 8. Diametral creep of cold-worked Zr–2.5Nb loop tube in WR-1 reactor.

Reprinted from Journal of Nuclear Materials, Volume 159,

V. Fidleris, "The Irradiation Creep and Growth Phenomena", pp 22-42,

Figure 3

Creep Components - CW Zr-2.5Nb Pressure Tube

650 K, 43 MPa Hoop Stress

a, c

Figure 4

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 4 of Reference 13

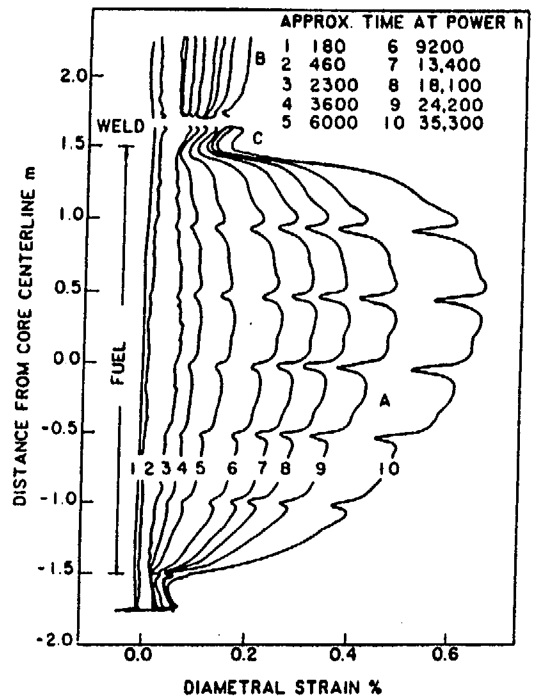


FIGURE 4 Diametral strain of cold-worked Zr-2.5 wt% Nb pressure tube vs axial location in NRU. Illustrating

A approximate cosine distribution of strain in fueled zone
B creep in upper extension, and
C suppression of creep near edge of core.

Figure 5

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 7 of Reference 14

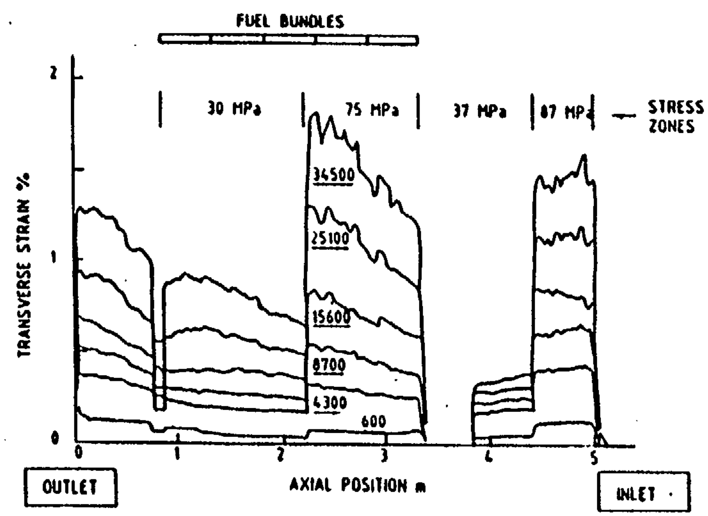


FIG. 7—*Transverse strain profiles of a pressure tube in WR1.*

Reprinted from Influence of Radiation on Material Properties: 13th International Symposium (Part II), ASTM STP 956, A. R. Causey, V. Fidleris, S. R. MacEwen and C. W. Schulte, "In-Reactor Deformation of Zr-2.5 wt% Nb Pressure Tubes", pp 54-68, Copyright 1987, with permission from ASTM.

Figure 6

Saturated Out-of-Reactor (Laboratory) Thermal Creep Reduction Factor

a, c

Figure 7

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 69 MPa

a, c

Figure 8

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 86 MPa

a, c

[ ]

Figure 9

CWSR Zr-4, B&W/EPRI, Lot S-1, 577-578 K, 103 MPa

a, c

Figure 10

CWSR Zr-4 Saturated Transient Component, B&W/EPRI, Lot S-1, 577-578 K

a, c

Figure 11

CWSR Zr-4 Steady State Component, B&W/EPRI, Lot S-1, 577-578 K

a, c

Figure 12

Comparison of Measured and Calculated Strain for CWSR Zr-4

Lot S-1, B&W/EPRI, 577-578 K

a, c

Figure 13

CWSR Zr-4, Lot S-1, B&W/EPRI, 581-582 K, 103 MPa

a, c

Figure 14

CWSR Zr-4 Apparent Temperature Dependence

Lot S-1, B&W/EPRI, 103 MPa

a, c

[redacted]

Figure 15

Comparison of In-Reactor and Out-of-Reactor Creep Rates

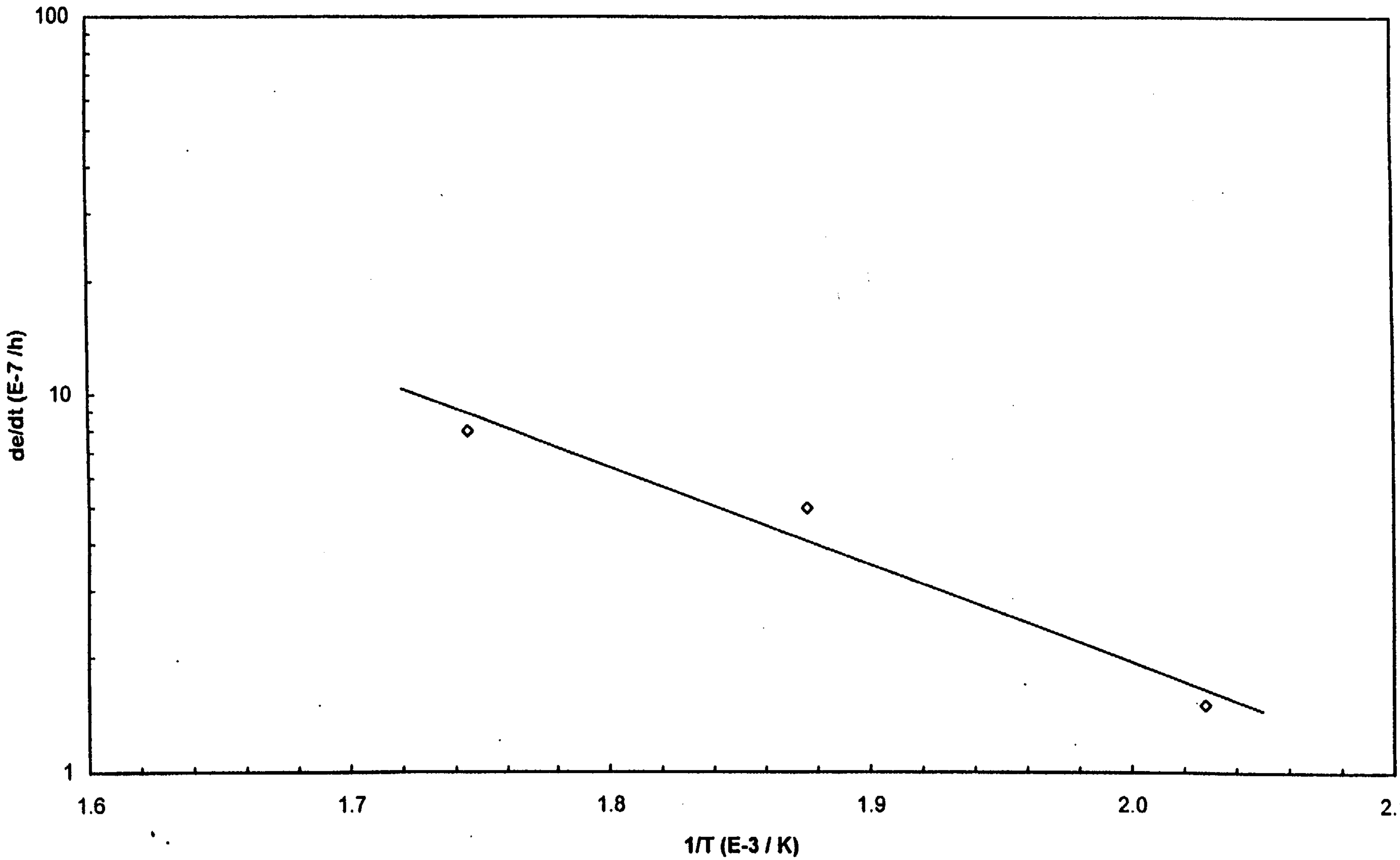
B&W/EPRI, 86 MPa

a, c

Figure 16

CW Zr-2 Irradiation Creep Temperature Dependence, 207 MPa

From Reference 16



Graphical representation of data from Reference 16

This figure was not included in Reference 16

Figure 17

CWSR IMP Zr-4 In-Reactor Creep

1.08×10^{22} n/cm^2 (E > 1 MeV), 41 MPa (6.0 ksi) Hoop Stress

a, c

SECTION D

Westinghouse Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

June 24, 1998
NSD-NRC-98-5723

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: Replacement Figure Pages for "Westinghouse In-Reactor Creep Model," WCAP-15063-P (Proprietary), WCAP-15064 (Non-Proprietary), June 1998

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5709, dated June 9, 1998

Dear Mr. Collins:

Enclosed are three copies of Figures 2, 4, 5, and 16 to be replaced in the Proprietary version of WCAP-15063-P, "Westinghouse In-Reactor Creep Model" and three copies of Figures 2, 4, 5, and 16 to be replaced in the Non-proprietary version (WCAP-15064) of the report. These figures were not included in the original transmittal, Reference 1, since copyright release authorization was being obtained. As discussed with you by phone, Westinghouse is now forwarding copies of these figures after obtaining copyright release authorization.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-98-1244 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-98-1244.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.5(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1244 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

copy to:
T. E. Collins, NRR
P. C. Wen, NRR

Westinghouse Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

June 24, 1998
AW-98-1244

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief,
Reactor Systems Branch
Division of Systems Safety and Analysis

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: Replacement Figure Pages for "Westinghouse In-Reactor Creep Model," WCAP-15063-P (Proprietary), WCAP-15064 (Non-Proprietary), June 1998

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5723, dated June 24, 1998

Dear Mr. Collins:

The application for withholding is submitted by Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse"), pursuant to the provisions of paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-98-1244 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-98-1244 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

cc: T. Carter / NRC (5E7)

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Copyright Notice

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 24th day
of June, 1998.

Notary Public

Notarial Seal
Janet A. Schwab, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires May 22, 2000
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Division, of the Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked Replacement Figure Pages for "Westinghouse In-Reactor Creep Model," WCAP-15063-P (Proprietary), WCAP-15064 (Non-Proprietary), June 1998, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSD-NRC-98-5723) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of T. E. Collins, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information as submitted by Westinghouse Electric Company is to provide information on the revised Westinghouse Creep Model that is used in the Westinghouse Performance Analysis and Design model (PAD). This information is provided for review and approval of this revised creep model.

This information is part of that which will enable Westinghouse to:

(a) Ensure proper fuel performance of fuel operating in reactors.

(b) Assist customers to obtain license changes resulting from fuel performance modeling.

Further this information has substantial commercial value as follows:

(a) Westinghouse can use this fuel performance modeling capability to further enhance their licensing position over their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Figure 2

CW Zr-2.5Nb Pressure Tube Diameter Data (the flux data are not accurate)

Figure 8 of Reference 11

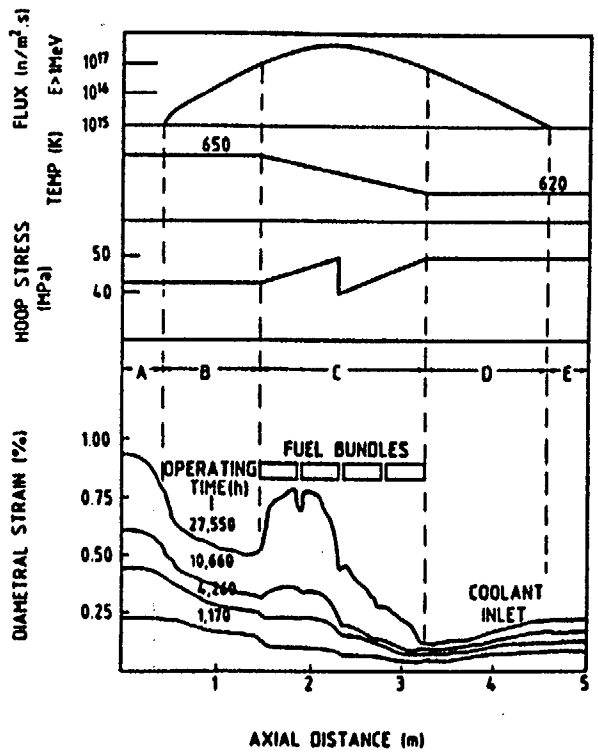


Fig. 8. Diametral creep of cold-worked Zr-2.5Nb loop tube in WR-1 reactor.

Figure 3

Creep Components - CW Zr-2.5Nb Pressure Tube

650 K, 43 MPa Hoop Stress

a, (

Figure 4

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 4 of Reference 13

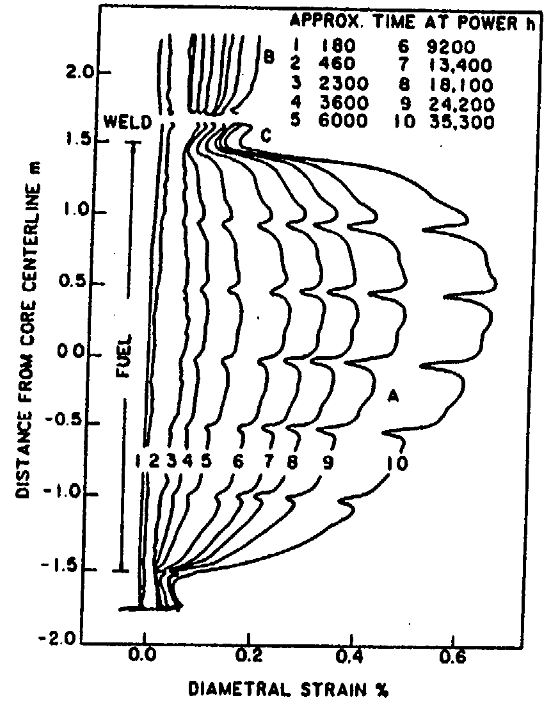


FIGURE 4 Diametral strain of cold-worked Zr-2.5 wt% Nb pressure tube vs axial location in NRU. Illustrating

A approximate cosine distribution of strain in fueled zone

B creep in upper extension, and

C suppression of creep near edge of core.

Figure 5

CW Zr-2.5Nb Pressure Tube Diameter Data

Figure 7 of Reference 14

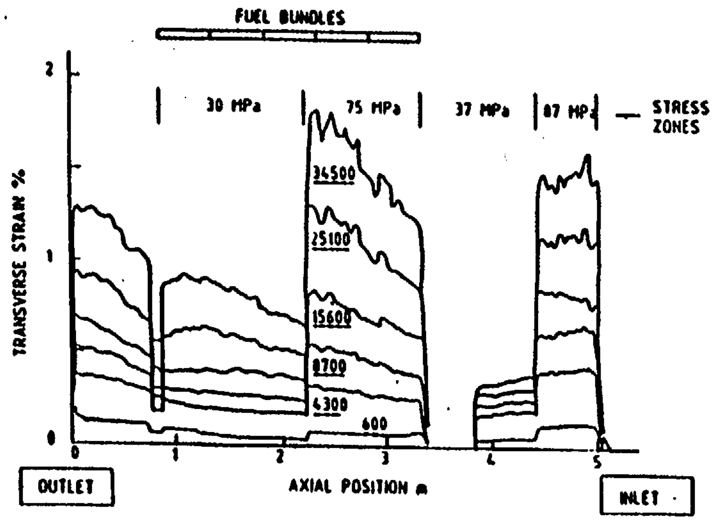


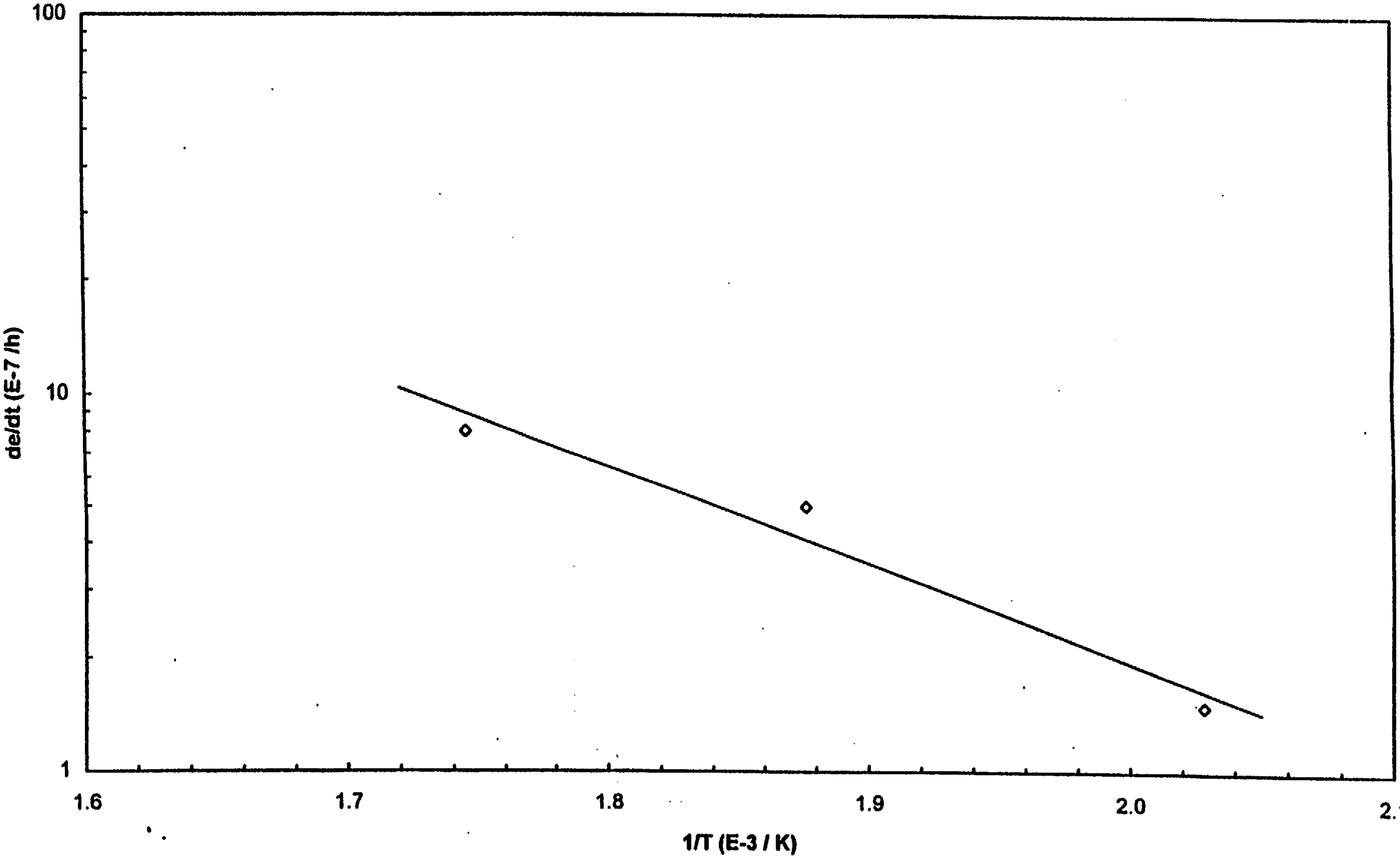
FIG. 7—*Transverse strain profiles of a pressure tube in WR1.*

Reprinted from Influence of Radiation on Material Properties: 13th International Symposium (Part II), ASTM STP 956, A. R. Causey, V. Fidleris, S. R. MacEwen and C. W. Schulte, "In-Reactor Deformation of Zr-2.5 wt% Nb Pressure Tubes", pp 54-68,

Figure 16

CW Zr-2 Irradiation Creep Temperature Dependence, 207 MPa

From Reference 16



Graphical representation of data from Reference 16

This figure was not included in Reference 16

SECTION E

Westinghouse
Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

September 11, 1998
NSD-NRC-98-5787

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: Revised PAD Code Information on Model Changes & Code V&V

Dear Mr. Collins:

Enclosed are copies of the Proprietary and Non-Proprietary versions of the Revised PAD Code Information on Model Changes & Code V&V.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-98-1284 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-98-1284.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.17(a)(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1284 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

cc: P. C. Wen, NRR/DRPM/PGEB (10H5)

/cad

Westinghouse Electric Corporation
Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

September 11, 1998
AW-98-1284

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief, Reactor Systems Branch
Division of Systems Safety and Analysis

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5787, dated September 11, 1998

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: Revised PAD Code Information on Model Changes & Code V&V [Proprietary]

Dear Mr. Collins:

The application for withholding is submitted by Westinghouse Electric Corporation ("Westinghouse") pursuant to the provisions of paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-98-1284 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-98-1284 and should be addressed to the undersigned.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

cc: T. Carter, NRR/DISP/ (5E7)

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Copyright Notice

AW-98-1284

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 11th day
of September, 1998.

Notary Public

Notarial Seal
Yvonne M. Thompson, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Aug. 2, 1999
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Division, of the Westinghouse Electric Company and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in the letter, "Revised PAD Code Information on Model Changes & Code V&V", dated September 11, 1998, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSD-NRC-98-5787) and Application for Withholding Proprietary Information from Public Disclosure, H. A. Sepp, W, Manager Regulatory and Licensing Engineering to the attention of T. E. Collins, Chief, Reactor Systems Branch. The proprietary information as submitted by Westinghouse Electric Company is to provide the material as presented to the NRC staff at the Revised PAD Code Information on Model Changes & Code V&V meeting on September 15, 1998.

This information is part of that which will enable Westinghouse to:

(a) Support extended burnup programs and advanced fuel designs

(b) Assist customers to obtain license

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of designing reactor cores

(b) Westinghouse can use this information to further enhance their licensing position with their competitors

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar licensing services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed information.

Further the deponent sayeth not.

Technical Meeting with NRC on Revised PAD Code

September 15th, 1998

Non-Proprietary

Agenda

- Introduction & Purpose of meeting
- Overview of PAD model changes
- Presentation of calibration and V&V results
- Detailed discussion of PAD model changes
- Discussion of creep model RAIs
- Licensing and implementation of revised PAD

Background

- Meeting held with NRC on May 5th, 1998
- Creep model was discussed as the only major model change
- At that meeting, Westinghouse committed to the following
  - submit revised creep model WCAP (complete 6/98)
  - provide confirmation of successful code V&V

Current Situation

- Revised creep model still remains the only major model change
- However, other model enhancements have been made that need NRC concurrence
- Model changes have been incorporated into the PAD code
  - code calibration and V&V have been completed
- Westinghouse internal verification and review process ongoing

Meeting Objective and Purpose

- Inform NRC of additional model changes
- Present and submit calibration and V&V results
- Submit detailed information on additional model changes for NRC review
- Obtain NRC feedback to factor into W review process
- Discuss NRC RAIs on the Revised Creep Model WCAP
- Obtain concurrence on licensing process and schedule

Licensing Process (Last slide of the day)

Preferred Licensing Process and Schedule

- Description and justification of additional model enhancements submitted at this meeting
- Calibration and V&V results submitted at this meeting
- NRC review and W response to questions (9/98 - 11/98)
- TER/SER (12/98 - 1/99)

Revised PAD Code Summary of Changes

The following changes have been incorporated into the revised PAD code:

1) Revised creep model (as submitted in WCAP-15063-P)
2) Revised rod irradiation growth model,
3) Updated Zr-4 and ZIRLO™ clad thermal conductivity values,
4) Updated Zr-oxide thermal conductivity value,
5) Updated Equation of State model (EOS),
6) Variable oxide-metal ratio model (as discussed during the W/NRC meeting May 5, 1998)
7) Gas absorption in cladding effect

1) Revised creep model

Description: Refer to WCAP-15063-P for creep model details. This is a substantial improvement in the creep model, which is an important model with wide-reaching impacts for all of the subsequent calculations in the revised PAD code.

Why Change?: The revised creep model is fundamentally sound and has a much more rigorous in-reactor data base to support the mechanistic understanding of in-reactor creep. The new model incorporates temperature-dependent irradiation creep and irradiation hardening.

Effect of change: The overall impact of the revised creep model in the revised PAD code on rod internal pressure predictions is favorable.

2) Revised rod irradiation growth model

Description: The current PAD model (WCAP 10851-P-A) does not have a temperature dependence for irradiation growth of zirconium alloys. The revised PAD model incorporates this temperature dependence.

Why change?: This change is based on work reported by the industry which has been demonstrated at EBR-II and DIDO that irradiation growth is a strong function of temperature, particularly for temperatures above 660 K (728°F).

Effect of change: This is a relatively small change which will only effect rod growth when high temperatures are present in the cladding.

3) Updated Zr-4 and ZIRLO clad thermal conductivity values

Description: PAD (WCAP 10851-P-A) currently uses conductivity values from open literature for zircaloy-4 and zircaloy-2, for Westinghouse Zr-4 and ZIRLO. The revised PAD code uses measured values on Westinghouse fuel products; for both ZIRLO and Zr-4.

Why change? Experimental work was conducted specifically to update the database for Westinghouse product, and when incorporated will substantially improve thermal model accuracy.

Effect: This update has a positive impact on rod internal pressure by slightly lowering clad temperatures for a given power level.

4) Updated Zr-oxide thermal conductivity values

Description: PAD (WCAP 10851-P-A) currently uses a value for zirconium-oxide thermal conductivity based on work done in 1979 on theoretically-dense zirconium-oxide in a vacuum. Recent EPRI-sponsored work shows that the oxide thermal conductivity is higher than that currently included in PAD. Oxide thermal conductivity has been revised in the new version of PAD based on this work.

Why Change?: Recent in-pile tests indicate that a more conductive thermal oxide layer is formed in PWR environments, which enhances the oxide thermal conductivity. This change will enable more accurate assessments of the rod thermal response characteristics consistent with industry understanding of zr-oxide properties.

Effect: This change yields a small reduction in clad average temperature and thus a reduction in fuel centerline temperature.

5) Equation of State (EOS) gas model

Description: PAD (WCAP-10851-P-A) currently uses the ideal gas law for calculating the pressure inside the fuel rods. A review of the available state-of-the art gas laws, show that a new equation of state (EOS) model is more accurate. The revised PAD code uses the Peng-Robinson EOS model for the calculation of fuel rod internal pressure.

Why change?: Changing the PAD gas model from the ideal gas law to the Peng-Robinson EOS will more accurately represent the internal gas pressure of Westinghouse fuel rods.

Effect: This model causes the predicted rod pressure to increase for a given burnup higher than the current ideal gas law and has a small negative effect on rod internal pressure.

6) Variable oxide-metal ratio model

Description: PAD (WCAP-10851-P-A) currently uses a constant theoretical oxide-metal ratio 1.56 to calculate metal wastage. Westinghouse previously identified to the NRC (May 1998) that we would be using a value of [

] a,c.

Why change?: The change in oxide characteristics as the thickness increases has been documented in public literature and measured on archive hot cell photomicrographs.

Effect: This change allows for accurate calculation of remaining wall thickness as oxide is generated and thus improves accuracy of the clad stress and creep calculations.

7) Gas absorption in cladding effect

Description: PAD (WCAP-10851-P-A) currently models that air can contribute to the internal pressure of the fuel rod throughout life. Air is rapidly absorbed into the cladding by forming hydrides, oxides and nitrides of zirconium and is eliminated from gas pressure calculations in the revised PAD code.

Why change?: Published literature on diffusion/reaction rates for gases in zirconium alloys, confirms a rapid consumption of any air or reactive gases is expected at operating fuel temperatures. [

] a,c.

Effect: This change will result in a small reduction in rod internal pressure.

Revised PAD Creep Model Calibration and Verification

An improved in-reactor irradiation and thermal creep model has been developed (WCAP-15063-P) and was incorporated into PAD. The new creep model is substantially different in form from the model used in PAD (WCAP-10851-P-A). Therefore, a full calibration, validation, and was conducted in order to incorporate this new model into PAD. This letter documents the results of that work.

The equations that govern the irradiation creep and thermal creep were modified to represent the new formulations documented in WCAP-15063-P. The creep model was developed to accurately model Conv. Zr-4, Imp. Zr-4, and ZIRLO™, however, to properly calibrate the model, [

]a,c.

Measured Fuel Rod Profilometry Data

The following is a table of fuel rod creep data used in the calibration and validation of the creep model. Profilometry data was obtained from [

]a,c. This data is the same data used in the creep calibration, validation, and verification of PAD (WCAP-10851-P-A) except for the addition of new [

]a,c Approximately [ ]a,c of the available data was randomly selected to use in the calibration of the creep model. The remaining data was held back for validation of the model calibration. The validation data is designated by a **V** and calibration by a **C** in the table below.

Table 1: Measured Profilometry Data Matrix

a,c

a,c

A summary of the profilometry database is given below:

	Conventional Zr-4	*Improved Zr-4*	*ZIRLO*
Verification Data (points) (all data)			
Calibration Data (points)			
Validation Data (points)			

a,c

Calibration Procedure Overview

The process used in performing the creep calibration involves comparing the experimentally measured fuel rod profilometry data with the PAD predicted profilometry for each of the calibration rods listed above. Both the measurements and the PAD results include the [

]a,c

[

]a,c

Independent calibrations were performed and [

]a,c. The values of [ ]a,c were chosen, to obtain a value which minimized the absolute value of the average Measured -minus - Predicted (M-P) fuel rod profilometry.

Only profilometry data obtained [

]a,c

Calibration Results

The revised PAD code was calibrated using the procedure presented above and in ref. 8. The results of the calibration defined the [ ]^{a,c} are as follows:

Table 3: Creep Calibration Coefficients

Conv. Zr-4	[	a,c
Imp. Zr-4		
ZIRLO	]	

The statistical results for the calibration, validation, and verification (total) data for all three alloys are shown below in table 4.

Table 4: Statistical results of creep calibration

	Conv. Zr-4	*Imp. Zr-4*	*ZIRLO*	
Calibration Data :				
Population				a,c
Avg. M-P(mils)				
Stdev. M-P(mils)				
Avg. M/P				
Stdev. M/P				
Validation Data:				
Population				a,c
Avg. M-P(mils)				
Stdev. M-P(mils)				
Avg. M/P				
Stdev. M/P				
Verification Data: ***(all data)***				
Population				a,c
Avg. M-P(mils)				
Stdev. M-P(mils)				
Avg. M/P				
Stdev. M/P				

Figure 1 shows the predicted creepdown data vs. measured creepdown data for conventional Zr-4, improved Zr-4, and ZIRLO. All of these comparisons show good agreement between measured and predicted data. The results are consistent with those determined for the previously licensed PAD (WCAP-10851-P-A) creep model.

Although there is a large variation in data population size between the three alloys calibrated, it was found through ANOVA analysis supports the contention that the creep model is equally good for conventional Zr-4, improved Zr-4, and for ZIRLO, as there is no significant difference in the measured-to-predicted populations. The only difference in the creep model between alloys is the [ ]^{a,c} which accounts for the known different creep rates of the three alloys.

Figures 2 through 5 show the residual dependence of the model on rod average burnup, axial elevation, time averaged temperature, and time averaged stress for all three alloys. No apparent model bias is seen over any of the plotted variables for conventional or improved Zr-4. For ZIRLO, there is a slight creep over-prediction trend with increasing burnup.

Examples of the comparison of the creep model with individual campaign creepdown data are shown in Figures 6 through 9 for Conventional Zr-4; Figure 10 for Improved Zr-4; and Figure 11 for ZIRLO. The comparisons with the Zion data over all five cycles of irradiation confirm that the PAD models for cladding creep and fuel densification and swelling correctly predict the transition from creepdown, due to system pressure greater than rod internal pressure, to creepout, due to fuel swelling, in the fifth cycle. The one cycle data for both improved Zr-4 and ZIRLO also shows excellent agreement with predictions.

Since the creep model is applicable to both creep-in and creep-out, uncertainties obtained from the verification data will be used in a manner consistent with the creep model. No directionality will be applied to the creep uncertainties.

Conclusions

The creep model has been successfully calibrated for use in the revised PAD code. The multipliers for [ ]^{a,c} have been determined and are shown in Table 3. All of the creep model comparisons show good agreement between measured and predicted data for creepdown and creepout. The results are similar with those determined for the PAD (WCAP-10851-P-A) creep model.

Figure 1: PAD Creep Model Predictions

a,b,c

Figure 2: PAD Creepdown M-P vs. Axial Elevation

a,b,c

[ ]

Figure 3: PAD Creepdown M-P vs. Burnup

a,b,c

Figure 4: PAD Creepdown M-P vs. Time Averaged Temperature

a,b,c

Figure 5: PAD Creepdown M-P vs. Time Averaged Stress

a,b,c

[ ]

Figure 6: Zion Average Profilometry (EOC-2)
Conventional Zr-4

a,b,c

[ ]

Figure 7: Zion Average Profilometry (EOC-3)
Conventional Zr-4

a,b,c

Figure 8: Zion Average Profilometry (EOC-4) Conventional Zr-4

a,b,c

[ ]

Figure 9: Zion Average Profilometry (EOC-5)
Conventional Zr-4

a,b,c

[ ]

Figure 10: Average Creepdown, Improved Zr-4 Rods

a,b,c

Figure 11: Average Creepdown, ZIRLO Rods (North Anna AM2)

a,b,c

[ ]

Revised PAD Thermal Model Calibration and Verification

The thermal model (gap conductance) has not been changed from that licensed in PAD (WCAP-10851-P-A). However, as a result of changes which were made to revise PAD in other models, the fuel rod centerline temperatures required re-calibration. The thermal model calibration was performed in the same manner as was presented in WCAP-8720 licensing submittal for PAD (WCAP-8720). Furthermore, the same Halden fuel rod centerline temperature data was used in the calibration as was used in WCAP-8720. The following is a summary of the calibration data and procedure and results.

PAD (WCAP-10851-P-A) Thermal Model

The PAD (WCAP-10851-P-A) gap conductance model for an open gap is given by :

[ ]a,c (1)

(2)

(3)

where:

h_{gap} = gap conductance (BTU/hr-ft-°F)

K_{mixt} = effective gas thermal conductivity (BTU/hr-ft-°F)

GAP = diametral gap (inches)

δ_r= effective surface roughness (feet)

[ ]a,c

Equation (2) is the gap conductance for a temperature drop across the annular gap. In this equation, [ ]a,c

Measured Fuel Rod Profilometry Data

Fuel temperature data from three instrumented assemblies, IFA-431, IFA-432, and IFA-513, irradiated in the Halden Reactor under NRC sponsorship, were used in this calibration. Each assembly contained six fuel rods instrumented with upper and lower thermocouples. The fuel was highly characterized and well instrumented. Descriptions and pre-characterizations of the fuel are reported in References (3) and (4), and power histories and fuel temperature data are given in References (5), (6), (7), and (8). The information used in the analysis was on computer tapes

obtained from EPRI, which had received the data from Pacific Northwest Laboratories. All geometric and physical data in the EPRI tapes were checked to assure there was correspondence with data in the pre-characterization reports. Random samples of the power history and thermocouple data were compared to data in the irradiation history reports to assure there was agreement between the data sets.

This calibration used thermocouple data in the burnup range of 0 to 5000 MWD/MTU. There were several reasons for limiting the burnup range. The range of experimental variables in this burnup interval (power, gap size, fuel density, and gas composition) covers the range expected over the entire irradiation of a pressurized PWR fuel rod. Thermocouples de-calibrate as a function of the thermal neutron fluence and there is some uncertainty about the rate of de-calibration. Limiting the burnup range of the investigation also reduces the uncertainties associated with cladding creep rates, fuel densification and swelling rates, and fission gas release rates. However, the thermal model calibrated from this data is valid for burnups greater than 5000 MWD/MTU in commercial LWR fuel because the ranges of the fuel variables included in the model derivation cover the range expected at much higher burnups. Furthermore, the validity of the PAD (WCAP-10851-P-A) thermal model into high burnup values (> 5000 MWD/MTU) has been addressed in response to NRC questions in WCAP-10851-P-A.

Data from fifteen rods (three assemblies) from Halden were available for calibration and validation. Eleven rods were selected at random for the temperature calibration. These rods were 431-1, 431-2, 431-5, 431-6, 432-1, 432-3, 432-5, 513-2, 513-3, 513-4, and 513-6. Rods 431-3, 432-6, 513-1, and 513-5 were held back for calibration.

Calibration Procedure Overview

The process used in performing the thermal calibration involves comparing the experimentally measured fuel rod centerline temperature data with the revised PAD predicted centerline temperature for each of the calibration rods listed above.

The calibration coefficient which determines the fuel rod centerline calibration is GAPRED. This variable is used as a gap reduction factor which controls the amount of heat transfer that occurs across the annular gap between the fuel pellet and the I.D. of the clad. The calibration process determines a value for GAPRED to obtain a value which minimized the absolute value of the average Measured -minus - Predicted (M-P) fuel centerline temperatures.

Calibration Results

The PAD code was calibrated using the procedure presented above and in ref. 8. The results of the calibration defined the [ ]a,c. The statistical results for the calibration, validation, and verification (total) data are shown below in Table 1.

Table 1: Statistical results of thermal calibration

Calibration Data:

Population	[	]a,c
Avg. M-P (deg. F)		
Stdev. M-P(deg. F)		
Avg. M/P		
Stdev. M/P		

Validation Data:

Population	[	]a,c
Avg. M-P(deg. F)		
Stdev. M-P(deg. F)		
Avg. M/P		
Stdev. M/P		

Verification Data:
(all data)

Population	[	]a,c
Avg. M-P(deg. F)		
Stdev. M-P(deg. F)		
Avg. M/P		
Stdev. M/P		

Figure 1 shows the predicted vs. measured thermal data. This comparison shows reasonable agreement between measured and predicted data for the revised PAD code. The results are similar and consistent with those determined for the PAD (WCAP-10851-P-A) thermal model.

Figures 2 through 4 show the residual dependence of the model on rod average burnup, local power, and gap size. No significant model bias inconsistent with the PAD (WCAP-10851-P-A) thermal model is seen over any of the variables plotted.

Conclusions

The Thermal model has been successfully calibrated for use in the revised PAD code. The value of [ ] a,c All of the thermal model comparisons show reasonable agreement between

measured and predicted data. The results for the revised PAD are consistent with those determined for the previously licensed PAD (WCAP-10851-P-A) thermal model calibration.

References

1. WCAP-8720, Addenda 2, "Revised PAD Code Thermal Safety Model", October 1982.
2. WCAP-15063-P, "Westinghouse In-Reactor Creep Model", June 1998.
3. Hann, C.R., et. Al.,"Test Design, Precharacterization, and Fuel Assembly Fabrication for Instrumented Fuel Assemblies IFA-431, and IFA-432,"NUREG/CR-0332, BNWL-1988 R3, November, 1977.\
4. Bradley,E. R., et. Al.,"Precharacterization Report for Instrumented Nuclear Fuel Assembly IFA-513," NUREG/CR-1077, FNL-3156, R-3, November, 1979.
5. Hann, C. R., et. Al., "Data Report for the NRC/PNL Halden Assembly IFA-431," PNL-2494, April, 1978.
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8. Bradley, E. R., et. Al., "Data Report for the Instrumented Fuel Assembly IFA-513," NUREG/CR-1838, PNL-3637,August,1981.
9. AW-86-080,"Response to NRC Questions on Topical Report, WCAP-10851 (Proprietary), "Improved Performance Models for Westinghouse Fuel Rod Design and Safety Evaluations", September, 1986.

Figure 1: Measured vs Predicted Fuel Centerline Temperatures

a,c

Figure 2: Measured - Predicted Fuel Centerline Temperatures vs. Burnup

a,c

Figure 3: Measured - Predicted Fuel Centerline Temperatures vs. Local Power

a,c

Figure 4: Measured - Predicted Fuel Centerline Temperatures vs. Gap

a,c

REVISED PAD CODE FISSION GAS RELEASE MODEL CALIBRATION AND VERIFICATION

An improved in-reactor irradiation and thermal creep model has been developed and incorporated into the revised PAD code. As a result of these and other changes going into the new code, a full calibration, verification and uncertainty analysis was conducted for both the steady-state and transient fission gas release models. This report documents the results of that effort.

Verification of Fission Gas Release Models

Fission gas release data from [ ]^{a,c} pressurized and unpressurized rods has been used to verify the steady-state fission gas release model. The range of fabrication and operating conditions covered by these rods is presented below in Table 1:

Table 1

[ ]^{a,c}

For clarity, the fission gas release data has been divided into two categories depending on the predicted temperature regime (i.e., high or low) in which the rod generates the majority of its fission gas inventory. In Reference 1 (WCAP 10051-PA) it is explained that the fission gas data was arbitrarily divided high and low temperature release by arbitrarily splitting the database into separate populations depending upon whether the measured fission gas release exceeded [ ]^{a,c} percent. However, this methodology has been improved upon in the most recent calibration by dividing the database based upon the predicted relative contributions of the two temperature regimes for each rod. By turning the high and low temperature fission gas release multipliers in the new PAD code on and off, it was possible to determine more precisely which temperature regime was dominating the fission gas release predictions of these rods. All rods for which the high temperature contribution exceeded one percent were then labeled as "high temperature" and the remaining rods were labeled as "low temperature" release rods.

Furthermore, it was found during calibration that calibrating all of the high temperature data as a single population tended to underpredict fission gas release at higher release fractions. Consequently, it was necessary to further divide the high temperature rods into a second subset. All subsequent calibrations were performed with the objective of minimizing the average M/P and M-P for the high temperature rods having measured fractional releases exceeding [ ]a,c percent. As a result, the best estimate fission gas release model as-calibrated tends to overpredict for high temperature fission gas release for measured data less than [ ]a,c percent. The data used for this and all other fission gas release calibration runs is summarized in Table 2.

Figures 1 and 2 compare the predicted and measured fission gas release for the portion of the database predicted to operate primarily in the low temperature regime. The agreement shown in these figures between the model and the data is quite good. Furthermore, there is no statistically significant trend of the measured-to-predicted ratios with burnup, showing that the model accounts for the burnup dependence of the fission gas release to the maximum rod average burnup in the data [ ]a,c.

Figures 3 and 4 compare the predicted and measured fission gas release for the entire steady-state fission gas release database. It can be seen that the high temperature fission gas release model has been calibrated so as to best model the data with measured fission gas release exceeding [ ]a,c percent.

Fission gas release data from [ ]a,c fuel rods subjected to overpower tests (i.e., "bump" tests) have been used to verify the transient fission gas release model. Comparisons of the measured and predicted fission gas release for these rods are shown in Figures 5 and 6. The data used in these comparisons are summarized in Table 3. It should be noted that most of these data are for KWU/CE rodlets, as very few of the rods are typical of Westinghouse design PWR fuel rods. There are major differences in the fuel and cladding behavior between the Westinghouse rods and the KWU/CE rodlets. However, the KWU/CE rodlet data have been included in the transient fission gas release model verification on the basis that it is inappropriate to ignore the majority of the available data. It should be recognized that the differences between the Westinghouse and KWU/CE fuel rod in-reactor behavior may conservatively bias the model when applied to Westinghouse fuel rod design and safety evaluations. In particular, the transient fission gas release model is a bounding model with respect to the Westinghouse rod data, not a best estimate model.

Table 2 - Steady-State Fission Gas Release Database

a,c

NSD-NRC-98-5787

a,c

a,c

a,c

Table 3 - Transient Fission Gas Release Database

a,c

NSD-NRC-98-5787

a,c

[ ] a,c

Calibration Results

The PAD code was calibrated by modifying three calibration coefficients (AFGRH, AFGRL and AFGRT) which act as simple multipliers on the modeled fission gas release rate for the high temperature, low temperature and transient regimes, respectively. The results of the calibration defined the calibration coefficients as follows:

[ ] a,c

The statistical results for the calibration, validation, and verification (total) data are shown below in table 4.

Table 4: Statistical results of fission gas release calibration

Calibration Data:	*Low-Temp*	*High Temp Meas>10%*	*Transient Meas>10%*	
Population	[		]	a,c
Avg. M-P (%)				
Stdev. M-P (%)				
Avg. M/P				
Stdev. M/P				
Validation Data:				
Population	[		]	a,c
Avg. M-P (%)				
Stdev. M-P (%)				
Avg. M/P				
Stdev. M/P				
Verification Data: (all data)				
Population	[		]	a,c
Avg. M-P (%)				
Stdev. M-P (%)				
Avg. M/P				
Stdev. M/P				

Conclusions

The steady-state and transient fission gas release models have been successfully calibrated for use in PAD. All of the fission gas release model comparisons show reasonable agreement between measured and predicted data. The results are similar with those determined for the PAD (WCAP-10851-P-A) fission gas release model calibration.

References

1. WCAP-10851-P-A, "Improved Fuel Performance Models for Westinghouse Fuel Rod Design and Safety Evaluations", June. 1985.

Figure 1: Measured vs. Predicted Fission Gas Release

(Low Temperature Data Only)

a,b,c

Figure 2: Measured/Predicted vs. Burnup

(Low Temperature Data Only)

a,b,c

[ ]

Figure 3: Measured vs. Predicted Fission Gas Release
(All Steady-State Fission Gas Release Data)

a,b,c

[ ]

Figure 4: Measured/Predicted vs. Burnup
(All Steady-State Fission Gas Release Data)

a,b,c

[ ]

Figure 5: Measured vs. Predicted Fission Gas Release

(Entire Transient Fission Gas Release Database)

a,b,c

Figure 6: Measured/Predicted vs. Burnup

(Entire Transient Fission Gas Release Database)

a,b,c

Revised Rod Irradiation Growth Model

Model Details

Extensive in-reactor testing has been performed in EBR-II (fast neutron spectrum) and DIDO (thermal spectrum). One set of tests reported by Rogerson determined the irradiation growth in DIDO and EBR-II with the same material (RXA Zr-2).[1] The result shows that the growth strain exhibited by the EBR-II sample is within the sample-to-sample scatter exhibited by the DIDO data. This result shows that irradiation growth data measured in a fast neutron spectrum (specifically EBR-II) is applicable to thermal neutron spectra. Therefore, the EBR-II data may be applied to PWRs.

The available CW irradiation growth data covers an extensive parameter range. The temperatures are in the range of 353 to 687 K (176 to 777°F), and the fluences extend up to values similar or higher than typical end-of-life PWR fuel rods (1.7×10^{22} n/cm^2 E>1 MeV). In the case of the EBR-II tests, large growth strains were observed (strains as large as 2.5%).[2] At high fluences (>0.5×10^{22} n/cm^2 E>1 MeV) and temperatures >650 K, the irradiation growth strain and strain rate is the same for CW and RXA material. Figures from reference 2 for 20% CWSR Zr-2 slab material show that this behavior is not texture or temperature dependent (for temperatures >650 K).

PAD Revision

The revised PAD irradiation growth equation was modified using the irradiation growth rate temperature dependence reported by Fidleris et. al. [3]. At temperatures >660 K, the irradiation growth rate increases rapidly with increasing temperature. The high temperature effect (for temperatures >660 K), was modeled by [

]^{a,c} (see Figure 1)

[.]^{a,c}

[

]^a,c

References

1. A. Rogerson, "Irradiation Growth in Annealed and 25% Cold Worked Zircaloy-2", J. Nucl. Mat. 154 (1988) 276-285.
2. R.P. Tucker, V. Fidleris and R.B. Adamson, "High-Fluence Irradiation Growth of Zirconium Alloys at 644 and 725 K", Zirconium in the Nuclear Industry: Sixth International Symposium, ASTM STP 824, 427-451.
3. V. Fidleris, R.P. Tucker and R.B. Adamson, "An Overview of Microstructural and Experimental Factors that Affect the Irradiation Growth Behavior of Zirconium Alloys", Zirconium in the Nuclear Industry: Seventh International Symposium, ASTM STP 939, 49-85.

Figure 1.

G/G_o VS Temp

a,c

Updated Zr-4 and ZIRLO™ Clad Thermal Conductivity Values

Model Description

Table 1 summarizes the thermal conductivity values calculated as a function of temperature. based on the tests conducted by the the "Properties Research Laboratory" in West Lafayette. Indiana. on Westinghouse Zircaloy-4 and ZIRLO™ cladding. [

] a.b.c

A linear fit of the data presented in Table 1 yields the following best estimate model for Zirclaloy-4. in the temperature range of [ ] a.b.c.

[ ] a.b.c (1)

where,

k = Thermal Conductivity in $Wcm^{-1}K^{-1}$

T = Temperature in °C

In the case of ZIRLO™, a linear fit of the data presented in Table 1 yields the following best estimate model in the temperature range of [ ] a.b.c.

[ ] a.b.c (2)

where,

k = Thermal Conductivity in $Wcm^{-1}K^{-1}$ and

T = Temperature in °C

Figure 1 represents the linear plots of thermal conductivity versus temperature for Zircaloy-4 and ZIRLO™ as represented by equations 1 and 2 respectively.

PAD Revision

In view of the fact that the maximum allowable clad design temperature for steady state operation for Zircaloy-4 is [ ] ^{a,c} and for ZIRLO™ is [ ] ^{a,c} respectively. and for condition II transients is [ ] ^{a,c} for zircaloy-4 and [ ] ^{a,c} for ZIRLO™ . models represented by equation (1) for Zircaloy-4 and equation (2) for ZIRLO™ clad will be used for thermal conductivity predictions as a function of temperature for Westinghouse fuel clad in the revised PAD code.

Table 1. Thermal Conductivity as a function of temperature

Temperature	Thermal Conductivity (W cm-1 K-1)

[ ] a,b,c

Figure 1

Thermal Conductivity as a Function of Temperature for Zircaloy-4 and ZIRLO (1st Order Fit)

a,b,c

Updated Zr-Oxide Thermal Conductivity Value

Description of Change

A best estimate value of [ ]^{a,b,c} has been used in PAD (WCAP-8720) for Zr-4 oxide layers, based on data from Reference 1. Since that time, additional data have become available (References 2,3) which indicates that the oxide layer thermal conductivity has a higher value. The purpose of this update is to use the appropriate data from References 2 and 3 to establish a revised best-estimate average value of the Zr oxide layer thermal conductivity.

The first set of new ramp tests (Reference 2) consisted of a set of 12 ramps on four rods with oxide layer thicknesses of 30, 54, 66, and 82 microns. Thermal conductivity values ranged from 1.4 to 3.7 W/mK with an average value of 2.4 W/mK.

The second set of ramp tests, Reference 3, was run because there was no clear dependence of oxide thermal conductivity on oxide layer thickness, and it seemed that crud could have been present on two of the rods and that could have affected the results. The two fuel rods were brushed and the tests were repeated.

During the second set of ramps, it was noted that the rod elongation during up-ramps was greater than contraction during down-ramps. It was postulated that pellet-cladding mechanical interaction could be occurring during the up-ramps, and it was recommended that only the down-ramps be used for thermal conductivity measurements. The oxide layers were re-measured, and it was found that the thickness of the 26 micron layer was actually 30 microns.

A total of seven down ramps were measured during the second set of experiments. The resulting thermal conductivity values are given in Table 3-2 of Reference 3. A summary of the thermal conductivities from the first set of ramps is given in Table 1.

a,c

These data were combined with data from the second set of ramps given in table 3-1 of Reference 3. The combined data are given in Table 2. The variables are the TEST series, 1 or 2, the RAMP number, UP1D2 = 1 for up ramps and 2 for down ramps, t = the oxide thickness, and K = the thermal conductivity.

a,c

a,c

The results of a statistical analysis of the Table 2 data for the down ramps are given below:

[ ]^{a,c}

Tests were performed to determine if the conductivity values are normally distributed. [

]^{a,c}

PAD Revision

In conclusion, the NFIR conductivity data can be characterized and included in the revised PAD code as follows:

[ ]^{a,c}

for evaluating cladding temperatures with oxide layers present.

References

1. NUREG/CR-0497, TREE-1280, "MATPRO- Version11," Feb. 1979. Methodology/Calculations.
2. EPRI-TR-107718-P1, "In-Pile determination of Thermal Conductivity of Oxide layer on LWR Cladding, Part 1: Irradiation Period July-October 1995." Final report, January 1997.
3. EPRI Draft Tr-107718-P2, Thermal Conductivity of Oxide layer on LWR Cladding, Part 2: Irradiation Period September-November 1996 and Crud Analysis," Draft Final Report, April 1997.
4. Ostle And Mensing, "Statistics in Research, Third edition," The Iowa State University Press, 1975.

Updated Equation of State Model (EOS)

Model Description

The relationship between pressure, temperature, and mass for a fission gas in PAD (WCAP-10851-P-A) is based on the Ideal Gas Law,

$$PV = N\Re T \tag{1}$$

where P and T and the pressure and temperature of the gas respectively. V is the volume occupied by the gas, and N is the number of moles of gas. The universal gas constant is R. Equation (1) is equivalent to:

$$Pv = RT \tag{2}$$

where v is the specific volume and R is a (particular) gas constant.

The Ideal Gas Law relationship is valid for many gases near room temperature and pressure, and is good for noble gases such as helium, neon, and argon up to moderate pressures (400 - 500 psia). At high pressures (P > 500 psia) however, the Ideal Gas Law becomes increasingly inaccurate. Figure 1 from reference 1, shows the compressibility of several gases at high pressure, where compressibility Z is defined as:

$$Z = \frac{Pv}{RT} \tag{3}$$

For an ideal gas, the compressibility Z = 1.0. Deviation from 1.0 is an indication of non-ideal behavior, and that the use of the Ideal Gas Law will lead to inaccurate results.

Figure 1 from reference 1, shows that above about 500 psia, inert gases do not exhibit ideal behavior. At end of life, when the rod internal pressure can exceed 2000 psia, none of these gases will exhibit ideal behavior. Therefore, use of the Ideal Gas Law to estimate rod pressure given the temperature and specific volume will be inaccurate. Since helium makes up the majority of the gas, and the compressibility of helium is greater than 1.0, the Ideal Gas Law will underpredict the actual rod pressure.

A survey was conducted to determine the most appropriate EOS. It was determined that the Peng-Robinson equation, ref. 2, gave the most accurate predictions for the range of interest. For fission gas mixtures even at end of life, helium has the highest mol fraction. To check these EOSs for high He mol fraction, the results were plotted as DP/P versus helium mol fraction. These results are shown in Figures 1 and 2. Measured data was obtained from references 3 through 7, for the various gas matrix evaluations.

Note that DP/P is defined as:

$$\frac{DP}{P} = \frac{P_{data} - P_{prediction}}{P_{data}} \tag{4}$$

This quantity is positive when the pressure is underpredicted, and negative when overpredicted.

FISSION GAS EQUATION of STATE

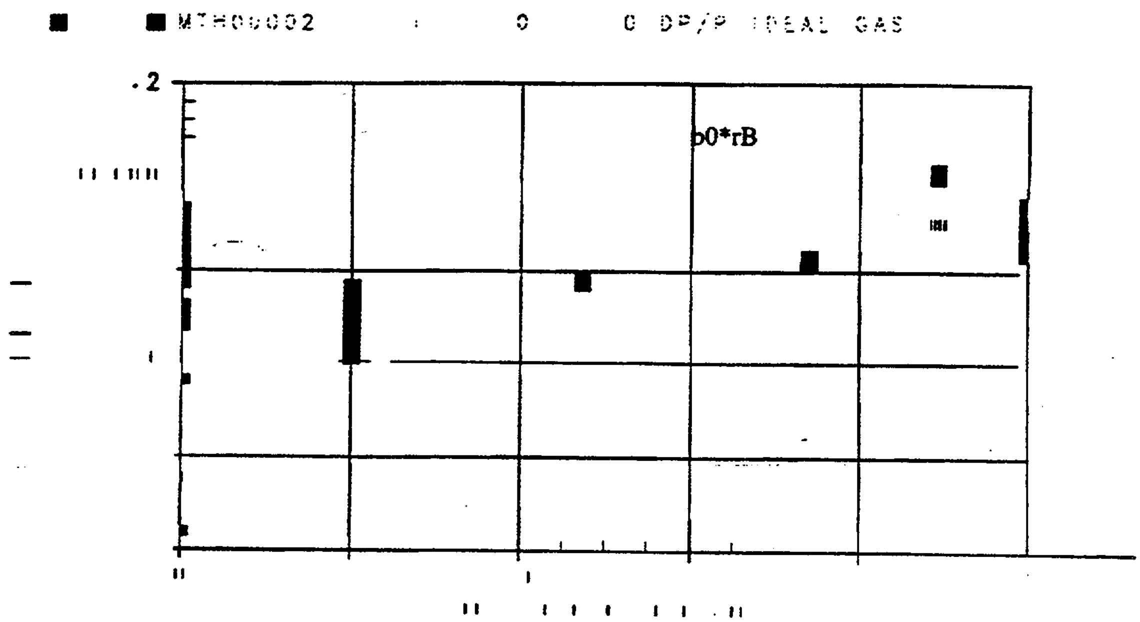


Figure 1 Ideal Gas EOS

FISSION GAS EQUATION of STATE

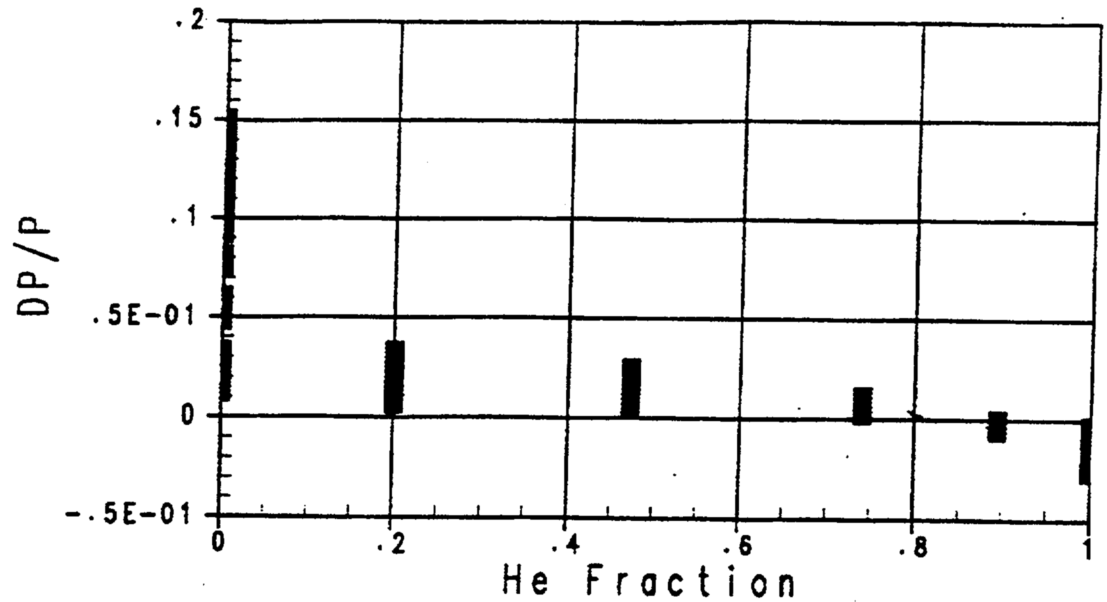


Figure 2. Peng-Robinson EOS.

From Figure 1 it becomes clear that for gas compositions rich in helium, the Ideal Gas Law may underpredict the actual pressures, in some cases by more than 10%.

The Peng-Robinson EOSs performs well at high He composition. For mol fractions greater than about 0.2, it predicts the pressure to within +/- 5%. At mol fractions approaching 1.0, the Peng-Robinson EOS overpredicts the pressure slightly, but never by more than 3% as shown in Figure 2.

FISSION GAS EQUATION of STATE

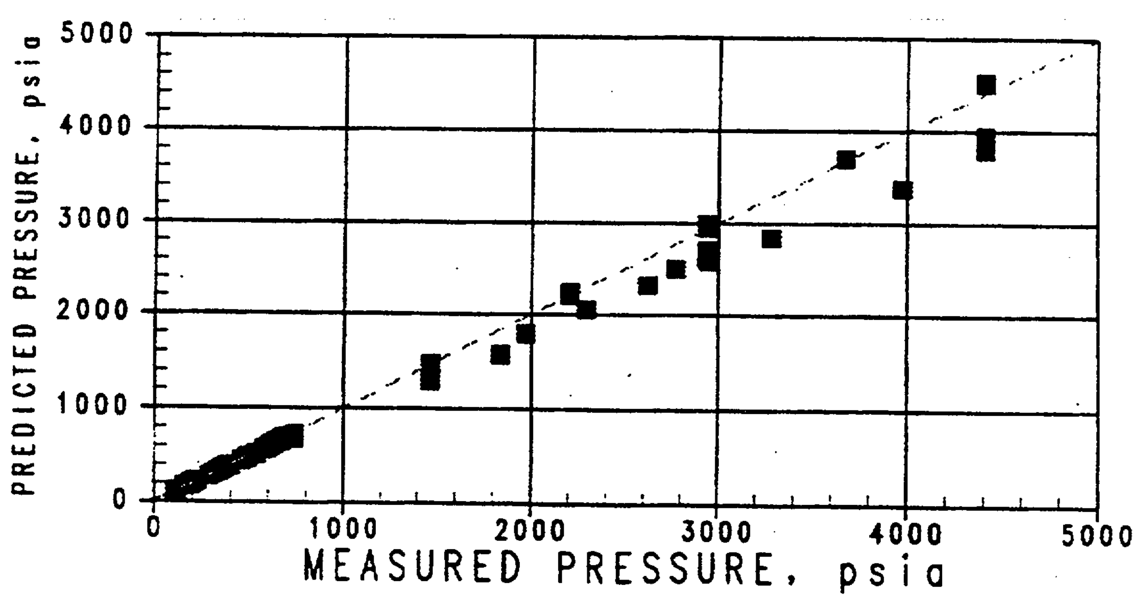


Figure 3. Peng-Robinson EOS.

Figure 3 shows the Peng-Robinson M-P plot results for various pressures. The pressure predictions for mixtures with high helium mol fractions are always predicted to within 5%.

Summary

The Ideal Gas Law was found to potentially underpredict pressure for compositions with high helium mol fraction. The more complex cubic Equations of State (Redlich-Kwong, Soave, and Peng-Robinson) were more accurate at high helium mol fraction, and tended to overpredict the pressure slightly. Of these three, the Peng-Robinson EOS was found to be slightly better than the other two.

Pad Revision

PAD revision investigations of several Equations of State applicable to gas mixtures when compared to available data over a range of pressure, temperature, and composition shows the Peng-Robinson EOS is most accurate and will be used in the revised PAD code.

The pressure-temperature-volume relationship for a pure fluid is often represented by a cubic Equation of State, which has the general form:

$$P = \frac{RT}{v-b} - \frac{a}{v^2 + ubv + wb^2} \tag{5}$$

where P is the pressure, T is temperature, v is specific volume, and R is the Universal Gas constant.

For the Peng-Robinson equation of state, $u = 2, w = -1$ with

$$b = \frac{0.07780RT_c}{P_c} \tag{6}$$

and

$$a = \frac{0.45724r^2T_c^2}{P_c}\left[1 + f\omega\left(1 - T_r^{0.5}\right)\right]^2 \tag{7}$$

where,

$$f\omega = o37464 + 154226\omega - 0.26992\omega^2 \tag{8}$$

In Equations (6) and (7), the subscript "c" denotes properties at the critcal point. The reduced pressure is defined as

$$T_r = \frac{T}{T_c} \tag{9}$$

The function for $f\omega$ given by Equation (8) uses the acentric factor ω.which is a parameter that represents the complexity of a molecule with respect to geometry and polarity. For monatomic gases. ω is usually zero or very small.

In the revised PAD code up to seven different gases can be present in the gas mixture. The following table lists these components and the properties assigned in the code as taken from Reference 2:

[ ] a. c

For gas mixtures, the attraction and repulsion between molecules of different components causes non-linear variation of some properties with composition. To account for this in Equation (5). a set of mixing rules can be defined to this non-linearity. The values of "a" and "b" in Equation(5) are re-defined. Based on the recommendations in Reference 4. the following mixing rules are used in the revised PAD code.

$$a_m = \sum_i \sum_j y_i y_j \left(a_i a_j\right)^{0.5} \left(1 - k_{ij}\right)$$

$$b_m = \sum_i y_i b_i$$

The b_i and a_i for each pure component are given by Equations (6) and (7) respectively. The term k_{ij} is used for some binary pairs to adjust for strong interactions and is determined from experimental data. In the revised PAD code $k_{ij} = 0$ .is assumed for all binary combinations.

REFERENCES

1 Cook, G. A., Argon. Helium. and the Rare Gases, Interscience Publishers. New York. 1961.

2 Reid, R. C., Prausnitz, J. M., and Poling, B., The Properties of Gases and Liquids, 4th Ed.. McGraw Hill, 1986.

3 Hurley, J. J., et al., "Virial Equation of State of Helium, Xenon, and Helium-Xenon Mixtures from Speed of Sound and Burnett PrT Measurements," Int. J. of Thermophysics, Vol. 18, No. 3. May 1997.

4 McCarty, R. D., "Thermophysical Properties of Helium-4 From 2 to 1500 K With Pressures to 1000 Atmospheres," COM 75-10334, National Bureau of Standards, Nov. 1972.

5 Matheson, Gas Data Book, 6th Ed.

6 Briggs, T. C., and Howard, A. R.,"Compressibility Data for Helium, Nitrogen, and Helium-Nitrogen Mixtures at 0°,25°, and 50° C and at Pressures to 1000 Atmospheres," Bureau of Mines Report of Investigations 7639, 1972.

7 Gandhi, J. M., and Saxena, S. C., "Correlated Thermal Conductivity Data of Rare Gases and Their Binary Mixtures at Ordinary Pressures," J. Chem and Eng. Data, Vol. 13, No. 3, July 1968.

Variable O-M Ratio Model

Model Background

In order to accurately model fuel rod clad temperatures and stresses in a fuel performance models as well as 17% metal wastage calculations, an accurate model of Zircaloy-4 oxide to metal ratio is needed for use in design. Due to the differences in densities of the oxide and the base metal. there is a volumetric change from the metal consumed to the oxide formation. This volumetric difference results in a thicker oxide than the metal that was consumed. The ratio of the volumes is characterized by the oxide-to-metal ratio (O/M). The theoretical oxide-to-metal ratio is referred to as the Pilling-Bedworth ratio. and for Zirconium based alloys the value of 1.56 is commonly used. However, during the in-reactor generation of ZrO_2, different mechanisms occur that cause the oxide density to be less than theoretical resulting in higher O/M ratios at increasing oxide thicknesses. Westinghouse metallographic O/M measurements from fuel rod hot cell programs were evaluated and a predictive model was generated which relates O/M with oxide thickness.[

] a,c. This model was first presented to the NRC by presentation on May 5. 1998.

Variable O/M Ratio Model Details

As the oxide grows, it transitions from a protective to a non-protective structure. The non-protective oxide contains cracks and pores and this transition occurs when the oxide is about [

]a,c In generating a model which predicts O/M ratio as a function of oxide thickness. the first [

]a,c of oxide should result in a constant theoretical value of O/M ratio. At higher oxide thicknesses. the data presented in the previous section is used to develop the relationship of O/M ratio with increasing oxide thickness.

The equations governing the O/M ratio as a function of oxide thickness are as follows:

$$ {}^{O}\!/_{M} = {}^{O}\!/_{M_{Th}}, \qquad t < [\quad]^{a,c} \qquad (1) $$

$$ {}^{O}\!/_{M} \Big[\qquad \Big]^{a,c} \qquad (2) $$

where:

O/M_{th} = theoretical value of O/M ratio = 1.56
a = fitting coefficient, [ ]^{a,c}
b = fitting coefficient
t = oxide thickness (mils)

Equations 1 and 2 are combined and plotted against the sorted data from O/M measurements in Figure 1.

[ ]a,b,c

Gas Absorption in Cladding Effect

Description of Effect

The fuel rod internal gas mixture includes (1)the fission gasses produced during operation, (2) gas from the pellets including the gas from the IFBA coating if present, (3) the gas from the rod pressurization and (4) the [ ]a,c. When the rod is pressurized and sealed during fabrication, the rod [ ]a,c. Both IFBA and non-IFBA rods contain this equivalent volume [ ]a,c. Zirconium alloys are known to react with [ ]a,c.

For example, assuming a plenum volume of about [ ]a,c and a gas mixture in [ ]a,c

With about [ ]a,c the corresponding weight gain for total [ ]a,c. Based on reaction rates in Reference2, [ ]a,c will occur within [ ]a,c; thus, all of the [ ]a,c.

Zirconium preferentially reacts with [ ]a,c are present. The reaction rate with [ ]a,c (Reference 2). When the [ ]a,c The absorption rate of [ ]a,c. Based upon the weight of [ ]a,c Thus, it will take about [

]a,c. This may be a lower than actual rate since rate is temperature dependent. [ ]a,c.

Irradiated rods were punctured in the hot cell and the gas present in the rod was captured and analyzed. In the 22, [ ]a,c measured and in 7 other rods from [ ]a,c there was [ ]a,b,c. The measurement sensitivity is reported as less than 0.01 % by volume. If the [ ]a,c pressurization and a resultant internal rod gas mixture with [[ ]a,c by volume. These levels if present in the rod at end of life are above the detection limit by factors of over 100.

PAD Change

Evaluations indicate that the [ ]a,c the Zirc 4 or ZIRLO microstructure and [ ]a,c. Based on this evaluation, revised PAD code will not use [ ]a,c.

References

1. Handbook of Chemistry and Physics, 41st Edition, page 3379.
2. Lustman and Kerze, "Metallurgy of Zirconium", McGraw-Hill Book Company, Inc., 1955, pages 578-608.

SECTION F

Westinghouse
Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

September 29, 1998
NSD-NRC-98-5792

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Reference 1) NSD-NRC-98-5787 dated September 11, 1998
2) AW-98-1284 dated September 11, 1998

Subject: Revised PAD Code Summary of Changes

Dear Mr. Collins:

In our submittal of September 11, 1998, letter NSD-NRC-98-5787 we had inadvertently attached the wrong file for the section titled "Revised PAD Code Summary of Changes". Attached are Proprietary and Non-Proprietary versions of the correct file, which corresponds to the text presented to you at the meeting of September 15 on the Revised PAD Code. Please replace the section marked "Revised PAD Summary of Changes" in letter number NSD-NRC-98-5787 with the attachments provided in this memo.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.17(a)(4). The proprietary material transmitted in this letter is of the same technical type as the proprietary material previously submitted in Reference 1. Further, the affidavit submitted to justify the material previously submitted, AW-98-1284, is equally applicable to this material.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with the previously submitted affidavit and application for withholding, AW-98-1284, dated September 11, 1998, a copy of which is attached.

This material is for your internal use only and may be used solely for the purpose for which it is submitted.

It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1284 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

cc: P. C. Wen, NRR/DRPM/PGEB (10H5)

/cad

SECTION G

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

October 8, 1998

Carol,
Copies for.
D Colburn K. Bahr
J. Foster T. Croyle
S. Sidner K. McAfee
S. Miller W. Slagle
P. Schueren R. Knott
J. Scarfutti H-Sepp
Thanks
Sumit.

MEMORANDUM TO: Thomas H. Essig, Acting Chief
Generic Issues and Environmental Projects Branch
Division of Reactor Program Management
Office of Nuclear Reactor Regulation

FROM: Peter C. Wen, Project Manager Peter C. Wen
Generic Issues and Environmental Projects Branch
Division of Reactor Program Management
Office of Nuclear Reactor Regulation

SUBJECT: SUMMARY OF SEPTEMBER 15, 1998, MEETING WITH WESTINGHOUSE REGARDING REVISED PAD CODE

On September 15, 1998, a public meeting was held at Westinghouse's offices in Rockville, Maryland, between members of Westinghouse and NRC staff. Attachment 1 lists attendees at the meeting. Most portions of the meeting involved discussion of proprietary information. Attachment 2 is a copy of the non-proprietary material handed out at the meeting.

The purpose of the meeting was to discuss the issues related to the revised PAD code. The meeting started with a Westinghouse representative presenting a meeting agenda and overview of PAD model changes. At this meeting, Westinghouse submitted the revised PAD code calibration and validation & verification (V&V) results (Westinghouse letter, NSD-NRC-98-5787, dated September 11,1998) for NRC review. The submittal also contained a description and justification of the changes requiring NRC approval that had been implemented in the revised PAD code.

During the meeting, Westinghouse presented the results of the code calibration and V&V as well as the model changes. In addition, a discussion was held to clarify the request for additional information (RAI) that had recently transmitted by the NRC to Westinghouse on the revised creep model (WCAP-15063-P).

A number of questions were generated at this meeting. These are listed in Attachment 3. Westinghouse agreed to respond to these questions on an expedited schedule.

With respect to the review of the revised PAD code, the staff agreed that Westinghouse's submittals of WCAP-15063-P and NSD-NRC-98-5787 are deemed as complete, and that no other submittals (other than responses to questions) are needed to continue the review.

It was explained by the Westinghouse representative that the target date for issuance of an SER in the December 98/January 99 time-frame is very important to them in order to meet the schedule of coming licensing applications. The staff replied that due to budgetary concerns, there would have to be an internal discussion before a commitment on schedule could be made.

Attachments: As stated

cc w/atts: See next page

NRC/WESTINGHOUSE MEETING ON REVISED PAD CODE
LIST OF ATTENDEES
September 15, 1998

NAME	ORGANIZATION
Jim Lyons	NRR/SRXB
Shih-Liang Wu	NRR/SRXB
Peter Wen	NRR/PGEB
Harold Scott	RES/RPSB
Carl Beyer	PNNL
Sumit Ray	Westinghouse
Ron Knott	Westinghouse
Scott Sidener	Westinghouse
David Colburn	Westinghouse
John Foster	Westinghouse

Attachment 1

Technical Meeting with NRC on Revised PAD Code

September 15th, 1998

Non-Proprietary

Attachment 2

Agenda

- Introduction & Purpose of meeting
- Overview of PAD model changes
- Presentation of calibration and V&V results
- Detailed discussion of PAD model changes
- Discussion of creep model RAIs
- Licensing and implementation of revised PAD

Background

- Meeting held with NRC on May 5th, 1998
- Creep model was discussed as the only major model change
- At that meeting, Westinghouse committed to the following
  - submit revised creep model WCAP (complete 6/98)
  - provide confirmation of successful code V&V

Current Situation

- Revised creep model still remains the only major model change
- However, other model enhancements have been made that need NRC concurrence
- Model changes have been incorporated into the PAD code
  - code calibration and V&V have been completed
- Westinghouse internal verification and review process ongoing

Meeting Objective and Purpose

- Inform NRC of additional model changes
- Present and submit calibration and V&V results
- Submit detailed information on additional model changes for NRC review
- Obtain NRC feedback to factor into W review process
- Discuss NRC RAIs on the Revised Creep Model WCAP
- Obtain concurrence on licensing process and schedule

Preferred Licensing Process and Schedule

- Description and justification of additional model enhancements submitted at this meeting
- Calibration and V&V results submitted at this meeting
- NRC review and W response to questions (9/98 - 11/98)
- TER/SER (12/98 - 1/99)

List of questions and requests generated during the 09/15/98 NRC/Westinghouse meeting on revised PAD models

1. What were the as-filled and operating pressures of the Zion rods used in the creep model calibration? What were the operating conditions of stress for those rods?

2. Please show the statistics and plots related to thermal verification data for powers in excess of 9 kW/ft. Please identify each of the individual rods in the plots.

3. Is rod 432-6 from the Halden thermal calibration data generally over-predicted in centerline temperatures?

4. Supply an explanation of overall gap conductance equations used in PAD.

5. Compare the revised PAD values of GAPRED, AFGRL, AFGRH, and AFGRT to those used in PAD 3.4.

6. Please plot fission gas release verification results residual plots using M-P instead of M/P.

7. Does the temperature effect on irradiation growth affect the nozzle gap calculation ?

8. Please supply individual creep verification rod data which includes time average stress, time average temperature, and fluence. Give min., max. and average values for temperature and stress.

9. Please supply typical plots of the following:

   a) Corrosion vs. Burnup
   b) Clad O.D. vs. Burnup
   c) CL-Temperature vs. Power and Burnup
   d) Rod Pressure vs. Burnup (IFBA and non-IFBA)
   e) Power vs. Burnup

10. Please correct Figure 3 of the fission gas release calibration section for proper axis titles.

Attachment 3

cc:

Mr. Nicholas Liparulo, Manager
Equipment Design and Regulatory Engineering
Westinghouse Electric Corporation
Mail Stop ECE 4-15
P.O. Box 355
Pittsburgh, PA 15230-0355

Mr. Jack Bastin, Director
Regulatory Affairs
Westinghouse Electric Corporation
11921 Rockville Pike
Suite 107
Rockville, MD 20852

Mr. Hank Sepp, Manager
Regulatory and Licensing Engineering
Westinghouse Electric Corporation
PO Box 355
Pittsburgh, PA 15230-0355

Mr. Sumit Ray, Manager
Fuel Licensing
Westinghouse Electric Corporation
PO Box 355
Pittsburgh, PA 15230-0355

SECTION H

Westinghouse Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

November 13, 1998
NSD-NRC-98-5808

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: Response to NRC "Request for Additional Information for Westinghouse Topical Report WCAP-15063-P, 'Westinghouse In-Reactor Creep Model'," dated September 10, 1998.

Dear Mr. Collins:

Enclosed are three copies of responses to the NRC's "Request for Additional Information for Westinghouse Topical Report WCAP-15063-P, "Westinghouse In-Reactor Creep Model". Please note that two of the questions have been marked as "Response deferred". These questions will be answered after accounting for additional information that the reviewer has asked Westinghouse to consider. It should also be noted that Westinghouse is in the process of completing QA documentation on some of the information provided in these responses. This effort is expected to be completed shortly. Westinghouse will notify the NRC and reviewer when this effort is completed.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-98-1305 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-98-1305.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.5(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1305 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

copy to:
T. E. Collins, NRR
P. C. Wen, NRR

Westinghouse
Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

November 13, 1998
AW-98-1305

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief,
Reactor Systems Branch
Division of Systems Safety and Analysis

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: Response to NRC "Request for Additional Information for Westinghouse Topical Report WCAP-15063-P, 'Westinghouse In-Reactor Creep Model'," dated September 10, 1998.

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5808, dated November 13, 1998

Dear Mr. Collins:

The application for withholding is submitted by Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse"), pursuant to the provisions of paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-98-1305 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-98-1305 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

cc: T. Carter / NRC (5E7)

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 13 day
of November, 1998.

Notary Public

Notarial Seal
Janet A. Schwab, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires May 22, 2000
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Division, of the Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked Response to NRC "Request for Additional Information for Westinghouse Topical Report WCAP-15063-P, 'Westinghouse In-Reactor Creep Model'," dated September 10, 1998, November 13, 1998, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSD-NRC-98-5808) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of T. E. Collins, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information as submitted by Westinghouse Electric Company is to provide response to the NRC's "Request for Additional Information" on the revised Westinghouse Creep Model that is used in the Westinghouse Performance Analysis and Design model (PAD). This information is provided for review and approval of this revised creep model.

This information is part of that which will enable Westinghouse to:

(a) Ensure proper fuel performance of fuel operating in reactors.

(b) Assist customers to obtain license changes resulting from fuel performance modeling.

Further this information has substantial commercial value as follows:

(a) Westinghouse can use this fuel performance modeling capability to further enhance their licensing position over their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Response to NRC "Request for Additional Information for Westinghouse Topical Report WCAP-15063-P, 'Westinghouse In-Reactor Creep Model'," dated September 10, 1998

Question 1: **Please provide a list of those licensing analyses to which this creep model will be applied.**

Response 1: *Since the creep model is an integral part of the PAD code, all fuel rod analyses analyzed with PAD or those safety analyses that use results from PAD as input parameters will be impacted by the use of the new creep model. The PAD code is used for determining fuel temperatures and the corresponding rod internal pressure for use in safety analyses, e.g., LOCA, overpower transients and fuel melting. For fuel rod design analyses, PAD is used to calculate fuel and cladding temperatures, rod internal pressures for both gap re-opening and DNB propagation, cladding stress, cladding strain and cladding fatigue.*

Question 2: **Please provide the temperature, flux, fluence and stress range to which this model will be applied.**

Response 2: *Response deferred.*

Question 3: **What is the specified fabrication range of tin content for IMP Zircaloy-4 (Zr-4)?**

Response 3: *The tin composition limits for IMP Zr-4 are 1.20 to 1.45 w/o.*

Question 4: **Please provide the one-sigma uncertainty in the following coefficients to the creep model: A, B, C, C_1, C_3, and C_4, based on the data from which they were derived. Also, please provide the data from which C_3 was derived.**

Response 4: *The uncertainty values for the creep coefficients were derived from the [*

]^{a,c} were reported during the W/NRC September 15, 1998 meeting.

An editorial change is necessary to be made to WCAP-15063-P in order that the method used to evaluate the coefficient C_3 is clearly presented. The evaluation of C_3 is correctly described in the last paragraph of page 14 but is not correctly described in the middle of page 6 of WCAP-15063-P. The editorial change involves the deletion of one sentence and the insertion of two sentences on page 6 of WCAP-15063-P. The sentence to be deleted on page 6 is "The equation was [ ]^{a,c} IMP Zr-4 out-of-reactor (laboratory) thermal creep tests [ ]^{a,c} and the out-of-reactor (laboratory) creep rate equation for [ ]^{a,c} according to:

[ ]^{a,c} (9)"

The two sentences to be inserted in place of the deleted sentence are, "The equation was [ ]^{a,c} out-of-reactor (laboratory) thermal creep rates [ ]^{a,c}. The calculation was performed for typical fuel rod parameters. The parameters used were [ ]^{a,c}. C_3 was evaluated according to:

[ ]^{a,c} (9)"

The results of the analysis are listed in Table 4-1. This correction will be incorporated into a revision of WCAP-15063-P.

Table 4-1
Calculated Values of the Coefficient C_3

T (K)	C_3
589	*[ ]^{a,c}*
616	*[ ]^{a,c}*
644	*[ ]^{a,c}*
672	*[ ]^{a,c}*
	avg. = [ ]^{a,c}

Question 5: **Please provide the one-sigma uncertainties in the irradiation-hardening coefficient derived from the Zr-2.5Nb data.**

Response 5: *The uncertainty values for the creep coefficients were derived from the [*

]^{a,c} were reported during the W/NRC September 15, 1998 meeting.

Question 6: **The derivation and application of coefficient C_3 assumes that irradiation creep is directly proportional to the out-of-reactor thermal creep. The NRC reviewers are aware that ex-reactor creep data can qualitatively rank the irradiation creep of some zirconium alloys, but are not aware of any published data that demonstrates they can be linked quantitatively. Please provide data or a publication with data that substantiates that ex-reactor creep is quantitatively proportional to irradiation creep.**

Response 6: *The out-of-reactor (laboratory) thermal creep rates are directly related to the in-reactor irradiation creep rates for a given zirconium alloy. This relationship [*

]^{a,c}.

In the case of the [

]$^{a, c}$.

In the case of the [

]$^{a, c}$.

References for Question 6:

6-1. *D. G. Franklin, G. E. Lucas and A. L. Bement, "Creep of Zirconium Alloys in Nuclear Reactors," ASTM STP 815, 1983.*

6-2. *D. L. Baty, W. A. Pavinich, M. R. Dietrich, G. S. Clevinger and T. P. Papazoglou, "Deformation Characteristics of Cold-Worked and Recrystallized Zircaloy-4 Cladding," Zirconium in the Nuclear Industry: Sixth International Symposium, ASTM STP 824, 1982, pp. 306-339.*

Table 6-1
ZIRLO™ [ ]$^{a, c}$ In-Reactor Creepdown and Out-of-Reactor Thermal Creepout.

Rod	Burnup (MWD/MTU)	Average Creepdown (mils)	Lot	Sample	Steady-State Creep Rate (10^{-3} %/hr)
[					] a, c

Figure 6-1
Westinghouse BR-3 Fuel Rod Profilometry (Creepdown)
ZIRLO™ 15x15 Cladding

a, b, c

Figure 6-2
Out-of-Reactor Thermal Creep (Creepout)
658 K (725 °F), 108 MPa (15.6 ksi) Equivalent Stress

a, b, c

Figure 6-3
Comparison of In-Reactor and Out-of-Reactor Creep Rates
Westinghouse ZIRLO™

a, b, c

Question 7: **The B&W/EPRI Oconee-2 in-reactor Zr-4 data are used in Section 3.2.1.2 of the report to demonstrate that the irradiation hardening factor for in-reactor thermal creep derived from Zr-2.5Nb data is conservative in relation to the irradiation hardening factor from this data. The B&W/EPRI Oconee-2 in-reactor data are dominated by irradiation creep, and thermal creep is negligible. Therefore, the derivation of an irradiation-hardening factor from the B&W/EPRI data for thermal creep is questionable. Please provide additional data or a publication with data that substantiates that the irradiation-hardening factor from Zr-2.5Nb material can be applied to Westinghouse Zr-4 cladding.**

Response 7: *Section 3.2.1.2 in WCAP-15063-P presents [*

] a, c. This shows that the Zr-2.5Nb data are applicable to Zr-4.

References for Question 7:

7-1. *M. Limback and T. Andersson, "A Model for Analysis of the Effect of Final Annealing on the In- and Out-of-Reactor Creep Behavior of Zircaloy Cladding," Zirconium in the Nuclear Industry: Eleventh International Symposium, ASTM STP 1295, ASTM, 1996, pp. 448-468.*

7-2. *P. A. Ross-Ross and C. E. L. Hunt, "The In-Reactor Creep of Cold-Worked Zircaloy-2 and Zirconium-2.5 wt % Niobium Pressure Tubes," Journal of Nuclear Material, Volume 26, 1968, pp. 2-17.*

7-3. *A. R. Causey, "In-Reactor Stress Relaxation of Zirconium Alloys," Zirconium in Nuclear Applications, ASTM STP 551, 1974, pp. 263-273.*

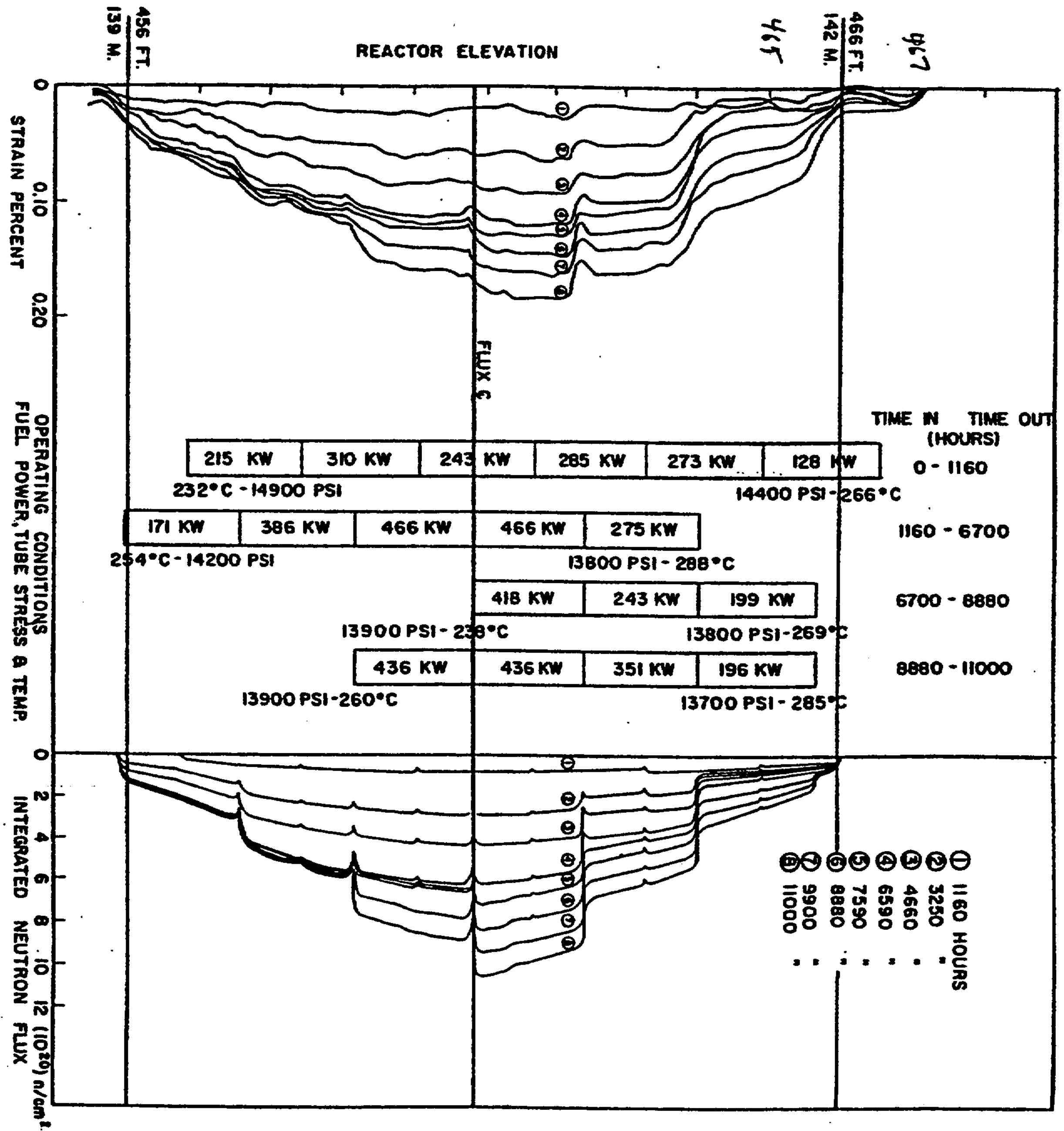
Table 7-1
Irradiation Hardening Reduction Factors

[ ]a, c

a, c

[ ]

Figure 7-1



Reprinted from P. A. Ross-Ross and C. E. L. Hunt, "The In-Reactor Creep of Cold-Worked Zircaloy-2 and Zirconium-2.5 wt % Niobium Pressure Tubes", J. Nucl. Mat., 26 (1968) 2-17, with permission from Elsevier Science.

Question 8: **The data used to determine the coefficients to the Westinghouse creep-model for Imp Zr-4 and ZIRLO™ are based on creep due to compressive stresses while the internal rod pressure analysis at end-of-life calculates creep due to tensile stresses. Please provide cold-worked Zr-2 or Zr-4 tube data that demonstrates that compressive in-reactor creep data can be used to predict in-reactor creep under tensile stresses.**

Response 8: *Response deferred.*

Question 9: **Is the creep rate shown in Equations 1 and 2 the generalized (i.e., effective) creep rate, rather than hoop strain rate?**

Response 9: *The creep rates shown in these equations are for both generalized and hoop strain rates since the generalized and hoop strain rates differ by a constant value.*

Question 10: **Is the constant (0.920) in Equation 16 directly imbedded in the constant C_1 in Equation 17? If not, please explain explicitly how PAD applies the creep strain rate to get hoop strain increments and hence cladding (inward) displacement during creepdown, and outward displacement during creepout.**

Response 10: *The coefficient C_1 is [*

]$^{a, c}$.

Question 11: **Why isn't strain hardening applied to the irradiation induced creep rate? Is there data to substantiate not doing so?**

Response 11: *Irradiation creep data are available which show that irradiation creep hardening occurs by [*

Figure 11-1

a, c

Reprinted from [

]^{a,c} with permission from General Electric.

Figure 11-2

a, c

[ ]

Reprinted from [ ]^{a,c} with permission from General Electric.

SECTION I

Westinghouse Electric Corporation
Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

November 13, 1998
NSD-NRC-98-5810

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Subject: Response to NRC Request for Additional Information on PAD Model Revisions based on NRC/Westinghouse Meeting, dated September 15, 1998.

Dear Mr. Collins:

Enclosed are three copies of responses to the NRC's Request for Additional Information on PAD Model Revisions based on the NRC/Westinghouse meeting held on September 15, 1998. Please note that one question has been marked as "Response deferred" since the reviewer has asked for additional information (i.e., comparison plots for the old and new version of PAD). It should also be noted that Westinghouse is in the process of completing QA documentation on some of the information provided in these responses. This effort is expected to be completed shortly. Westinghouse will notify the NRC and reviewer when this effort is completed.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-98-1307 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-98-1307.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.5(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-98-1307 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

copy to:
T. E. Collins, NRR
P. C. Wen, NRR

Westinghouse Electric Corporation
Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

November 13, 1998
AW-98-1307

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: T. E. Collins, Chief,
Reactor Systems Branch
Division of Systems Safety and Analysis

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: Response to NRC Request for Additional Information on PAD Model Revisions based on NRC/Westinghouse Meeting, dated September 15, 1998.

Reference: Letter from H. A. Sepp to T. E. Collins, NSD-NRC-98-5810, dated November 13, 1998

Dear Mr. Collins:

The application for withholding is submitted by Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse"), pursuant to the provisions of paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-98-1307 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-98-1307 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

cc: T. Carter / NRC (5E7)

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 13 day
of November 1998.

Notary Public

Notarial Seal
Janet A. Schwab, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires May 22, 2000
Member, Pennsylvania Association of Notaries

JANET A. SCHWAB
COMMONWEALTH PENNSYLVANIA
NOTARY PUBLIC

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services Division, of the Westinghouse Electric Company, a division of CBS Corporation ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked Response to NRC Request for Additional Information on PAD Model Revisions based on NRC/Westinghouse Meeting, dated September 15, 1998, November 13, 1998, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (NSD-NRC-98-5810) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of T. E. Collins, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information as submitted by Westinghouse Electric Company is to provide response to the NRC's "Request for Additional Information" on the additional revisions made to the Westinghouse Performance Analysis and Design model (PAD). This information is provided for review and approval of this revised PAD model.

This information is part of that which will enable Westinghouse to:

(a) Ensure proper fuel performance of fuel operating in reactors.

(b) Assist customers to obtain license changes resulting from fuel performance modeling.

Further this information has substantial commercial value as follows:

(a) Westinghouse can use this fuel performance modeling capability to further enhance their licensing position over their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Response to NRC "Request for Additional Information on PAD Model Revisions based on NRC/Westinghouse Meeting September 15, 1998

Question 1: **What were the as-filled and operating pressures of the Zion rods used in the creep model calibration? What were the operating conditions of stress for those rods?**

Response 1: *The as-fabricated initial gas pressure in the Zion rods was [ ] a, c. The internal pressure during operation ranged from [ ] a, c. The operating conditions of stress are included in the response to Question 8.*

Question 2: **Please show the statistics and plots related to thermal verification data for powers in excess of 9 kW/ft. Please identify each of the individual rods in the plot.**

Response 2: *The statistics and plots related to thermal verification data for powers in excess of 9 kW/ft are given below. Table 1 contains the verification data statistics. Figure 1 shows the measured versus predicted data. Figures 2 through 4 show the residuals as a function of burnup, local power, and gap respectively. Figures 5 through 9 show the individual rod measured and predicted data. The "U" and "L" in the rod identification designates upper or lower thermocouple data. Figure 10 shows the measured - predicted data histogram.*

Table 1: Statistical results of thermal calibration

Verification Data:
(all data)

	a, b, c
Population	
Avg. M-P(deg. F)	
Stdev. M-P(deg. F)	
Avg. M/P	
Stdev. M/P	

Figure 1: Measured vs. Predicted Fuel Centerline Temperatures

(power ≥ 9KW/FT)

a, b, c

Figure 2: Measured - Predicted Fuel Centerline Temperature vs. Burnup

(power ≥ 9KW/FT)

[ ]a, b, c

Figure 3: Measured - Predicted Fuel Centerline Temperature vs. Local Power

(power ≥ 9KW/FT)

[ ] a, b, c

Figure 4: Measured - Predicted Fuel Centerline Temperature vs. Gap

(power $\geq$ 9KW/FT)

a, b, c

Figure 5: Measured vs. Predicted Fuel Centerline Temperatures (Assembly 431, power ≥ 9KW/FT)

a, b, c

Figure 6: Measured vs. Predicted Fuel Centerline Temperatures (Assembly 432-1,3, power $\geq$ 9KW/FT)

a, b, c

Figure 7: Measured vs. Predicted Fuel Centerline Temperatures (Assembly 432-5,6, power ≥ 9KW/FT)

a, b, c

Figure 8: Measured vs. Predicted Fuel Centerline Temperatures (Assembly 513-1,2,3, power ≥ 9KW/FT)

a, b, c

Figure 9: Measured vs. Predicted Fuel Centerline Temperatures (Assembly 513-4,5,6, power ≥ 9KW/FT)

a, b, c

Figure 10: Verification Data Measured - Predicted Histogram (power ≥ 9 KW/FT)

[ ] a, b, c

Question 3: **Is rod 432-6 from the Halden thermal calibration data generally over-predicted in centerline temperatures?**

Response 3: *Yes, rod 432-6 is generally overpredicted. The data is shown in Figure 7 of Response 2.*

Question 4: **Supply an explanation of overall gap conductance equations used in PAD.**

Response 4: *The thermal model (gap conductance) has not been changed from that licensed in PAD 3.4. The details of the model are given below:*

The PAD3.4 gap conductance model for an open gap is given by Equation (3):

[ ] a, c

PAD selects the maximum gap conductance as calculated from Equation (2) or Equation (3). Equation (3) is an empirical correlation derived from analysis of thermocouple and melt radius data for use with finite gaps. Equation (2) is the gap conductance for a temperature drop across the annular gap. In this equation, the gap size has been adjusted by an empirical factor, GAPRED. This factor was defined to produce a best fit of predicted fuel centerline temperature based on the analysis of selected test rods from the Halden program.

Equation (2) is Equation 1 of WCAP-8720 Addenda 2, and Equation (3) is Equation 9 of WCAP-8720. Equation (3) is described as the "PAD 3.3 minimum gap conductance model" in "Response to NRC Questions on Westinghouse Topical Report, WCAP-10851.

Question 5: **Compare the revised PAD values of GAPRED, AFGRL, AFGRH, and AFGRT to those used in PAD 3.4.**

Response 5:

	PAD 3.4	*New PAD*
GAPRED	[ ] a, c	[ ] a, c
AFGRL		
AFGRH		
AFGRT		

Question 6: **Please plot fission gas release verification results residual plots using M-P instead of M/P.**

Response 6: *M-P versus M/P plots are provided in Figures 6-1 through 6-3 on pages 14-16.*

Question 7: **Does the temperature effect on irradiation growth affect the nozzle gap calculation?**

Response 7: *No, the temperature effect on growth is only used in the calculation of rod diameter not rod length.*

Question 8: **Please supply individual creep verification rod data which includes time average stress, time average temperature, and fluence. Give min., max. and average values for temperature and stress.**

Response 8: *Table 8-1, starting on page 18, contains the requested data for each rod at the end of each cycle modeled. The data is shown as a function of axial elevation.*

Question 9: **Please supply typical plots of the following:**

a) **Corrosion vs. Burnup**
b) **Clad O.D. vs. Burnup**
c) **CL-Temperature vs. Power and Burnup**
d) **Rod Pressure vs. Burnup (IFBA and non-IFBA)**
e) **Power vs. Burnup**

Response 9: *Response deferred.*

Question 10: **Please correct Figure 3 of the fission gas release calibration section for proper axis titles.**

Response 10: *Corrected Figure 3 axis titles are presented in Figure 10-1 on page 17.*

Figure 6-1
Steady-State Fission Gas Release: Low-Temperature Regime Data
Measured - Predicted vs. Burnup

a, b, c

[ ]

Figure 6-2
Entire Steady-State Fission Gas Release Database:
Measured - Predicted vs. Burnup

a, b, c

[ ]

Figure 6-3
Entire Transient Fission Gas Release Database:
Measured - Predicted vs. Burnup

a, b, c

[ ]

Figure 10-1
Entire Steady-State Fission Gas Database:
Predicted versus Measured

a, b, c

Table 8-1
Fuel Rod Profilometry Data

Elevation (in)	Burnup MWD/MTU	Fluence (n/cm^2)	Avg. Temp. (F)	Avg. Stress (psi)	Min. Temp. (F)	Max. Temp. (F)	Min. Stress (psi)	Max. Stress (psi)

a, b, c

Table 8-1 (cont.)
Fuel Rod Profilometry Data

Elevation (in)	Burnup MWD/MTU	Fluence (n/cm^2)	Avg. Temp. (F)	Avg. Stress (psi)	Min. Temp. (F)	Max. Temp. (F)	Min. Stress (psi)	Max. Stress (psi)

a, b, c

Table 8-1 (cont.)
Fuel Rod Profilometry Data

Elevation (in)	Burnup MWD/MTU	Fluence (n/cm^2)	Avg. Temp. (F)	Avg. Stress (psi)	Min. Temp. (F)	Max. Temp. (F)	Min. Stress (psi)	Max. Stress (psi)

a, b, c

Table 8-1 (cont.)
Fuel Rod Profilometry Data

Elevation (in)	Burnup MWD/MTU	Fluence (n/cm^2)	Avg. Temp. (F)	Avg. Stress (psi)	Min. Temp. (F)	Max. Temp. (F)	Min. Stress (psi)	Max. Stress (psi)

a, b, c

Table 8-1 (cont.)
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