EPRI

Guidance and Recommended Procedures for Maintaining and Using RACKLIFE Version 1.10

Technical Report

Guidance and Recommended Procedure for Maintaining and Using RACKLIFE Version 1.10

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REPORT SUMMARY

RACKLIFE is a spent fuel rack management tool that can be applied to extend the useful service life of racks utilizing Boraflex as the neutron absorber material for nuclear criticality control. This document provides procedures and guidance for maintaining and using RACKLIFE models.

Background

The spent fuel rack management tool RACKLIFE is generally exercised by the utilities on a frequency dictated by the refueling cycle. Thus RACKLIFE would usually only be used once every 18 or 24 months, typically following the refueling outage in which the fuel moves from the previous outage are incorporated into RACKLIFE and the state point files advanced to the next outage. Because of this infrequency of use, the user generally expends considerable time and effort in refreshing his RACKLIFE skills relative to the actual time spent updating and maintaining the model.

Objectives

To develop guidance and a comprehensive procedure for maintaining and using RACKLIFE models; to help users save time during the updating and maintaining of RACKLIFE models.

Approach

The project team developed a procedure and guidance document for maintaining and using RACKLIFE models. The document assumes no previous experience with RACKLIFE or the history of the Boraflex issues. Accordingly, it includes a detailed chronology of the Boraflex problem as well as a detailed bibliography. The project team has provided embedded hyperlinks in the electronic version of the report so that experienced users can bypass the background material and refer quickly to the update and maintenance sections.

Results

"Guidance and Recommended Procedures for Maintaining and Using RACKLIFE Version 1.10 Models" is a comprehensive and easy to use document for both first time and experienced RACKLIFE users. Its use will result in considerable timesavings as utilities update and maintain their RACKLIFE models.

EPRI Perspective

This report is designed to target the specific question of "How do I use the RACKLIFE software to manage my Boraflex degradation problem?" By giving strategic guidance on when and how the RACKLIFE software should be used, this document provides utility users a roadmap that enables them to better manage their problems and to better anticipate and schedule the RACKLIFE analytical effort. This document is not intended to provide the detailed technical or

software basis for the RACKLIFE code as these have been covered in a series of previously published EPRI reports (the user’s manual for RACKLIFE is EPRI publication TE-114975). However, the report does contain a brief summary of all relevant background documents along with complete reference information.

Keywords

RACKLIFE
Computer software
Boraflex

ABSTRACT

The purpose of this report is to provide guidance for both first time and experienced RACKLIFE computer code users on how to maintain RACKLIFE models and use the results of RACKLIFE simulations in managing their spent fuel pools. This includes sections on the following topics:

1. Boraflex and the RACKLIFE code in general (most useful for new users);

2. A schedule for collecting and entering input data to keep the model current with the actual state of the spent fuel pool;

3. RACKLIFE model development issues; and

4. How to interpret the results.

The following section, A Quick Entry Into This Document, links the reader to the appropriate section of the report based on a sequence of questions about what the reader is trying to accomplish.

A QUICK ENTRY INTO THIS DOCUMENT

Do you want an introduction to Boraflex and/or RACKLIFE?

Yes: go to Section 1.0

Do you want to know when to get data and enter data for RACKLIFE?

Yes: go to Section 2.0

Do you want to create or update a RACKLIFE model?

Yes: go to Section 3.0

Do you want to use your RACKLIFE loss results?

Yes: go to Section 4.0

CONTENTS

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INTRODUCTION

1.0 Introduction

Do you want to know what Boraflex is and what its problems are?

Yes: go to Section 1.1

Do you want to know what the RACKLIFE computer code is?

Yes: go to Section 1.2

Do you want to know how to start RACKLIFE?

Yes: go to Section 1.3

Do you want to know how to verify your RACKLIFE installation?

Yes: go to Section 1.4

Do you want to see a glossary of RACKLIFE related terms?

Yes: go to Section 1.5

1.1 References on Boraflex

1.1.1 Select Journal Articles, EPRI Reports, and User's Group Reports

Listed below in chronological order are numerous reference citations with summary abstracts. These references include journal articles, EPRI reports, and Boraflex User Group (BUG) Reports. At the end of the list all BUG Workshops are cited.

An Assessment of Boraflex Performance in Spent-Nuclear-Fuel Storage Racks, EPRI Report NP-6159. EPRI: Palo Alto, California; December 1988.

> Data from utility surveillance programs, test reactor irradiations, and the open literature have been collected and evaluated to assess the effect of service environment in spent nuclear storage racks on the neutron absorber material, Boraflex. Radiation induced

> changes in the properties of Boraflex have been identified. The observed formation of gaps in the full length panels of Boraflex in some spent fuel racks has been attributed to one such change, shrinkage, in combination with mechanical restraint. Mechanisms of gap formation and growth are also discussed. Factors which may influence the ultimate service life of Boraflex in spent fuel storage racks have been identified. Continuation of coupon surveillance programs to verify the serviceability of Boraflex in the spent fuel pool environment is recommended. Guidelines for coupon surveillance programs have been developed.

Boraflex Test Results and Evaluation, EPRI Report TR-101986. EPRI: Palo Alto, California; February 1993.

> New data, since the issuance of EPRI Report NP-6159 in December 1988, have been developed, collected, and evaluated to further assess the in-pool performance of the neutron absorber material, Boraflex. The data are from new EPRI test programs, utility surveillance programs, and blackness testing at a number of plants. This new data provides a basis for quantifying the gap phenomenon in full length panels of Boraflex in spent fuel racks, the maximum anticipated gap size, frequency of gap occurrence, and axial distribution of gaps. Methods have been developed to assess the reactivity effects of gaps and Boraflex shrinkage. The analyses presented demonstrate that the reactivity effect of gaps is very small, not much larger than the statistical variations inherent in the calculational method. The data and analyses presented serve to close the issue of gap formation and shrinkage in panels of Boraflex and the effect of such gaps and shrinkage on the reactivity of the fuel/rack configuration. Ongoing EPRI programs to assess the long term performance of Boraflex in spent fuel storage racks are described.

Guidelines for Boraflex Use in Spent-Fuel Storage Racks, EPRI Report TR-103300. EPRI: Palo Alto, California; December 1993.

> New data, since the issuance of EPRI Reports NP-6159 in December 1988, and TR-101986 in February 1993, have been acquired and evaluated to further assess the in-pool performance of the neutron absorber material Boraflex. The data are from on-going EPRI test programs as well as utility measurements of spent fuel pool silica levels. This new data provides a basis for identifying Boraflex as a source of silica contamination in spent fuel pools. Other data from long-term laboratory tests have identified those factors which have the greatest influence on the rate of silica release from Boraflex. A model has been developed which describes the kinetics of silica transport from the Boraflex into the bulk volume of the spent fuel pool. With further refinements the model may provide a basis for projecting Boraflex service life on a plant-by-plant basis. Guidelines have been developed for utilities with spent fuel racks containing Boraflex for extending the service life of this material and for surveillance.

Lindquist, K., D. E. Kline, and R. Lambert. *Radiation-induced changes in the physical properties of Boraflex, a neutron absorber material for nuclear applications.* Journal of Nuclear Materials: Vol. 217, p. 223-228; 1994.

> Boraflex is a neutron absorber material and is currently used in about 75 storage pools around the world for the control of reactivity of LWR fuel in storage. In this work, the effects of gamma radiation on the physical properties of Boraflex including dimensions, weight, Shore A hardness, density, and dynamic shear modulus were investigated. Specimens of Boraflex were irradiated in de-ionized water in a ^{60}Co facility to an integrated dose of 1 x 10^{10} rad. The experimental results provide the asymptotic values of dimension changes, saturation dose levels and a basis for inferring property changes on a micro-scale. Results presented here aid in identifying the in-service property changes of Boraflex and represent the most accurate data for this material yet available.

Inspection and Testing of Boraflex from the Fort Calhoun Spent Fuel Racks. NETCO Report NET-092-02, prepared for EPRI under RP-3907-01. Northeast Technology Corp.: Kingston, New York; March 1995.

> [No abstract; summary of introduction follows.] In 1994 the Fort Calhoun Station (a Combustion Engineering PWR) removed their Boraflex PAR racks to increase on-site storage with maximum density replacement racks. Two cells from the Region 1 racks were inspected during the dismantling/compaction process. One of the cells inspected had received freshly discharged fuel assemblies from six core offloads and had been in use for ten years, resulting in approximately 2.0E+10 rads to the lead panel. During the inspection photographs were taken and samples were collected for further laboratory analysis. This report describes the results of the on-site inspection as well as the laboratory testing.

The Boraflex Rack Life Extension Computer Code – RACKLIFE: Theory and Numerics, EPRI Report TR-107333. EPRI: Palo Alto, California; September 1997.

> This theory and numerics report further describes the development of the Boraflex dissolution kinetics model first presented in EPRI report TR-103300. The model is solved via a data-intensive, but user-friendly, Fortran 90 computer code package called RACKLIFE. Documentation on the design, expression, and testing of this code, as well as a user's manual that includes a tutorial, are part of this report. The RACKLIFE code contains a mass balance calculation of silica in the spent fuel pool, from its source (solubilization of the Boraflex matrix), subsequent transit into the bulk pool volume, and removal via the pool cleanup system. Calculated results include the gamma radiation dose absorbed by panels of Boraflex, the average and peak rates of boron-carbide loss from all panels, the percentage of boron-carbide lost from each panel, and estimates of pool silica concentrations to compare with the measured spent fuel pool chemistry data. The RACKLIFE output data can be presented graphically in a format to facilitate decision making on the optimal shuffling of discharged fuel in the spent-fuel pool and other rack management strategies to preserve Boraflex integrity. Output data can also be

directed to ASCII files for import into user application packages such as spreadsheets, wordprocessors, databases, and other external software.

BADGER, a Probe for Nondestructive Testing of Residual Boron-10 Absorber Density in Spent-Fuel Storage Racks: Development and Demonstration, EPRI Report TR-107335. EPRI: Palo Alto, California; October 1997.

This report covers the equipment, operation, and utilization of BADGER, the Boron-10 Areal Density Gage for Evaluating Racks. Developed by Northeast Technology Corp. for the Electric Power Research Institute, BADGER is a device which allows the non-destructive in-situ measurement of the boron-10 areal density of the neutron absorber material installed in spent fuel racks. Two BADGER systems have been fabricated and tested: one appropriate for BWR spent fuel racks and one for PWR racks. This report describes the systems and then focuses on the demonstration tests of these systems and also compares the results of these tests with calculations performed with the EPRI computer code RACKLIFE, which simulates the loss of boron-10 from the racks.

The BWR BADGER test was conducted in April 1996 at PECO Energy's Peach Bottom Atomic Power Station Unit 2. The BWR BADGER proved capable at measuring panel average areal density to within ±8% (at a 1 sigma level) and at identifying local anomalies such as gaps. While the BADGER system was not specifically calibrated for measuring gap size and panel length in this test, the test data provided information that was consistent with prior blackness data. The RACKLIFE model results are consistent with the BADGER measurements. Some revised test procedures and design modifications were identified to improve the measurement precision and accuracy.

The PWR BADGER test was conducted in January 1997 at Duke Power's McGuire Nuclear Station 2, implementing the improvements identified in the BWR demonstration. The spent fuel pool had both Region 1 (flux trap) and Region 2 (egg crate) type racks. In Region 2 the PWR BADGER proved very capable at measuring panel average areal density to ±3% to 5% and at identifying local anomalies. Anomalies include thinning around some rack wrapper plate inspection ports and regions of increased areal density postulated to represent concentrated deposits of boron carbide released as a result of dissolution. Gap data distributions were also determined based on a calibration cell with resolution better than that available with blackness testing. The RACKLIFE model results are consistent with the BADGER measurements for the lower dose Region 2 panels, although some of the higher dose panels show more boron carbide loss than predictions. In Region 1 the measurement uncertainty ranged from ±10% to 15%. This was due to poorer counting statistics resulting from the large attenuation of neutrons that soluble boron in the flux trap causes. The comparison with the RACKLIFE predictions are not conclusive possibly because of uncertainties in cleanup system operation and/or potentially a bias in the BADGER Region 1 areal density measurements. Recommendations have been developed for work leading to resolution of these issues.

A Synopsis of the Technology Developed to Address the Boraflex Degradation Issue, EPRI Report TR-108761. EPRI: Palo Alto, California; November 1997.

> This synopsis report provides an overview and summary of the work performed by the Electric Power Research Institute over the last 10 years relative to the in-service degradation of the neutron absorber material, Boraflex. Boraflex is one neutron absorber material which has been used in the spent fuel storage racks in some 50 reactor pools in the U.S. Its function is to maintain the fuel storage sufficiently subcritical. This report describes the issues of Boraflex shrinkage/gap formation and the gradual dissolution of the matrix in the service environment of the spent fuel pool. A multi facet test program is described which provides data leading to an understanding of these degradation mechanisms and those factors which influence the rate of deterioration. Tools, developed under the umbrella of the EPRI program, to assist utilities in managing Boraflex degradation in spent fuel racks include: Boron-10 Areal Density Gauge for Evaluating Racks (BADGER) – a non-destructive, in-situ method for determining the residual Boraflex remaining in BWR and PWR fuel racks; RACKLIFE – a PC based computer program for managing fuel storage racks and projecting their service life; zinc solubility inhibitors and RACKSAVER poison inserts. In addition, during the course of this project, industry-wide data has been collected, evaluated and stored in an extensive EPRI database. This data further serves to provide a firm understanding of the behavior of this material in the spent fuel pool environment. An overview of the management tools and database is given; the details are contained in six separate EPRI reports.

MCNP Validation of BADGER, EPRI Report GC-110539. EPRI: Palo Alto, California; May 1998.

> The Boron-10 Areal Density Gage for Evaluating Spent Fuel Racks (BADGER) was developed by Northeast Technology Corp. (NETCO) for the Electric Power Research Institute (EPRI). The development of BADGER was prompted by the observed in-service degradation of Boraflex, a neutron absorber material used for criticality control in spent fuel storage racks.(1) BADGER is a nondestructive, in-situ method for determining the boron-10 areal density remaining in the Boraflex neutron absorber.
>
> BADGER systems for BWR and PWR spent fuel racks have been developed and demonstrated. The BWR system was demonstrated at the Peach Bottom 2 Station and the PWR system was demonstrated subsequently in the McGuire 2 spent fuel pool in both Region 1 and Region 2 PWR spent fuel racks.
>
> This report describes the validation of the BADGER test measurement technique using the Monte Carlo N-Particle Transport Code, MCNP. MCNP is a Monte Carlo solution to the particle transport equations and can treat neutrons, photons, and electrons. In this application, MCNP has been used to simulate the transport of neutrons from the Cf-252 source in BADGER through the source head and Boraflex to the four BF3 detectors in the adjacent rack cell. MCNP is unique in that its cross section libraries are continuous as opposed to having a discrete energy structure as most libraries do.

The major conclusions of this MCNP/BADGER comparison is that both the MCNP models and BADGER provide the same detector response except at low areal densities approaching zero. Comparison of the neutron spectrum at the detectors with full density Boraflex with the corresponding spectrum for zero density Boraflex (no neutron absorber) indicates a considerably "softer" neutron spectrum in the latter case. It is believed that the model used for the conversion of the MCNP computed neutron fluxes to detector count rates may be deficient when large changes in the neutron spectrum occur. While this in no way alters the conclusion that BADGER does accurately measure variations in boron-10 areal density, some recommendations for resolving this MCNP/BADGER discrepancy at low areal densities are offered.

The Performance of Irradiated Boraflex under Seismic Conditions, EPRI Report TR-109927. EPRI: Palo Alto, California; September 1998.

The flexural strength and Young's Modulus of irradiated Boraflex have been measured on specimens having been exposed to a range of gamma doses up to $>3x10^{10}$ rads. The measurements were performed on specimens prepared from small coupons irradiated in a Co-60 facility as well as material destructively removed from fuel racks at two PWRs. The material taken from fuel racks shows no decrease in flexural strength at the higher doses whereas the samples prepared from small coupons do. The latter is attributed to accelerated aging in small coupons. Weibull analyses of the data provides threshold stresses for failure below which the failure probability is essentially zero.

Spent fuel racks structural design/licensing reports and other information were reviewed for six spent fuel pools. The cases evaluated were in the East, Midwest, and West Coast regions of the U.S. These represented nine distinct fuel rack designs by four rack manufacturers. The fuel racks were designed for BWR and PWR fuel including fuel manufactured by ABB Combustion Engineering, General Electric and Westinghouse. From the licensing reports peak strains in the stainless steel rack structure during the limiting safe shutdown earthquake were developed. Conservative assumptions were applied in determining how the strains in the structural stainless steel are transferred to the Boraflex using experimentally determined values of Young's Modulus, the peak stresses in the Boraflex were computed. In all cases the calculated Boraflex stresses were less than the threshold failure stress by a substantial margin.

The Boraflex Rack Life Extension Computer Code – RACKLIFE: Verification and Validation, EPRI Report TR-109926. EPRI: Palo Alto, California; March 1999.

Using ANSI/ANS-10.4 as a guide, validation and verification of the computer code RACKLIFE was performed. To independently perform the requisite design reviews (verification) and performance tests (validation), the reviewers defined a process, established requirements and tested the code for compliance thereto.

Code design was reviewed to determine that the intended code functions were consistent with the problem to be solved, the design specifications were consistent with intended code functions, and that the source code was consistent with design requirements.

RACKLIFE models were reviewed to determine that the physical phenomena underlying Boraflex dissolution were faithfully represented and that code algorithms properly depicted the physical models. The source code was examined to determine conformity with the Fortran 90 standard.

Performance testing was conducted to demonstrate that RACKLIFE performed as intended. The reviewers compiled and executed individual sections of the code. RACKLIFE results were compared with results calculated by independent means. For example, MCNP was used to calculate Boraflex panel gamma dose. The full code was executed for several test cases. Calculated values for pool silica concentration and individual panel boron carbide loss were compared with actual measurements.

The reviewers concluded that application of the V&V review process provided assurances that RACKLIFE calculations are dependable and that the code functions as intended.

The Surface Composition and Solubility of Irradiated Boraflex and Silica Treated in Metal Ion Solutions, EPRI Report TE-114126. EPRI: Palo Alto, California; November 1999.

Solution modeling, solution chemistry and surface analysis of irradiated Boraflex and other silica materials have provided insight as to how the spent fuel pool water chemistry can be controlled to retard the rate at which Boraflex degrades in its service environment. This is significant not only for preserving the reactivity control characteristics of Boraflex but also for managing soluble silica in the spent fuel pool and interconnected plant systems.

Specific potential chemistry control measures for BWR and PWR spent fuel pools have been identified. For the former, a reduction in the pool pH from near neutral to 5.5 alone reduces the dissolution rate of irradiated Boraflex by a factor of 5. If zinc or zirconium ions are introduced to the pool water at a pH of 5.5, a further reduction in the dissolution rate by a factor of 3 is realized. The overall effect of pH reduction and metal ion addition is a factor of 15 reduction in the dissolution rate of irradiated Boraflex. These effects on the dissolution rate of irradiated Boraflex could clearly make the difference between premature degradation of this material and the spent fuel storage racks achieving their design service life.

For PWRs pools which typically operate with 2500 ppm at a pH of 4.0 to 4.5, conditions do not favor the deposition of dissolution inhibiting metal ions on the surface of the Boraflex. Analyses and tests conducted in the present program demonstrate that by using a buffering agent (e.g., KOH) to temporarily bring the pH of the boric acid solution to 7.5, metal ion deposition on the Boraflex surface can be promoted. This is significant as it suggests that temporary pH buffering of PWR spent fuel pool water with concurrent metal ion treatment is a means to retard Boraflex degradation in PWR spent fuel racks. Additional testing needs to be completed to determine whether, once treated in this manner, the Boraflex dissolution rate is retarded when the pool conditions are returned to normal (pH = 4 - 4.5). Previous testing has indicated that once the metal species have been deposited their effect on the dissolution rate persists, even at the lower pH.

Another significant finding of this work is the identification of Zr^{+4} as a suitable solubility inhibiting agent. Zr^{+4} could be used in spent fuel pools in its naturally occurring isotopic abundance. Zn^{+2}, on the other hand, can only be added to spent fuel pools as Zn depleted in Zn^{64} which increases costs.

Recommendations have been developed for some additional laboratory testing including solution chemistry and surface analysis to provide the basis for optimizing metal ion treatment and pH control in both BWR and PWR pool conditions. This laboratory testing would be guided by solution modeling as has been done in the present work. The objectives of the supplemental work would be to define all parameters so that a field implementation and demonstration could be completed in BWR and PWR spent fuel pools.

LWR Plant Water Silica Database, Revision 4. EPRI: Palo Alto, California; February 2000.

Chronology

Revision 0: January 1996
Revision 1: July 1996
Revision 2: September 1997
Revision 3: November 1998
Revision 4: February 2000

This database now contains data from some 41 PWR pools and 18 BWR pools. The bulk of the data consists of chronological measurements of reactive (soluble) silica concentrations determined from samples from the spent fuel pool (SFP) water. Some utilities have provided silica measurement data from the reactor coolant system (RCS) and refueling water storage tank (RWST) as well. These volumes of water communicate with the SFP volume during refueling operations, and can become contaminated with silica.

For comparative purposes, the database also contains some limited data for plants with other neutron absorbers (BORAL and borated graphite) which are not a source of pool water silica. Among the PWR plants Beaver Valley 1 and St. Lucie 2 do not use Boraflex as the neutron absorber for the fuel racks. Comparison with their sister units, Beaver Valley 2 and St. Lucie 1 clearly indicates the effect of Boraflex on plant water systems silica levels. Similarly, Connecticut Yankee, which uses borated graphite neutron absorbers, has a low silica concentration (1.5 ppm and below). For the BWR plants, data are presented for Hatch 1 and 2 and Limerick 1 and 2 which do not have Boraflex in the spent fuel pools. Data from Limerick 1 and 2 can be compared with data from Peach Bottom 2 and 3, all of which are operated by PECO.

Almost all reported data are for measurements of soluble (reactive) silica. In two cases (Farley 1 and 2) the utility reported colloidal silica concentration as well as total silica (reactive plus colloidal). Reactive silica is conventionally measured as this can be done in a relatively simple manner using standard colormetric methods. Colloidal or total silica requires a technique such as inductively coupled plasma spectroscopy (ICPS) which is generally not available at the plant chemistry lab.

RACKLIFE Version 1.10: Nuclear Spent Fuel Pool Boraflex Rack Life Extension Rack Management Tool -- User's Manual. EPRI: Palo Alto, California; March 2000.

RACKLIFE simulates the irradiation and dissolution of Boraflex neutron absorber panels as used in spent fuel pool storage racks. The data is presented graphically in a format to facilitate decision making on the optimal shuffling of discharged fuel in the pool to preserve Boraflex integrity. The effect of spent fuel pool environment and cleanup systems on Boraflex integrity can also be explored.

This document serves as an introduction and tutorial for using the RACKLIFE Version 1.10 code. It details the computer system requirements to run the program, the files needed by the program to start, how to start the program, how the program is organized, and a tutorial that uses a simple fictitious "pool" to illustrate how to use the features and functions of RACKLIFE.

RACKLIFE is designed to run on Intel Pentium PCs under the PC and MS DOS operating systems. It can also be used on Intel 386/387, 486DX, and Pentium hardware, and under Windows 95/98/NT DOS boxes.

1.1.2 User's Group Workshop Notes

EPRI Workshop #4: Boraflex Update. St. Louis, Missouri; 17 May 1990.

Data collected from utility programs: coupons and blackness measurements at four plants. EPRI surveillance assembly at Beaver Valley. Long term stability tests at Penn State. Test Irradiations at AFRRI. Utility data expected in the near term. Additional blackness tests at two plants.

EPRI Workshop #5: Boraflex Update. Washington, D.C.; 19 June 1991.

Utility Boraflex database, coupon programs, rack blackness tests, conclusions on shrinkage. EPRI test/development programs at Beaver Valley 2, Millstone 2, and Penn State. Boraflex dose calculational procedure. The silica issue: Boraflex composition, long-term stability, and pool silica levels. USNRC licensing issues.

EPRI Workshop #6: Boraflex Update. Washington, D.C.; 29 July 1992.

> New Boraflex data. Wrap up: gap formation, gap growth, and total shrinkage. Reactivity effects of gaps. Silica. Licensing issues. Utility reports: blackness testing, pool silica levels, and pool cleanup experience.

EPRI Workshop #7: Boraflex Update. Washington, D.C.; 28 July 1993.

> Report TR-101986 [*Boraflex Test Results and Evaluation*]: discussion and questions. Update/status of EPRI programs. Silica release: new test data, pool silica levels, silica release/Boraflex performance modeling, proof-of-principle testing. Long-term mitigation: in-situ measurement of areal density, soluble boron credit in PWRs, burnup credit in BWRs, administrative controls, credit for actual B-10 loading. Utility reports: licensing activity, blackness testing, surveillance program results, pool silica levels, pool cleanup experience.

EPRI Workshop #8: Enhanced Boraflex R&D Program. Washington, D.C.; 22 September 1994.

> Report of recent tests, inspections, and evaluations: Beaver Valley/EPRI surveillance assembly third inspection, Millstone 2/EPRI special coupons second inspection, Millstone 2 dosimeter tests, analysis of Boraflex for Sulfur. Discussion of planned inspection of Fort Calhoun Boraflex. Evaluation of Palisades coupon experience. EPRI's participation in soluble boron credit. Status of in-situ equipment for B-10 areal density measurements. Pool silica model development report: model description, Fortran implementation, demonstration of a working PWR model, status and schedule for completion. Utility reports on Boraflex activities, pool silica levels, and USNRC licensing activities. Discussion on enhanced Boraflex R&D program working group organization/structure.

EPRI Workshop #9: Enhanced Boraflex R&D Program. Washington, D.C.; 1-2 June 1995.

> Inspection of Boraflex from th Fort Calhoun racks. Laboratory test results on Zinc solubility inhibitors. Millstone 3 dosimeter test. Status of the B-10 areal density meter. Overview/status RACKLIFE software. RACKLIFE demonstration. Pool filter experience/analysis at San Onofre. Soluble boron credit at Prairie Island. Blackness testing at South Texas. Enrichment extension at Diablo Canyon. Cost analysis of removing SFP silica at Farley. Boraflex strategies and status. Future plans for the working group.

EPRI Workshop #10: Enhanced Boraflex R&D Program. Washington, D.C.; 14-15 February 1996.

> Special projects update: laboratory test results on zinc solubility inhibitors, fourth inspection of t Beaver Valley 2 test rig. RACKLIFE update/feedback from users. BADGER testing status. Plant water silica database. Future plans for working group. USNRC generic letter. Mitigation measures for degraded Boraflex. Hardware fixes:

> RACKSAVER demonstrations. Boron credit – USNRC update. Group discussion on USNRC generic letter: status/schedule, response strategies. Utility round table.

EPRI Workshop #11: EPRI Boraflex User's Group (Phase II) – Boraflex Generic Letter Response Coordination. Palo Alto, California; 1-2 August 1996.

> Phase II Boraflex User's Group membership and budget status. Results of BADGER demonstration test. Update on LWR plant silica database. Preliminary results of the third inspection of the Millstone 2 coupons. Zinc solubility inhibitor demonstration. Overview of White Paper on Boraflex performance in Spent Fuel Storage Racks. Group discussion of contents (intent/requirements) of the Generic Letter. Mitigation measures for degraded Boraflex. Group discussion on mitigation measures. Individual utility anticipated strategies for responding to Generic Letter.

EPRI Workshop #12: EPRI Boraflex User's Group. Washington, D.C.; 24-25 June 1997.

> Special topics: Byron spent fuel pool filter analysis, Point Beach rack cell deformation, LaSalle full panel inspection, and loss of pool cooling analysis. BADGER testing at Quad Cities. PWR BADGER demonstration at McGuire. Upcoming BADGER test campaigns. Update on Zinc solubility inhibitor demonstration. RACKLIFE update/feedback from RACKLIFE users. Utility RACKLIFE perspective. Rack design questionnaire. Future plans for the working group. LWR Plant Silica Database. Utility round table discussion describing plant status and planned future action.

EPRI Workshop #13: EPRI Boraflex User's Group. Hyatt Islandia Hotel: San Diego, California; 5-6 March 1998.

> Zinc demonstration at Oyster Creek: the utility perspective, BADGER test results, and Zinc addition experience at Oyster Creek. RACKLIFE: status of verification and validation. Boraflex issues at Commonwealth Edison's stations. Boraflex issues at Peach Bottom. Seismic performance of irradiated Boraflex. MCNP validation of BADGER. Boraflex issues at McGuire. BADGER testing at Ginna. Status of BADGER testing. Regulatory issues and status. Group discussion: utility/NRC interaction. Planned enhancements to RACKLIFE. Utility roundtable discussion.

Boraflex User's Group Workshop #14 Washington, D.C.: Presentation Material. Washington, D.C.; 19-20 November 1998.

> Zinc demonstration at Oyster Creek: conclusions. RACKLIFE: status of verification and validation. Updated Silica Database, Revision 3. Pool clarity issues at Byron/Braidwood. Seismic performance of Boraflex: conclusions. PWR Zinc demonstration. Fifth inspection of the EPRI/Beaver Valley test assembly. Regulatory issues and status. Regulatory perspective by Larry Kopp, USNRC. Vendor presentations. New release and Windows version of RACKLIFE. Utility roundtable discussion.

Wet Storage User's Group Workshop #15 San Diego, CA: Presentation Material. Hyatt Islandia Hotel: San Diego, California; 10-11 June 1999.

> RACKLIFE: status of verification and validation. Operability assessments: Boraflex degradation at McGuire and Oconee. Pool clarity issues at Byron/Braidwood. Status of Boraflex at LaSalle and Quad Cities. CASK LOADER: program for dry cask loading objectives and strategy. First look at the CASK LOADER program. CASK LOADER schedule and financial structure. Corrosion of Boral coupons. Broken wrapper plate welds at Beaver Valley. Surface chemistry of Boraflex treated with Zn and Zr. Limerick re-rack project. Boron distribution in borated stainless steel. Overview RACKLIFE Version 1.10. Blackness testing at Grand Gulf. Utility roundtable discussion.

Wet Storage User's Group Workshop #16 Palo Alto, CA: Presentation Material. Palo Alto, California; 24-25 February 2000.

> Technical Specification submittals at McGuire and Oconee. Surface chemistry of Boraflex treated with metal ions. Status of CASK LOADER program. CASK LOADER program demo. CASK LOADER first use. Status of METAMIC qualification program. Update on the LWR silica database. BADGER test results from LaSalle 2. Status of dry cask storage program at McGuire. Full size panel inspection at Nine Mile Point 2, SFP storage status for Entergy plants. New RACKLIFE manual and tutorial. Status of Boraflex surveillance at Peach Bottom. Utility roundtable discussion. RACKLIFE clinic.

Boraflex Working Group Workshop #17 New Orleans, LA: Presentation Material. New Orleans, Louisiana; 29-30 March 2001.

> Group organization, work scope, and funding structure. Results of recent BADGER testing and overview of all BADGER test results to date. Metal ion solubility inhibitor status. RACKLIFE version 1.10 overview. METAMIC update: qualification program and commercial status. Final inspection of special Millstone 2 coupons. Caskloader update. Caskloader experience. Modeling the reactivity effects of Boraflex deterioration. Utility special reports: Millstone 2 cell/panel inspections, Boraflex degradation accommodation at McGuire, storage expansion at Fermi 2, storage expansion at Nine Mile Point Units 1&2. Roundtable discussion: utility experience. RACKMAN: managing fuel storage in multi-region racks. RACKLIFE hands-on workshop.

1.1.3 NRC Information Notices and Generic Letters

Citations for the three information notices and one generic letter from the US NRC pertaining to Boraflex are given below in chronological order. The full text of these follows on subsequent pages.

NRC Information Notice No. 87-43: *Gaps in Neutron-Absorbing Material in High-Density Spent Fuel Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington D.C.; 8 September 1987.

NRC Information Notice 93-70: *Degradation of Boraflex Neutron Absorber Coupons*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington D.C.; 10 September 1993.

NRC Information Notice 95-38: *Degradation of Boraflex Neutron Absorber in Spent Fuel Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington, D.C.; 8 September 1995.

NRC Generic Letter 96-04: *Boraflex Degradation in Spent Fuel Pool Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington, DC; 26 June 1996.

NRC Information Notice No. 87-43: *Gaps in Neutron-Absorbing Material in High-Density Spent Fuel Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington D.C.; 8 September 1987.

> Purpose:
>
> This notice is to alert recipients to a potentially significant problem pertaining to gaps identified in the neutron absorber component of the high-density spent fuel storage racks at Quad Cities Unit 1. The safety concern is that certain gaps might excessively reduce the margin of nuclear subcriticality in the fuel pool. The NRC expects that recipients will review this notice for applicability to their facilities and consider actions, if appropriate, to preclude a similar problem occurring at their facilities. However, suggestions in this notice do not constitute NRC requirements; therefore, no specific action or written response is required.
>
> Description of Circumstances:
>
> On May 1, 1987, Commonwealth Edison Company (CECO), the licensee at Quad Cities 1 and 2, presented data to the NRC regarding gaps measured in Boraflex, a neutron-absorbing material used in the high-density fuel storage racks manufactured by the Joseph Oat Corporation (OAT). Boraflex is a trade name for a boron carbide dispersion in an elastomeric silicone matrix manufactured by Bisco Products, Inc. (BISCO). Data pertaining to the gap size and distribution had been obtained by National Nuclear Corporation (NNC) under contract to CECO.
>
> The licensee had retained Northeast Technology Corporation (NETCO) to interpret the data. NETCO prefaced their assessment as preliminary, noting that available data was limited, but concluded that the gap formation mechanism may be related to large local stresses in the Boraflex from fabrication-induced restraint within the rack and to tearing and shrinkage of the material.
>
> The average gap size is 1-1/2 inches, with the largest 4 inches. The gaps occur in the upper two-thirds of the cell length. These gaps are inferred from anomalies in "blackness" testing results by NNC. The existence of a gap in the Quad Cities neutron

absorber panel has been confirmed by underwater neutron radiography conducted by Nusurtec, Inc.

CECO also discussed the effects these gaps might have on the approved safety analysis for the spent fuel storage racks. CECO used conservative assumptions for gap size, gap location, and fuel burnup. Considerable margin in k-eff appears to be available before the licensing limit of 0.95 would be approached.

In July 1986, Wisconsin Electric Company, the licensee at Point Beach 1 and 2, reported to the NRC that test coupons of Boraflex material had shown considerable degradation under high radiation. However, the licensee asserted that this result did not represent the actual condition of Boraflex used in its spent fuel storage racks because of differences in methods of encapsulation, sample geometry, and handling frequency. Additionally, the coupons had been subjected to about 5 times more radiation than is associated with the average fuel rack position. Subsequent examination of full-length panels disclosed two results: in one panel examined for effects of the water environment but exposed to negligible gamma radiation, there was no degradation of the Boraflex. In another panel exposed to significant gamma radiation, 1-2 percent of the surface showed a gray discoloration at the edges, similar to the degradation of the coupons.

Discussion:

The concern is that separation of the neutron-absorbing material used in high density fuel storage racks might compromise safety. Although Quad Cities reports that its racks, even with gaps in the Boraflex as large as 4 inches, can meet the criticality criterion of k-eff less than or equal to 0.95, this may not be the case for larger gaps or for other plants. A list of the 31 sites using Boraflex is given in Attachment 1. Related information is given in "Behavior of High-Density Spent-Fuel Storage Racks," EPRI NP-4724, Electric Power Research Institute, August 1986.

Efforts to understand the gap formation have revealed several topics on which information is needed. Accordingly, the material supplier (BISCO) and the Electric Power Research Institute (EPRI) have undertaken research programs to collect this information. Some of their objectives are described below.

The BISCO program aims to establish with increased accuracy the relationship between radiation dose and size changes. The program also evaluates the potential effects of handling and restraint, during and subsequent to the fuel rack fabrication, on gap formation.

The EPRI program will correlate data from utilities' neutron absorber coupon surveillance programs. EPRI will further examine data obtained from CECO, as well as from BISCO and other sources, to improve the understanding of possible or actual gap formation models, including the effects of rack fabrication methods and irradiation damage mechanisms. The EPRI Program will also attempt to model the specific Quad Cities experience considering absorbed gamma dose as a function of axial elevation, neutron absorbing sheet restraint, and fractional change in length.

The effect of rack design and manufacturing methods on the consequences of stress, temperature, and chemical environment to irradiated Boraflex is uncertain. Recent blackness test results at Turkey Point, who uses a Westinghouse spent fuel storage rack, did not indicate the presence of gaps in the Boraflex. The research programs are designed to evaluate each consequence and, in particular, to improve the understanding of stress caused by method of attachment of the Boraflex panel to the stainless steel wall of the cell.

Together, these programs are designed to improve the industry understanding of the safety implications of the observed gaps in the Boraflex neutron absorber component of the OAT high-density spent-fuel storage racks at Quad Cities.

No specific action or written response is required by this information notice. If you have any questions about this matter, please contact the Regional Administrator of the appropriate regional office or this office.

Charles E. Rossi, Director
Division of Operational Events Assessment
Office of Nuclear Reactor Regulation

Technical Contacts: Vern Hodge
Albert D. Morrongiello

Attachment 1

LIST OF PLANTS WITH BORAFLEX STRUCTURES IN THE SPENT FUEL POOL

1. Arkansas 1,2
2. Beaver Valley 1
3. Diablo Canyon 1,2
4. Calvert Cliffs 2
5. Farley 1,2
6. Fermi 2*
7. Ft. Calhoun
8. Ginna
9. Grand Gulf 1,2*
10. McGuire 1,2
11. Millstone 1,2,3
12. Nine Mi. Pt. 1,2
13. North Anna 1,2
14. Oconee 1,2,3
15. Oyster Creek*
16. Peach Bottom 2,3
17. Pilgrim
18. Pt. Beach 1,2
19. Pr. Island 1,2
20. Quad Cities 1,2*
21. Rancho Seco*
22. River Bend
23. Robinson 2
24. Summer*
25. Trojan
26. Turkey Pt. 3,4
27. Waterford 3
28. Seabrook 1,2
29. Watts Bar 1,2
30. Comanche Peak 1,2
31. Harris

*Plants having spent fuel storage racks fabricated by Joseph Oat Corporation.

NRC Information Notice 93-70: *Degradation of Boraflex Neutron Absorber Coupons*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington D.C.; 10 September 1993.

> Purpose
>
> The U.S. Nuclear Regulatory Commission (NRC) is issuing this information notice to alert recipients to a potentially significant problem pertaining to degradation of Boraflex neutron absorber coupons. It is expected that recipients will review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. However, suggestions contained in this information notice are not NRC requirements; therefore, no specific action or written response is required.
>
> Background
>
> Palisades has high-density fuel storage racks installed in the spent fuel pool that use Boraflex, a proprietary neutron absorbing material that was manufactured by Brand Industrial Services, Incorporated (BISCO). The storage racks are supplied by Westinghouse. The Boraflex is attached to the walls of each canister and is held in place by a stainless steel wrapper, which is spot welded to the walls.
>
> The licensee has a surveillance program using Boraflex coupons to indicate the status of the Boraflex contained in the high density storage racks in the spent fuel pool. Recently observed degradation of several of these coupons, which may be due to exposure to high level gamma radiation in conjunction with interaction with pool water, raised questions about the integrity of the Boraflex contained in the storage racks. Significant loss of Boraflex in the high-density fuel racks could result in loss of the subcriticality margin in the spent fuel pool.
>
> Through a commitment to the NRC, Palisades was required to test and inspect the Boraflex coupons after 5 years of use. The tests include opening the coupons for visual observation, neutron attenuation determination, and a Boraflex hardness test.
>
> Description of Circumstances
>
> During a period from August 17 through 19, 1993, 5 of the existing 10 Boraflex coupons were removed from the spent fuel pool, 4 being full-length coupons and 1 a short-set coupon (see Figure 1). During removal of the full-length coupons a powdery substance and a grey debris cloud were observed emanating from the coupons. Further investigation of the full-length coupons revealed that one coupon had lost an estimated 90 percent of its Boraflex, two others 50 percent, and one 38 percent. Investigation of the short-set coupon showed that it had retained 100 percent of its Boraflex. The licensee has determined that the Boraflex in the 4 full-length coupons and the short-set coupon came from different lots of material.

A principal difference between the short-set and the full-length coupons is their geometrical design. The short-set coupon consists of eight compartments encapsulating the Boraflex with pool water accessing only the edges of the coupons. However, in the full-length coupon Boraflex is sandwiched axially over the entire length of coupon and bolted between two 0.51-mm [0.020-inch] stainless steel metal strips. The licensee postulated that a much larger area of the full-length coupon was exposed to the pool water environment and flow. In addition, the full-length coupon has a 12.7-mm [0.5-inch] hole through the metal strip on the top portion of the coupon, which contributes to the pool water flow around the Boraflex. The licensee has no immediate plans for removal or testing of the remaining five coupons in the spent fuel pool, but does intend to conduct neutron "blackness" testing in the spring of 1994.

The licensee also had initiated measurements of the silica content of the spent fuel pool water. No increase in silica above normal 1-4 ppm levels have been observed except in instances when the pool boron concentration was increased. Because silica filler material is a constituent of Boraflex, the presence of silica in the water may be an indication of degradation of the Boraflex in the fuel pool.

Discussion

Potential degradation mechanisms for Boraflex include (1) gamma flux, which changes the material characteristics of the base polymer, and (2) chemical environment, namely the accessibility of water to the Boraflex. The licensee has not drawn firm conclusions as to (1) the root cause of the observed degradation of Boraflex in the coupons, or (2) the correlation of the behavior of Boraflex in the coupons to that in the storage racks.

Degradation of the Boraflex in fuel storage racks could reduce the subcriticality margin in the spent fuel pool. The design basis assumes a 5 percent subcriticality margin on the basis of lowest pool temperature, no boron concentration in the pool water, and minimum spacing between fuel assemblies. In its preliminary analysis, the licensee assumed no boron in the pool water and a complete loss of Boraflex from the fuel storage racks. This reduced the subcriticality margin from greater than 5 percent to about 2 percent. However, the licensee used the burnup for the currently stored fuel in the criticality calculation. This is higher than the design burnup value, implying less reactive fuel in the fuel pool than assumed in the design calculation.

The licensee took several compensatory measures, including (1) making the operating staff aware not to dilute the spent fuel pool, (2) increasing the spent fuel pool chemistry sampling frequency to daily, and (3) keeping the boron concentration in the spent fuel pool above 1800 ppm, which exceeds the technical specification requirement for boron concentration. With these precautions a subcriticality margin greater than 5 percent would be maintained.

Degradation of Boraflex has been previously addressed by NRC in Information Notice 87-43, "Gaps in Neutron-Absorbing Material in High-Density Spent Fuel Storage Racks," September 8, 1987. The Electric Power Research Institute, which has been studying this phenomenon for several years, has recently published an interim report, "Boraflex Test Results and Evaluation," TR-101986, February 1993.

Brian K. Grimes, Director
Division of Operating Reactor Support
Office of Nuclear Regulatory Regulation

Technical contacts: Kombiz Salehi, RIII
K. I Parczewski, NRR
Larry Kopp, NRR
Vern Hodge, NRR

[Figure 1 is not included here.]

NRC Information Notice 95-38: *Degradation of Boraflex Neutron Absorber in Spent Fuel Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington, D.C.; 8 September 1995.

> Purpose
>
> The U.S. Nuclear Regulatory Commission (NRC) is issuing this information notice to alert addressees to a potentially significant problem pertaining to degradation of the Boraflex neutron absorber material in spent fuel storage racks. It is expected that recipients will review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. However, suggestions contained in this information notice are not NRC requirements; therefore, no specific action or written response is required.
>
> Background
>
> Degradation of Boraflex has been previously addressed by the NRC in Information Notice (IN) 87-43, "Gaps in Neutron-Absorbing Material in High-Density Spent Fuel Storage Racks," September 8, 1987, and IN 93-70, "Degradation of Boraflex Neutron Absorber Coupons," September 10, 1993. The Electric Power Research Institute (EPRI) has been studying the phenomenon of Boraflex degradation for several years and recently issued EPRI report TR-103300, "Guidelines for Boraflex Use in Spent-Fuel Storage Racks," December 1993, identifying two issues with respect to using Boraflex in spent fuel storage racks. The first related to gamma radiation-induced shrinkage of Boraflex and the potential to develop tears or gaps in the material. The second concerned gradual long-term Boraflex degradation over the intended service life of the racks as a result of gamma irradiation and exposure to the spent fuel pool environment. This second issue has previously been observed in degradation of Boraflex surveillance coupons at the Palisades plant (IN 93-70), but further testing of the actual Palisades storage racks indicated no similar degradation. Because of the relatively watertight Boraflex panel enclosures in most spent fuel storage rack designs, this type of degradation was typically not previously considered.
>
> The potential exists for a gradual release of silica and boron carbide from Boraflex following gamma irradiation and long-term exposure to the spent fuel pool environment. When Boraflex is subjected to gamma radiation in the aqueous environment of the pool, the silicon polymer matrix becomes degraded and silica filler and boron carbide are released. Because Boraflex is composed of approximately 25 percent silica, 25 percent polydimethyl siloxane polymer, and 50 percent boron carbide, the presence of silica in the pool provides an indication of depletion of boron carbide from Boraflex. The loss of boron carbide (washout) from Boraflex is characterized by slow dissolution of the silica from the surface of the Boraflex and a gradual thinning of the material. In a typical spent fuel pool, the irradiated Boraflex represents a significant source of silica (several thousand kilograms) and is the most likely source of pool silica contamination. The boron carbide loss will result in an increase in the reactivity of the matrix of fuel and Boraflex in the spent fuel pool.

EPRI report TR-103300 has identified several factors that influence the rate of silica release from Boraflex. The presence of water around the Boraflex panels is perhaps the most significant factor influencing the rate of silica dissolution from Boraflex. Because of the different rack designs, this rate will vary from plant to plant. The rate of dissolution also increases with higher pool temperature and gamma exposure, suggesting that Boraflex degradation can be reduced by keeping pool temperatures low and by not placing freshly discharged fuel assemblies in the same storage cells at each refueling outage.

Description of Circumstances

The South Texas Project, Unit 1, has fuel storage racks installed in the spent fuel pool that use Boraflex as a neutron absorber. The pool contains two rack types. The Region 1 racks are designed to receive high reactivity fuel assemblies, including fresh fuel, and use Boraflex panels in a removable stainless steel box. The Region 2 racks are designed for low reactivity spent fuel assembly storage and contain fixed Boraflex panels between the cell walls. The Boraflex panels were designed to ensure that adequate negative reactivity would be maintained if the pool were accidentally flooded with unborated water.

Blackness (neutron absorption) testing was performed during August 1994 on selected South Texas Project Unit 1 spent fuel pool storage racks to determine the condition of the Boraflex and to determine the size and location of any gaps that may have developed. However, in addition to gap development, which is a known phenomenon, the results also indicated that the Boraflex had significantly degraded due to a decrease of the boron content in several of the storage cells tested. Of the eight cells that had been designated to receive an accelerated gamma dose in Region 1, five cells exhibited large areas of degradation (0.9 to 1.4 meters [3 to 4.5 feet] in length) postulated to result from accelerated dissolution of the Boraflex caused by pool water flow through the panel enclosures as well as the high accumulated gamma dose.

Similar Boraflex degradation was discovered at the Fort Calhoun Station. As part of their rerack project, the old spent fuel storage racks containing Boraflex were removed and disassembled in December 1994 to determine the condition of the Boraflex. Two cells from the removed Boraflex racks which had experienced the highest gamma flux since 1983 were inspected. Only 40 percent of the Boraflex remained in one of the panels from these cells while another panel in the same cell exhibited no loss of Boraflex. An adjacent cell had a panel which had some Boraflex loss but subsequent attenuation and density tests confirmed that the average boron-10 areal density still exceeded the material minimum certifications. The new Fort Calhoun Station storage racks do not contain Boraflex.

Discussion

Because Boraflex is used in the South Texas Project spent fuel storage racks for absorption of neutrons, a reduction in the amount of Boraflex could result in an increase in the reactivity of the spent fuel pool configuration, which may approach, or even exceed, the current NRC acceptance criterion of k_{eff} no greater than 0.95.

In response to the identified Boraflex problem, Houston Lighting & Power Company, the licensee for the South Texas Project, developed restrictions to not use the substantially degraded storage cells in Region 1 for discharged spent fuel. In addition, the licensee is developing a long-term neutron absorption panel management plan, as well as a dose-to-degradation correlation, which will aid in establishing restrictions for use of the spent fuel racks in both Units 1 and 2. The licensee also cited criticality analyses that showed that the fuel will remain subcritical by at least 5 percent, even with no Boraflex, as long as the soluble boron concentration is at least 2,500 ppm.

Although pressurized-water reactor spent fuel pool water is normally borated to approximately 2,000 ppm of boron, current regulatory requirements do not allow credit for the soluble boron except under accident conditions. Many boiling-water reactor (BWR) storage racks also contain Boraflex. Because BWR spent fuel pool water does not contain boron, any significant Boraflex degradation in a BWR pool may challenge the 5 percent subcritical margin.

This information notice requires no specific action or written response. If you have any questions about the information in this notice, please contact one of the technical contacts listed below or the appropriate Office of Nuclear Reactor Regulation (NRR) project manager.

Dennis M. Crutchfield, Director
Division of Reactor Program Management
Office of Nuclear Reactor Regulation

Technical contacts: Laurence I. Kopp, NRR
K. I. Parczewski, NRR

NRC Generic Letter 96-04: *Boraflex Degradation in Spent Fuel Pool Storage Racks*. United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation: Washington, DC; 26 June 1996.

> Purpose
>
> The U.S. Nuclear Regulatory Commission (NRC) is issuing this generic letter to inform all addressees of issues concerning the use of Boraflex in spent fuel storage racks. Although this generic letter is being issued to all licensees of operating nuclear power reactors, only those licensees that use Boraflex are required to respond. Each addressee that uses Boraflex as a neutron absorber in its spent fuel storage racks is requested to (1) assess the capability of the Boraflex to maintain a 5-percent subcriticality margin and (2) submit to the NRC a plan describing its proposed actions if this subcriticality margin cannot be maintained by Boraflex material because of current or projected future Boraflex degradation.
>
> Background
>
> Degradation of Boraflex has been previously addressed by the NRC in Information Notice (IN) 87-43, “Gaps in Neutron-Absorbing Material in High-Density Spent Fuel Storage Racks,” September 8, 1987; IN 93-70, “Degradation of Boraflex Neutron Absorber Coupons,” September 10, 1993; and IN 95-38, “Degradation of Boraflex Neutron Absorber in Spent Fuel Storage Racks,” September 8, 1995. The Electric Power Research Institute (EPRI) has been studying the phenomenon of Boraflex degradation for several years and has identified two issues with respect to using Boraflex in spent fuel storage racks. The first issue related to gamma radiation-induced shrinkage of Boraflex and the potential to develop tears or gaps in the material. This phenomenon is typically accounted for in criticality analyses of spent fuel storage racks. The second issue concerned long-term Boraflex performance throughout the intended service life of the racks as a result of gamma irradiation and exposure to the wet pool environment.
>
> Description of Circumstances
>
> Palisades Nuclear Power Station
>
> During the removal of several Boraflex surveillance coupons from the Palisades spent fuel pool in August 1993, a loss of as much as 90 percent of the Boraflex was observed and has been attributed to exposure to high-level gamma radiation in conjunction with interaction with the pool water. The Boraflex in these coupons was sandwiched and bolted between two stainless steel strips, allowing a relatively large area of Boraflex to be exposed to the pool water environment and flow. Neutron attenuation testing (blackness tests) of the actual Palisades storage racks indicated that because of the relatively watertight Boraflex panel enclosures, there was no similar degradation.

South Texas Project

The results of blackness tests performed in August 1994 at South Texas indicated that the Boraflex was degraded, as evidenced by gaps and/or localized washout of the boron content in 20 of the 37 storage cells tested. Of the eight cells that had been designated to receive an accelerated gamma dose, five cells exhibited substantial degradation (0.91 to 1.37 m [3 to 4.5 ft]). The licensee postulated that the degradation mechanism was washout-accelerated dissolution of the Boraflex caused by pool water flow through the panel enclosures. As a justification for continued operation, the licensee has placed restrictions on the use of the degraded storage cells to ensure compliance with the required subcriticality margin. In addition, a long-term neutron absorption panel management plan is being developed, as well as a dose-to-degradation correlation that will aid in establishing restrictions for the use of the spent fuel racks.

Fort Calhoun Station

As part of the Fort Calhoun Station rerack project, the old spent fuel storage racks containing Boraflex were removed and disassembled in December 1994 to determine the condition of the Boraflex. The new storage racks do not contain Boraflex. As part of the overall EPRI research program, the licensee inspected two cells from the removed Boraflex racks which had experienced the highest gamma flux since 1983. Only 40 percent of the Boraflex remained in one of the panels from these cells while another panel in the same cell exhibited no loss of Boraflex. An adjacent cell had a panel which had some Boraflex loss but subsequent attenuation and density tests confirmed that the average boron-10 areal density still exceeded the material minimum certifications. Visual observations made during the course of the rack disposal process indicated that the vast majority of cells had not undergone a significant loss of Boraflex. The licensee has determined that there was sufficient Boraflex in the walls of each cell to meet the minimum requirements in the design-basis criticality analysis.

Discussion

Experimental data from test programs, including blackness tests performed at various boiling-water reactor (BWR) and pressurized-water reactor (PWR) spent fuel storage pools, confirmed that when Boraflex is exposed to gamma radiation, the material may shrink by as much as 3 to 4 percent. Shrinkage saturates at an integrated gamma exposure of about 1 to 2×10^{10} cGy (1 to 2×10^{10} rad). The application of realistic assumptions based on these tests has demonstrated that the reactivity effects of Boraflex shrinkage and gaps are very small and can generally be accommodated within the existing design basis of most storage racks.

Data from laboratory tests and spent fuel pool silica measurements have identified a second factor that could affect storage rack service life, i.e., the potential gradual release of silica from Boraflex following gamma irradiation and long-term exposure to the wet pool environment. When Boraflex is subjected to gamma radiation in the pool aqueous environment, the silicon polymer matrix becomes degraded and silica filler and boron carbide are released. Since irradiated Boraflex typically contains 46 percent of silica, 4 percent of polydimethyl siloxane polymer and 50 percent of boron carbide by weight, the presence of silica in the pool indicates the likely depletion of boron carbide from Boraflex. The loss of boron carbide from Boraflex is characterized by slow dissolution of the Boraflex matrix from the surface of the Boraflex and a gradual thinning of the material. In a typical spent fuel pool, the irradiated Boraflex represents a significant potential source of silica (several thousand kilograms) and is the most likely source of pool silica contamination. The boron carbide loss, of course, can result in a significant increase in the reactivity of the storage racks. An additional consideration is the potential for silica transfer through the fuel transfer canal into the reactor core during refueling operations and its effect on the fuel clad heat transfer capability.

EPRI has identified several factors that influence the rate of silica release from Boraflex. The access of water to and around the Boraflex panels is perhaps the most significant factor influencing the rate of silica dissolution from Boraflex. Because of the different rack designs, this water access will vary from plant to plant. The rate of dissolution also increases with higher pool temperature and gamma exposure, suggesting that pool temperatures be maintained as low as practical and that freshly discharged fuel assemblies should not be placed in the same storage cells at each refueling outage. Experimental data indicates that once silica reaches an equilibrium value, the rate of dissolution is dramatically reduced. However, when water purification systems are used to remove silica from the pool water, the solubility equilibrium becomes unbalanced and panel dissolution resumes. Thus, although pool temperatures should be maintained as low as practical, additional cooling may require an increase in pool water flow and create the negative effect of forcing more water past the Boraflex panels thereby disturbing any localized silica equilibria.

Because Boraflex is used in spent fuel storage racks for nonproductive absorption of neutrons, a reduction in the amount of Boraflex could result in an increase in the reactivity of the spent fuel pool configuration, which may approach, or even exceed, the current NRC acceptance criterion of k_{eff} no greater than 0.95. The NRC has established this 5-percent subcriticality margin to comply with General Design Criterion (GDC) 62 of Appendix A to Part 50 of Title 10 of the Code of Federal Regulations (10 CFR Part 50), which addresses the prevention of criticality in fuel storage and handling. Those plants that have installed storage racks containing Boraflex have the 5-percent subcriticality margin included in the plant technical specifications and/or a written commitment to meet this subcriticality margin, as reflected in the plant updated final safety analysis report (FSAR). The technical specifications for most other operating power reactors also include this 5-percent subcriticality requirement.

Several corrective actions have been used to account for any reactivity increase due to Boraflex loss. Many licensees have taken credit for the reactivity decrease associated with fuel depletion or have restricted storage patterns to a checkerboard-type configuration. Others have inserted neutron absorber rods into stored assemblies with protective features to prevent inadvertent removal. The NRC is also presently evaluating a proposed methodology by which credit could be taken for the soluble boron in PWR pool water. Although some of these schemes cannot be used for BWR fuel storage facilities, there have been discussions and demonstrations of specially designed neutron absorbing inserts as a replacement for deteriorating Boraflex which would be applicable to both PWR and BWR storage racks.

Safety Assessment

On the basis of test and surveillance information from plants that have detected areas of Boraflex degradation, no safety concern exists that warrants immediate action. Boraflex dissolution appears to be a gradual and localized effect forewarned by relatively high silica levels in the pool water. This occurrence of increased pool silica is more pronounced in PWRs than BWRs because of the greater effectiveness of silica removal by the BWR demineralizers in the non-borated pool water environment. Because of the safety margin present in spent fuel storage pools, compliance with the required subcriticality margin (or conformance with the same margin to which licensees have committed in their updated FSARs) can be expected to be maintained during the initial stage of Boraflex degradation. This safety margin is due to the conservatism in treating the reactivity effects of possible variations in material characteristics and mechanical tolerances and the generally lower reactivity of stored fuel than that assumed in the safety analysis. However, to verify compliance with both the regulatory requirements of GDC 62 and the 5-percent subcriticality margins, either contained in the technical specifications or committed to in the updated FSARs, and to maintain an appropriate degree of defense-in-depth measures, the NRC staff has concluded that it is appropriate for licensees to submit the following information.

Requested Information

All licensees of power reactors with installed spent fuel pool storage racks containing the neutron absorber Boraflex are requested to provide an assessment of the physical condition of the Boraflex, including any deterioration, on the basis of current accumulated gamma exposure and possible water ingress to the Boraflex and state whether a subcritical margin of 5 percent can be maintained for the racks in unborated water. Monitoring programs or calculational models in effect or being developed, or an estimation of anticipated concerns based on the specific rack design, are considered an appropriate basis for this response. All licensees are further requested to submit to the NRC a description of any proposed actions to monitor or confirm that this 5-percent subcriticality margin can be maintained for the lifetime of the storage racks and describe what corrective actions could be taken in the event it cannot be maintained. Licensees should describe the results from any previous post operational blackness tests and state whether blackness testing, or other in-situ tests or measurements, will be periodically performed. Chronological trends of pool reactive silica levels, along with the timing of significant events such as refuelings, pool silica cleanups, etc., should be provided. Implications of how these pool silica levels relate to Boraflex performance should be described. All licensees are requested to submit the information to the NRC to ensure that the onsite storage of spent fuel is in compliance with GDC 62 for the prevention of criticality in fuel storage and handling and with the 5-percent subcriticality margin position of the NRC staff to assure compliance with GDC 62.

Required Response

All addressees that use Boraflex in their spent fuel storage racks are required to submit a written response to the information requested above within 120 days of the date of this generic letter. If an addressee chooses not to respond to specific questions, an explanation of the reason and a description of any proposed alternative course of action should be provided, as well as the schedule for completing the alternative course of action (if applicable), and the safety basis for determining the acceptability of the planned alternative course of action.

Address the required written reports to the U.S. Nuclear Regulatory Commission, ATTN: Document Control Desk, Washington, D.C. 20555, under oath or affirmation under the provisions of Section 182a, Atomic Energy Act of 1954, as amended, and 10 CFR Part 50.54(f). In addition, submit a copy to the appropriate regional administrator.

Backfit Discussion

This generic letter only requires information from the addressees under the provisions of Section 182a of the Atomic Energy Act of 1954, as amended, and 10 CFR Part 50.54(f). Therefore, the staff has not performed a backfit analysis. The information requested will enable the NRC staff to determine whether licensees are complying with the current licensing basis for the facility with respect to GDC 62 for the prevention of criticality in fuel storage and handling and 5-percent subcriticality margins either contained in the technical specifications, or committed to in the updated FSARs, of plants containing Boraflex in the spent fuel storage racks. The staff is not establishing a new position for such compliance in this generic letter. Therefore, this generic letter does not constitute a backfit and no documented evaluation or backfit analysis need be prepared.

Federal Register Notification

A notice of opportunity for public comment was published in the Federal Register (60 FR 56359) on November 8, 1995. Comments were received from 15 licensees and 1 industry organization. Copies of the staff evaluation of these comments have been made available in the public document room.

Paperwork Reduction Act Statement

This generic letter contains information collections that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et seq.). These information collections were approved by the Office of Management and Budget, approval number 3150-0011, which expires July 31, 1997.

The public reporting burden for this collection of information is estimated to average 150 hours per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. The U.S. Nuclear Regulatory Commission is seeking public comment on the potential impact of the collection of information contained in the generic letter and on the following issues:

1. Is the proposed collection of information necessary for the proper performance of the functions of the NRC, including whether the information will have practical utility?

2. Is the estimate of burden accurate?

3. Is there a way to enhance the quality, utility, and clarity of the information to be collected?

4. How can the burden of the collection of information be minimized, including the use of automated collection techniques?

Send comments on any aspect of this collection of information, including suggestions for reducing this burden, to the Information and Records Management Branch, T-6 F33, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, and to the Desk Officer, Office of Information and Regulatory Affairs, NEOB-10202 (3150-0011), Office of Management and Budget, Washington, DC 20503. The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless it displays a currently valid OMB control number.

If you have any questions about this matter, please contact one of the technical contacts listed below or the appropriate Office of Nuclear Reactor Regulation (NRR) project manager.

Brian K. Grimes, Acting Director
Division of Reactor Program Management
Office of Nuclear Reactor Regulation

Technical contacts: Larry Kopp, NRR
Krzysztof Parczewski, NRR

Lead Project Manager: Steven Bloom, NRR

1.1.4 Documents Your Company May Have

1. A response to US NRC Generic Letter 96-04, "Boraflex Degradation in Spent Fuel Storage Racks".

Your response will typically describe a defense in depth strategy for monitoring the degradation of Boraflex in your spent fuel pool racks. In particular, your response may contain commitments on the following:

- coupon surveillance,
- spent fuel pool silica measurements and trending,
- RACKLIFE modeling, evaluation, and projections,
- BADGER testing, including frequency and number of panels
- mitigation measures, including soluble boron concentration at PWRs.

The response was intended to demonstrate how you will assure that any spent fuel pool racks containing Boraflex will continue to meet their design basis of maintaining overall spent fuel pool sub-criticality with a margin of 5% or greater (i.e., $k_{eff} \leq 0.95$).

2. A program plan for Boraflex monitoring

This will include commitments to conduct a Boraflex coupon surveillance program. This typically involves removing one or more Boraflex coupons from a coupon tree (which resides in a spent fuel storage cell) for testing. These tests often include the following:

visual inspection and photography;
length, width, and thickness measurements;
dry weight and specific gravity;
neutron attenuation testing; and
hardness measurements.

"Long-term" coupons are often placed in a given cell, and then fuel is permanently discharged from the next operating cycle around the cell. "Short-term" coupons typically have fuel from each subsequent cycle discharged around it, displacing whatever fuel was there from the previous discharge. Thus short-term coupons accumulate dose faster than long term coupons after the second discharge. In this manner the long-term coupons are intended to simulate the behavior of the racks in general, while the short-term coupons are accelerated tests that bound the actual doses to panels in the pool.

Unfortunately, the coupons are often clad in a different manner from the Boraflex panels in the rack. Thus the exchange of pool water and coupon cavity water may be significantly different from the exchange of pool water and panel cavity water. Further, the coupons may be shaped differently than the panels, and may have been cut from a different batch of Boraflex than the majority of the panels. Therefore, the coupons are sometimes of questionable value in determining the modes of dissolution and the amount of dissolution that the Boraflex panels may have sustained in the bulk pool.

1.2 The RACKLIFE Computer Code

1.2.1 Summary from the Theory and Numerics Report

RACKLIFE simulates the loss of the criticality controlling neutron absorber boron carbide (B_4C) from Boraflex as the latter dissolves in the spent fuel pool water. The boron carbide itself does not dissolve in water, but the silica matrix that binds it does, particularly after irradiation. Since silica can be measured in the pool water, silica dissolution and transport can be simulated based on the measured data, and from the results the amount of boron carbide loss from each panel can be calculated.

The amount of data that RACKLIFE can generate is potentially enormous. Consider a moderate sized BWR spent fuel pool with 2,500 rack storage cells and 5,000 panels of Boraflex. Simulation data (the state variables of silica, temperature, radiation dose, boron carbide loss, etc.) must be computed for each of these panels at each time step. In addition, the numerical solution of the silica kinetics equations must be executed simultaneously for all of the panels and the pool. Tracking all eleven state variables for just 5,000 panels hourly for a 20 year simulation results in well over 100 billion floating point operations performed on 10 billion state point variables over 175,000 time steps. Thus RACKLIFE has been organized to be selective in its output of all of this data. (It has also been organized to optimize a balance between computational speed and memory requirements, but this should be transparent to the user.)

Each Boraflex panel is contained in a water-filled volume referred to as a panel cavity. The Boraflex panel provides a (finite) source of silica which can dissolve into the cavity water. The amount of silica dissolution is a function of the radiation dose that the Boraflex has absorbed, the temperature, the pH, the presence of solubility inhibitors, and the amount of silica already in solution.

The dissolved silica results in some concentration of aqueous reactive silica in the panel cavity. Reactive silica has an equilibrium concentration, above which no further silica will dissolve into the water. As silica concentrations in the water increase, however, reactive silica will form polymerized silica and colloidal particles, without limit, thereby reducing the reactive silica concentration and allowing for more Boraflex dissolution. The sum of reactive and polymerized/colloidal silica is referred to as total silica. Concentrations of reactive silica are relatively easy to measure, while total silica is quite difficult.

The panel cavities are manufactured such that they communicate with the bulk pool. Water flows into and out of a cavity at a rate called the escape coefficient. The water flowing out of the cavity transports both reactive and polymerized silica to the pool water, where it is measured by pool chemistry. The amount of total silica in the pool would be a good indicator for the amount of silica lost on average from all of the panels were it not for the effect of cleanup systems, letdowns and makeups, and mixing with the reactor water during refueling operations. These systems and operations generally remove silica from the pool water.

1.2.2 RACKLIFE References

RACKLIFE Version 1.10: Nuclear Spent Fuel Pool Boraflex Rack Life Extension Rack Management Tool – User's Manual. EPRI: Palo Alto, California; March 2000.

> This document serves as an introduction and tutorial for using the RACKLIFE Version 1.10 code. It details the computer system requirements to run the program, the files needed by the program to start, how to start the program, how the program is organized, and a tutorial that uses a simple fictitious "pool" to illustrate how to use the features and functions of RACKLIFE.

The Boraflex Rack Life Extension Computer Code -- RACKLIFE: Theory and Numerics, EPRI Report TR-107333. EPRI: Palo Alto, California; September, 1997.

> This report details the theoretical and experimental models and numerical methods behind the RACKLIFE code.

The Boraflex Rack Life Extension Computer Code -- RACKLIFE: Verification and Validation, EPRI Report TR-109926. EPRI: Palo Alto, California; March, 1999.

> This report concludes that, through application of a verification and validation process based on ANSI/ANS-10.4, RACKLIFE calculations are dependable and the code functions as intended.

1.2.3 A Chronology of RACKLIFE Development

1991) LWRDOSE.WK1 spreadsheet template for calculating dose to Boraflex surveillance coupons and rack panels (as detailed in EPRI Report TR-101986; February 1993).

1993) NETCO develops a very large spreadsheet to analyze just a few panels as research into the kinetics of Boraflex dissolution (as detailed in EPRI Report TR-103300; December 1993).

1995) Utility interest in a spent fuel pool Boraflex degradation predictor increases as NRC interest in Boraflex increases; RACKLIFE 1.0 is rapidly developed (as detailed in EPRI Workshop #9 Notes; June 1995).

1996) RACKLIFE 1.0 is released. It uses a database input paradigm for familiar data input by clerical staff (as detailed in EPRI Workshop #10 Notes; February 1996).

1996) RACKLIFE 1.01 fixes bugs and adds features.

1997) RACKLIFE 1.02 fixes bugs and adds features (as detailed in EPRI Report TR-107333; September 1997).

1997) RACKLIFE 1.02.01 fixes a bug in the 1.02 installation routine.

2000) RACKLIFE 1.10 changes the input paradigm to a spreadsheet, adds many features, is verified and validated (as detailed in EPRI Report TR-109926; March 1999), and has a new User's Manual (as detailed in EPRI Report TE-114975; April 2000).

1.2.4 What Can You Do with RACKLIFE Results?

RACKLIFE is ideally suited to provide input for five specific applications.

1. Plan a BADGER campaign

RACKLIFE can display and/or list in a text file the distribution of current and/or projected panel absorbed dose and panel B_4C losses throughout the spent fuel pool racks. Even if the model has not been benchmarked, the results have always been sufficient to select a spectrum of relatively high, moderate, low, and zero (if available) loss panels to perform BADGER testing on. This spectrum insures that the “worst” panels in the pool can be tested and that any trends with absorbed dose and estimated loss can be observed.

2. Corroborate BADGER measurements

BADGER testing is a part of validating a RACKLIFE model for a specific spent fuel pool. However, BADGER is an *in-situ* diagnostic tool that can occasionally be subject to experimental error (e.g., signal spikes if the detector cables are accidentally bumped). A RACKLIFE model can help to identify such anomalous features in the results by providing the BADGER operator a sense of what is expected. Further, RACKLIFE results are also useful in deciding if a Boraflex panel feature is worth investigating in more detail during a campaign. For example, a high loss area in a panel that RACKLIFE suggests should exhibit moderate or low loss might be the result of a dropped assembly that bent a panel cover plate, allowing a higher flow of pool water over the panel. Querying plant personnel about the possibility of such an event has led to positive correlations between external events and observed degradation features in the past.

3. Estimate global dissolution B_4C losses

The silica kinetics models in RACKLIFE are very good at predicting panel average B_4C losses via global dissolution throughout the spent fuel pool racks. With very few exceptions, the reactive silica measured in the spent fuel pool is the result of Boraflex dissolution. This measurable loss, plus whatever the cleanup systems have removed, is accurately apportioned by the RACKLIFE kinetics models among the Boraflex panels according to their rate of irradiation over time. This provides a basis for deciding if further testing (e.g., BADGER testing) is required to precisely quantify the amount of global and local dissolution. One limitation of the RACKLIFE model is that it can not predict local dissolution effects such as non-uniform thinning, panel edge effects (e.g., scallops), and gap edge effects (where a gap becomes wider than it would due to radiation-induced shrinkage alone). However, low predicted-loss panels typically do not exhibit these features.

4. Make projections

Once a RACKLIFE model has been fully tuned (usually using BADGER data) it can then be used to project the future dissolution of Boraflex. This provides a basis for testing various rack management strategies, as discussed under item 5, below. In addition, it also can serve to predict when pool silica levels become "high", typically greater than 30 ppm. Spent fuel pools with greater than this concentration of reactive silica have been observed to have pool clarity problems. In particular, fuel move operations have had to be suspended because of clarity problems. RACKLIFE projections also provide a basis for extending into the future the validity of a criticality safety analysis that accounts for some level of degradation. BADGER testing measures the state of a set of Boraflex panels at a point in time. BADGER results can be used to confirm that a spent fuel pool still meets its criticality design basis at that point in time. A RACKLIFE projection can then be used to extrapolate these results into the future.

5. Manage the movement of spent fuel in the pool

Once you decide to keep some or all of your Boraflex racks, a next step is to consider designating each rack module (or groups of cells in and among rack modules) as

available for sacrifice, or
to be preserved.

Panels available for sacrifice are candidates for freshly discharged spent fuel. Among the factors that determine the rate of dissolution of Boraflex, accumulated absorbed dose is the most important. Thus spent fuel assemblies with the highest dose rates, which are the most recently discharged assemblies, should be placed in non-Boraflex racks if available, and in the sacrificial racks if there are any so designated. At the next fuel discharge, the assemblies in the sacrificial racks could then be moved to other Boraflex racks to make room for the new discharge.

RACKLIFE would be used to track the accumulating dose in the racks to be preserved to optimize the movement of fuel into these racks. If all Boraflex racks in the pool are to be preserved as long as possible, then RACKLIFE can be used to "spread out" the dose among the panels so that the dose to all panels is uniformly moderate, as opposed to having some panels with a high dose and consequent high dissolution rates, while other panels have a low dose. In particular, the practice at some plants of discharging fuel to the same most convenient rack modules every outage should be stopped. While the residence time may be relatively short, the cooling time is also short, so these cells build up their absorbed dose rapidly. It is better to discharge the assemblies to a cell where they will remain. Alternatively, the discharge rack modules could be varied outage to outage to spread the dose around.

1.3 Do you know how to start RACKLIFE?

1.3.1 Your Operating System

RACKLIFE Version 1.10 is designed to run under the DOS operating system. This includes the following versions of DOS:

- PC or MS DOS 6.x, 7.x, 2000 as a stand-alone operating system
- Windows 95, 98 DOS command prompts
- Windows NT 4.x, 2000 command prompts
- OS/2 2.1, 3.0, 4.0 full screen DOS windows

Note that RACKLIFE was originally designed to run under a stand-alone DOS operating system. It does not take advantage of any Windows native capabilities such as common user interface, common print management, dynamic data exchange, and multitasking. RACKLIFE does not prevent multitasking of other programs designed to run under Windows, but switching from RACKLIFE to another window while RACKLIFE is running may suspend RACKLIFE execution until you return to the RACKLIFE window. Thus, under some versions and configurations of Windows, RACKLIFE will not run state point calculations in the background while you do other work.

The following system specifications are also required:

CPU:	386 with 387, 486DX, and Pentium class processors
RAM:	16 MB (If more than 16 MB is available, allocating some to a disk cache will improve performance.)
Hard Drive:	5 MB free space (50 MB is suggested)
Video:	VGA graphics mode at 640 x 480 x 16 colors

1.3.2 Finding RACKLIFE on Your System

The primary RACKLIFE executable is RACKLIFE.EXE. Performing a search for this file will locate the RACKLIFE directory. Under Windows use “Start / Find / Files or Folders… / Named: *RACKLIFE.EXE* / Find Now”. DOS does not have an intrinsic filename search capability, but many systems come with filename search utilities, such as “WHERE” and “FINDFILE”.

It is possible that you will find multiple versions of RACKLIFE.EXE on your system. Upgrading RACKLIFE to a new version will overwrite RACKLIFE.EXE with the new version. However, prior to upgrading the user is always cautioned to make a backup of the existing RACKLIFE directory. Thus a user may make a copy of the entire RACKLIFE directory (including RACKLIFE.EXE) and place the copy on a different drive, in another folder, or under another folder name. If you find multiple copies, the safest approach is to take inventory and record the results for yourself and future users. Run each executable in turn and note from the opening banner what version of RACKLIFE that code is. (Under Windows you can simply double click on the RACKLIFE.EXE file icon.) An alternative is to examine the date and time of the RACKLIFE.EXE file, assuming it has not been changed. Version 1.10 of RACKLIFE has its executable date and time stamped as 1999-09-29 01:10. Prior versions will have dates that precede this.

1.3.3 Opening a Command Prompt Window

To enter the RACKLIFE program you must be at a command prompt in the same directory that RACKLIFE.EXE resides in. (Under Windows you can usually double-click on the RACKLIFE.EXE icon, unless your directory structure is unusual.)

DOS is a command prompt operating system and so needs no further instructions. Under Windows 95 and 98 you can open a DOS window by selecting “Start / Programs / MS-DOS Prompt”. Under Windows NT and 2000 the command prompt is referred to as such, and not as DOS prompt; it is also opened via the “Start / Programs” menu.

1.3.4 Changing to the RACKLIFE Directory

Typically RACKLIFE is installed to the “RACKLIFE” directory on the “C” drive. To change to the RACKLIFE directory requires the following command, in upper or lower case and using the backslash (“\”) key, followed by the “Enter” key:

```
cd\racklife
```

Suppose instead your file search found the proper version of RACKLIFE.EXE on the “X” drive in directory “\My Files\RACKLIFE”. Under Windows 95 or 98 you would then open the DOS command prompt window and enter the following commands, each followed by the “Enter” key:

```
x:

cd\myfile~1\racklife
```

Note the following about this second example:

1. You must change to the “X” drive first, and then in a separate command change directories.
2. The slashes in the directory path are back slashes (“\”), not forward slashes (“/”).
3. The commands are case insensitive: any mixture of upper and lower case is acceptable.
4. Windows permits long file names with a wide variety of characters (such as spaces), but DOS does not. Thus Windows 95 and 98 will create mangled file and directory names that

can be read by DOS. This is why “My Files” under Windows turns into “myfile~1” under DOS. To see the mangled names, use the “dir /p” command in the DOS window. (For more information on the “dir” command consult your operating system manual or help files, or issue the command “dir /?”.)

5. Under stand-alone DOS you could not create a directory named “My Files”. Thus you would not have to worry about mangled names.
6. Under Windows NT and 2000 there is no name mangling, so changing directories would be performed as follows:

```
cd  \my files\racklife
```

1.3.5 Starting the RACKLIFE Program

This information is also detailed in Section 2.1 of the *RACKLIFE Version 1.10 User’s Manual* (EPRI; March 2000).

Having opened a command prompt window and changed to the RACKLIFE directory, you can now execute RACKLIFE by typing its name at the command prompt and then pressing the “Enter” key:

```
racklife
```

You may see a brief banner appear while the RACKLIFE program loads into memory. The last line of this banner shows how much memory RACKLIFE detects for its use. This should be at least 16384 Kb for RACKLIFE to function correctly. RACKLIFE has been used successfully with less memory but may crash unexpectedly when very large problems are executed.

Next a title screen will appear. You will need to press the enter key to proceed past the title screen. Any mouse click or key press during the animated title screen will skip the rest of the title screen and proceed directly to the main screen.

1.4 Do You Know How to Verify RACKLIFE?

1.4.1 The Need for Verification

Verification and validation (V&V) is a necessary part of software quality assurance. The V&V document *The Boraflex Rack Life Extension Computer Code -- RACKLIFE: Verification and Validation* (EPRI Report TR-109926; March, 1999) addresses verification and validation at the software development level. However, verification remains an issue at the user level. For proper software quality assurance, it is important that users verify that the delivered software performs as expected on the user’s computer hardware under its operating system and operating conditions. This level of verification can be achieved by executing a sequence of sample problems provided as part of the RACKLIFE tutorial.

1.4.2 Verifying Your RACKLIFE Installation

Under the RACKLIFE\TUTORIAL directory are three state point and associated pool state files for three verification scenarios. The scenario file name is “VERIFY”, the state point file extensions are “S01”, “S02”, and “S03”, and the pool state file extensions are, similarly, “Z01”, “Z02”, and “Z03”. These were created using the same tutorial data files detailed in Sections 3.0 through 7.0 of the *RACKLIFE Version 1.10 User’s Manual* (EPRI; March 2000). Note that the tutorial problems are designed to exercise many of the computational elements of RACKLIFE; they are not representations of an actual spent fuel pool.

Chapter 7.0 of the *RACKLIFE Version 1.10 User’s Manual* (EPRI; March 2000) is devoted to executing RACKLIFE for three different tutorial problems. The three resulting sets of state point (Snn) and pool state (Znn) files, when executed, can be compared with the files VERIFY.S01, VERIFY.S02, VERIFY.S03, VERIFY.Z01, VERIFY.Z02, and VERIFY.Z03, described above, to verify that RACKLIFE is computing identical results on your computer. Note that only the numerical results need be checked for verification; user input comments and date/time stamps will vary.

Before executing the state point computations, the “REFRESH” program in the TUTORIAL directory should be run. This will reset the tutorial files to what they were when RACKLIFE was installed, eliminating any changes that may have been made to them during the tutorial or by other users. This process is described in Appendix A of the *RACKLIFE Version 1.10 User’s Manual*.

1.4.3 Verifying Your Input Data

In the typical use of commercial grade software, only about 10% of all errors in the results are due to errors in the software. The remaining 90% are from errors in input data. These errors are controlled through three mechanisms: prevention, detection, and correction. RACKLIFE Version 1.10 has been designed with this in mind.

RACKLIFE can verify your input data at two levels. First, when entering data in a grid editor (as described in Section 4.5 of the *RACKLIFE Version 1.10 User’s Manual*, EPRI; March 2000), the results can be checked at any time at the request of the user. The checks include plots to visualize the data (e.g., to visually detect outliers), low-level statistical analyses (e.g., averages, trends, minima and maxima), and line-by-line checks for unusual and impossible conditions. An example of an unusual condition is a very low assembly burnup, which may be correct for a failed fuel assembly, but is likely a typo for a typical assembly. An example of an impossible condition is two assemblies simultaneously resident in one storage cell.

The second level of checking is invoked whenever a state point simulation is run. The line-by-line checking is performed regardless of any previous checking performed by the user. Warnings (e.g., an unusually low burnup) are ignored at this level, but errors (e.g., a date of 31 February) will always terminate the simulation. Thus any errors detected must be resolved before any results can be computed.

1.5 A Glossary of RACKLIFE Related Terms

Terms in italics are entries in the glossary.

Amorph.WK4

Given the specific gravity and loading (in weight percent) of *boron carbide* and *Elastomer* 170A and 170B in *Boraflex*, this spreadsheet will calculate the mass density, the weight percent of *boron carbide*, and the weight percent of *amorphous silica* in the *Boraflex*. The input is usually obtained from material certification data sheets for the *Boraflex*. This spreadsheet is located in the "TUTORIAL" directory under the RACKLIFE installation directory. For example, if RACKLIFE was installed to the default "C:\RACKLIFE" directory, then the spreadsheet may be found in directory "C:\RACKLIFE\TUTORIAL"

Amorphous Silica

A phase of *silica* characterized by a random (non-crystalline) structure of silicon atoms. This phase has a higher dissolution rate in water than *crystalline silica*. The silica in *Boraflex* is typically somewhat less than half *amorphous silica* and somewhat more than half *crystalline silica* by mass. The amount of *amorphous silica* in *Boraflex* can be calculated using the *Amorph.WK4* spreadsheet.

Areal Density

The grams of *boron-10* per square centimeter of surface area on the front face of a *Boraflex* panel or coupon. For example, consider a 0.19 cm thick Boraflex coupon with a mass density of 1.7 g/cm^3 that is 49% B_4C by mass. Using an approximate conversion factor of 0.14 g ^{10}B / g B_4C (which is calculated from atomic mass data and typical atom fractions in *Boraflex*), the areal density of *boron-10* is then calculated as follows:

1.7 g Boraflex/cm^3	(given mass density)
· 0.49 g B_4C / g Boraflex	(given as 50% by mass)
· 0.14 g ^{10}B / g B_4C	(given conversion factor)
· 0.19 cm	(given coupon thickness)
≈ 0.022 g ^{10}B / cm^2	

Boraflex

A registered trademark of Brand Industrial Services (BISCO) for a neutron absorbing material. The material is a mixture of:

- boron carbide (B_4C),
- elastomer 170 (a silicon rubber-like polymer which, when irradiated, reduces to amorphous silica), and
- crystalline silica (used as a filler to improve the tensile strength of Boraflex).

Boron Carbide (B_4C)

A molecule of four boron atoms and one carbon atom, symbolized as B_4C. The *boron-10* isotope of boron is a strong neutron absorber. The *boron carbide* in *Boraflex* starts as a finely divided powder.

Boron-10 (^{10}B)

An isotope of boron with a very large thermal neutron cross section. Natural boron is typically about 19.9 atom percent ^{10}B (with a thermal neutron cross section of about 3840 barns) and 81.1 atom percent ^{11}B (with a thermal neutron cross section of about 5 millibarns). The atom percentages have been known to vary across samples, so the actual percentage of ^{10}B in boron (or *boron carbide*) is typically reported in material certifications.

Colloidal Silica

See *polymerized silica*.

Cooling Time Corrected (CTC) Dose Methodology

RACKLIFE contains two methodologies for calculating the *dose* from spent fuel to an adjacent *Boraflex* panel. One employs the *LWRDose Methodology*, which is described under that glossary heading; that entry should be read before reading further. Subsequent to the development of the *LWRDose Methodology*, some experimental dose data was acquired which could be compared to the *LWRDose Methodology*. The results showed that, for that particular experimental geometry, the *LWRDose Methodology* overpredicted the *dose* to the Boraflex. Analysis showed that this was to be expected given the biases and conservatisms in the computer codes used to develop the *LWRDose Methodology*. In particular, the bias was shown to have a dependence on cooling time. Thus an empirical “cooling time correction” was developed to correct the original methodology. The RACKLIFE Verification and Validation report (EPRI Report TR-109926; March 1999) subsequently showed that the actual *dose* absorbed typically falls between what is predicted by the two methodologies, but the *LWRDose Methodology* is generally the more accurate of the two when spent fuel racks are full of spent fuel with no empty cells. In racks with many vacant cells around discharged assemblies, the *cooling time corrected dose methodology* may be more accurate.

Crystalline Silica

A phase of silica characterized by a crystalline structure of silicon and oxygen atoms, typically a silicon tetrahedron. Ordinary sand is *crystalline silica*. For further details, see the glossary entry for *amorphous silica*.

Dissolution

In RACKLIFE this refers to the process by which the amorphous silica in Boraflex dissolves. The amount of silica dissolution is a function of the radiation dose that the Boraflex has absorbed, the temperature, the pH, the presence of solubility inhibitors, and the amount of silica already in solution (via its *equilibrium concentration*).

Dose

In RACKLIFE, "*dose*" always refers to the gamma dose absorbed by a panel of Boraflex. The source of the *dose* is spent fuel assemblies that reside on either side of the panel. The dose is computed in RACKLIFE using either the *LWRDose Methodology*, as was used in the *LWRDose.WK4* spreadsheets, or the *cooling time corrected dose methodology*.

Elastomer-170

This constituent of *Boraflex* is polydimethyl siloxane, PDMS, a type of silicone rubber. It serves to retain the neutron absorber filler material, *boron carbide*, in *Boraflex*. As a *Boraflex panel* accumulates *dose*, the *elastomer-170* converts to a material composed predominantly of *amorphous silica*.

Equilibrium Concentration

The dissolved *silica* results in some concentration of aqueous *reactive silica* in the *panel cavity*. *Reactive silica* has an *equilibrium concentration*, above which no further *silica* will dissolve into the water. As *silica* concentrations in the water increase, however, *reactive silica* will form *polymerized silica* and colloidal particles, without limit, thereby reducing the *reactive silica* concentration and allowing for more *Boraflex dissolution*.

Escape Coefficient

The *panel cavities* are manufactured such that they communicate with the bulk pool. Water flows into and out of a cavity at a rate called the *escape coefficient*. The water flowing out of the cavity transports both *reactive silica* and *polymerized silica* to the pool water, where it is measured by pool chemistry. In RACKLIFE, the *escape coefficient* is an empirical "tuning" parameter entered by the user. For a given *panel* and its associated *panel cavity*, the *escape coefficient* is the rate of fluid flow from the *panel cavity* to the bulk pool (and thus the rate of fluid flow from the bulk pool to the *panel cavity*) in liters/day per volume of fluid in the *panel cavity* in liters. It is thus a volumetric exchange rate normalized to the volume of the *panel cavity*.

Initial Conditions

In simulating a spent fuel pool, the first *state point file* would give conditions just as the *Boraflex* was put in service. Every *panel* would have zero *dose* and have as-built quantities of *boron carbide*. This would serve as the *initial conditions* for computing a subsequent state point in the future.

LWRDose Methodology

As developed for the *LWRDose.WK4* spreadsheets, this is a methodology for calculating the absorbed gamma dose from spent fuel to Boraflex. The methodology is based on correlations of spent fuel gamma source strength with fuel dimensional characteristics (such as fuel mass and volume), operational parameters (such as assembly power sharing and burnup), and cooling time (since reactor discharge). The fuel source strength was calculated separately for BWRs and PWRs using the ORIGEN-PC code. The Microshield code was used to correlate gamma energy deposition rates with source/sink separation distance, intervening water thickness, and intervening stainless steel thickness. An analytical integration routine computes the cumulative gamma dose as a function of fuel residency time next to a *panel* of *Boraflex*.

LWRDose.WK4

This is actually two spreadsheets: BWRDose.WK4 and PWRDose.WK4. These spreadsheets are detailed in Appendix A of *Boraflex Test Results and Evaluation* (EPRI Report TR-101986; February 1993). They are used to calculate the gamma dose

1. absorbed by a *panel* of *Boraflex* contained in the rack between two storage cells, and

2. absorbed by a surveillance coupon located in a storage cell.

The calculation methodology developed for these spreadsheets is referred to as the *LWRDose Methodology*.

Panel

A panel of the neutron absorber Boraflex. Boraflex panels are typically as long as the active fuel length (e.g., ~144 inches for a PWR and ~150 inches for a BWR), but may be shorter with credit for axial neutron leakage. The panels are typically about as wide as a fuel assembly (e.g., ~7.5 inches for a PWR and ~5.9 inches for a BWR). The thickness of Boraflex panels typically vary from ~0.05 inches to ~0.15 inches.

Panel Cavity

Boraflex panels are typically enclosed in stainless steel racks. Sometimes this enclosure takes the form of a picture frame with rack cell walls on either side. Other rack designs have the *Boraflex* against a rack cell wall and covered by a wrapper plate (also called a cover plate or capture plate) that is bent around the sides and ends of the *panel*. These designs typically leave some space between the rack structure and the *panel*. This space, which is filled with spent fuel pool water, is called the *panel cavity*. The *escape coefficient* quantifies the amount of fluid that flows between the bulk pool and the *panel cavity*.

Polymerized Silica

In RACKLIFE, polymerized silica refers to both *polymerized silica* and colloidal particles containing silica. As *silica* concentrations in the water increase, *reactive silica* will form *polymerized silica* and colloidal particles without limit.

Pool

RACKLIFE defines a *pool* as a contained volume of water with only occasional letdown and makeup of fluid volume. Thus two spent fuel pools side by side but unconnected must be modeled as two separate *scenarios*. Two pools intimately and constantly connected with continuous fluid mixing between them, however, would be modeled as a single *scenario*.

Pool State File

In simulating historical state points, those that have already occurred and for which some data is known from pool chemistry records, the computed results can be compared with the data to refine certain difficult-to-measure parameters in the model for a more accurate simulation. Because data is critical in refining parameters, pool state data (bulk pool silica levels, bulk pool temperature, etc.) is saved daily during the computation. This allows a more accurate comparison of pool data results with recorded pool chemistry data.

Power Sharing

This is the end-of-cycle (EOC) power sharing of an assembly. The power sharing for a given assembly is the ratio of that assembly's power (e.g., in MegaWatts) to the average assembly power in the core at end of cycle. It is sometimes difficult for some users to obtain the end of cycle power sharing, and so the cycle average power sharing is used as an approximation. Sensitivity analyses may be used to bound the effects of this approximation.

Reactive Silica

Reactive silica is the amorphous silica dissolved in water. It is referred to as reactive because it reacts readily with reagents for a relatively easy concentration determination by pool chemistry. *Reactive silica* has an *equilibrium concentration*, above which no further *silica* will dissolve into the water. However, *reactive silica* can polymerize and form colloids (see *polymerized silica*). Thus, in practice, equilibrium is never reached and silica dissolution can continue indefinitely.

Scenario

The filename associated with data files, *state point files*, and *pool state files* in RACKLIFE a *scenario* name. Essentially, each spent fuel *pool* you simulate will have a different *scenario* name. For flexibility, you could also do "what if?" types of simulations under different scenario names.

Sensitivity Analyses

It is not unusual to have less data to input to RACKLIFE than one would wish. For example, as discussed under "Power Sharing", the cycle average power sharing is sometimes used as an approximation to the end of cycle power sharing. As another example, sometimes the annual average spent fuel pool temperature is used instead of periodic (e.g., monthly, weekly) data. The effects of these approximations, as well as the effects of uncertainty in the data that is available, can be bounded by sensitivity analyses.

Silica

Silica is a combination of silicon and oxygen atoms. See glossary terms *amorphous silica* and *crystalline silica* for chemistry information; see glossary terms *reactive silica* and *polymerized silica* for measurement and RACKLIFE prediction information.

State Point

This is the state of the pool and *Boraflex* panels at a single point in time. The state variables include the *reactive silica* levels, panel *dose* levels, *boron carbide* loss, among others. RACKLIFE saves these state variables in a *state point file*.

State Point File

When it is desirable to know the state of the entire pool -- the *reactive silica* levels, panel *dose* levels, *boron carbide* loss, etc. -- for every *panel* and the pool as a whole, RACKLIFE produces a *state point file*. This file contains a snapshot of the state of the pool and *Boraflex* panels at a single point in time. In simulating a spent fuel pool, the first *state point file* would give conditions just as the *Boraflex* was put in service. The panels would be unirradiated and at as-built quantities of *boron carbide*. This would serve as the *initial conditions* for computing a subsequent state point in the future. For example, subsequent state points could be computed at the time of each refueling outage, just before another batch of spent fuel is moved into the spent fuel pool. In simulating a typical reactor lifetime of 40 years, then, you may only generate about 20 to 40 state point files.

Surveillance Coupon

A surveillance coupon is an as-built *Boraflex* coupon provided for monitoring the state of the *Boraflex* in the pool. These coupons are contained in *Boraflex* test assemblies, which are placed in the spent fuel pool racks. Sometimes two assemblies are used: one for accelerated coupons that are placed next to freshly discharged fuel every cycle so that they lead the *Boraflex* in the pool; and a second to keep pace with the actual exposure of the *Boraflex* in the pool. A selection of coupons is periodically removed for testing.

Total Silica

The sum of *reactive silica* and *polymerized silica* is referred to as *total silica*. Concentrations of *reactive silica* are relatively easy to measure, while *total silica* is quite difficult. The amount of *total silica* in the pool would be a good indicator for the amount of *amorphous silica* lost on average from all of the panels were it not for the effect of cleanup systems, letdowns and makeups, and mixing with the reactor water during refueling operations. These systems and operations generally remove *silica* from the pool water.

2

A SCHEDULE FOR USING RACKLIFE

2.0 A Schedule for Using RACKLIFE

Do you want to know how often to collect RACKLIFE input data

Yes: go to Section 2.1

Do you want to know when to enter data into RACKLIFE and run it?

Yes: go to Section 2.2

2.1 RACKLIFE Input Data that Evolves Over Time

The following table summarizes the frequency at which data input to RACKLIFE will evolve over time. It can be used for guidance on how often a user may interact with RACKLIFE. The forms of the data are discussed in Section 1.3 of the *RACKLIFE Version 1.10 User's Manual*.

Frequency	RACKLIFE Data File	RACKLIFE Data File Extension
Daily to Quarterly	Pool History Data	HIS
Occasional to Once	Cleanup System Data	CLE
Outage, or more often	Assembly Move Data	MOV
Outage	Assembly Data	ASB
Outage	Cycle Data	Rnn
Outage, or less often	Escape Coefficient Data	ESC
Rerack	Pool Geometry Data	GEO
Once	Reactor Data	Rnn

2.1.1 HIS: Pool History Data

CONCLUSIONS

1. Tracking reactive silica data at least quarterly will alert users to any significant changes in Boraflex dissolution. This tracking does not have to be performed in RACKLIFE; almost any spreadsheet will do.

2. Reactive silica data is most useful if available at least monthly. Weekly silica data does not significantly improve tuning the escape coefficient unless there is less than four years of data available.

3. Temperature data is important only to establish trends (e.g., seasonal variation, outage transients), if any. These trends can be averaged and projected back in time for years when data may be difficult to obtain. Monthly temperature data will improve the accuracy of the model; more often than that provides little improvement except for resolving transients (e.g., temperature excursions during outages).

4. The spent fuel pool pH typically exhibits little variance, so only enough data to establish its average value and small variance is necessary. Monthly or quarterly data is usually sufficient to do this.

5. Polymerized/colloidal silica is generally not worth obtaining.

DISCUSSION

The pool history data includes the following:

- pool reactive silica concentration, in ppm
- pool polymerized/colloidal silica concentration, in ppm
- bulk pool temperature, in degrees F
- bulk pool pH

Each plant's pool chemistry department measures these at their own frequency. Usually all of this data is measured at least weekly, though monthly reactive silica measurements are not uncommon and some measure silica only quarterly. Typically the most recent data is available on-line, but historical data may be very difficult to walk down. Of this data, the pool reactive silica concentration is of the most importance, followed by temperature and then pH. Measuring polymerized/colloidal silica is difficult to do accurately and so the test is seldom if ever performed at most plants.

The reactive silica data is important for visually tuning the escape coefficient. Thus the more data available the easier and more accurate this process will be. Monthly data is generally sufficient when more than four years of data is available. Quarterly data is difficult to work with because discontinuous events such as an outage, a cleanup system change, a letdown/makeup event, or a temperature transient will often not be noticed.

The temperature data is important only if the spent fuel pool temperature fluctuates significantly even for a short period of time, or moderately for an extended period of time. Many plants observe moderate seasonal variations in pool temperature which should be accounted for in the RACKLIFE model since they persist for on the order of months. At some plants spent fuel discharges during outages will significantly increase pool temperatures; these should also be accounted for because of the large temperature difference, even though they generally persist for only a few weeks. It is not unusual to lack historical temperature data. If this is the case, the user can apply current temperature trends backward in time; for example, assume that the seasonal variation averaged over the last few years cycled similarly for all time. Alternatively, the user can perform a sensitivity analysis to determine how important it may be to try to obtain this data.

The pH data generally varies little with time. Thus only a few historical values need to be known to confirm its small variance.

The total silica data is almost impossible to obtain and is of limited value to anyone but the most experienced of RACKLIFE users. It is generally not worth obtaining, if it is even available.

2.1.2 CLE: Cleanup System Data

CONCLUSIONS

1. Cleanup systems that are “always on” can be started when the Boraflex was installed and “stopped” on the convenient date of “3333-01-01”

2. Cleanup system outages (e.g., for backwashing, maintenance, etc.) that last less than a few days can be ignored.

3. Since pool silica levels will likely be tracked on a monthly or quarterly basis, silica transients should be classified as they are observed. When the user updates the model to run a state point simulation these transients can then be modeled with confidence as letdown or makeup events.

DISCUSSION

RACKLIFE simulates four types of cleanup systems: filters, demineralizers, combined powder filter/demineralizers, and reverse osmosis systems. Two other cleanup-like situations can also be simulated: letdown and makeup.

Filters, demineralizers, combined powder filter/demineralizers are generally operated continuously. Thus their operating efficiencies are entered once and the dates of operation range from when the Boraflex was installed in the pool to some date far in the future. A convenient date “far in the future” that RACKLIFE will not give a warning about is 3333-01-01. If a cleanup system is shutdown for a significant length of time (more than a few days) the pause should be modeled in RACKLIFE to maintain accuracy, particularly in tuning the escape coefficient. Sometimes filter/demineralizers are used intermittently. In these cases it is often better to track their operation by noting sharp drops in the pool silica measurements and then to model their effect as a letdown, discussed below.

Reverse osmosis cleanup systems are generally started and then used continuously until they are stopped. Thus these systems are easily modeled in RACKLIFE.

In a letdown event the RACKLIFE solution for reactive and polymerized silica concentrations is forced by the user to a specified value. This is usually the result of the user noticing a silica data transient and correlating it with an event. For example, during an outage, when spent fuel pool water may be allowed to mix with reactor water, the silica concentration in the pool water will fall. It is not important to a RACKLIFE simulation why the concentration fell, but it is important to model the fall. Since the user should be tracking pool silica anyway, the user should also note any transients as they occur and try to correlate them with plant operations. When the user updates the model to run a state point simulation, these letdown events can then be included.

Similar to letdowns, makeup events will also be observed by users when tracking pool silica data. These should be handled similarly to letdowns.

2.1.3 MOV: Assembly Move Data

CONCLUSIONS

1. Spent fuel assemblies offloaded from the core are usually the most important moves to track since they have the highest dose rate.

2. Moving an "old" (long cooling time) assembly out of the racks generally has little effect on the Boraflex dissolution rate.

DISCUSSION

The following types of moves are typically performed in spent fuel pools:

- partial or full core offloads to the pool

  these generally occur only during refueling outages between outage maintenance shutdowns can be treated as an outage
- movement of discharged fuel from its offload cell to a "permanent" cell

  these typically occur shortly after an outage
- movement within the pool, e.g., for maintenance operations

  these are usually rare but can happen at any time
- movement out of the racks

  only if cask storage options or alternate spent fuel pools are available

The most important of these moves are the offloads since assemblies offloaded from the core will have the least cooling time of any assemblies in the spent fuel pool, and thus will have the highest dose rate irradiating any adjacent Boraflex. Next are the movements from the discharge location to a permanent location, since these typically are performed shortly after an outage when the assemblies will still have a significant dose rate. The potential impact of movements within the pool must be evaluated on a case by case basis since moving "old" fuel is likely of no consequence, while recently discharged fuel may have an effect. Movement out of the racks is typically of negligible consequence since this fuel has generally had at least ten years of cooling time.

To gauge the importance of fuel moves in distributing the dose to Boraflex, consider the following approximate rule of thumb. (The rule is based on an assembly discharged approximately seven days after reactor shutdown using the LWRDose methodology.) The cumulative absorbed dose doubles with each successive time step row.

Relative Dose	Days	Weeks	Years
1	4	0.5	0.01
2	10	1.5	0.03
4	25	3.5	0.07
8	72	10	0.2
16	365	52	1
32	6575	940	18

For example, the dose from a spent fuel assembly absorbed by a Boraflex panel in the first four days after discharge is approximately half of the dose absorbed in the first ten days after discharge. The dose after 18 years is twice the dose after 1 year.

2.1.4 ASB: Assembly Data

CONCLUSIONS

1. Assembly data is best updated after assemblies are discharged from the reactor.

DISCUSSION

A typical assembly will appear in the assembly data file multiple times: once for each of the cycles it is depleted in. The end of cycle power sharing and the cumulative burnup of an assembly are generally only known with confidence after the cycle has finished. Thus it is best to wait for this data to become available from end of cycle core follow statepoint computations. Since the end of the cycle leads to an outage, a busy time, this update can be performed after the outage is complete.

2.1.5 Rnn: Reactor Cycle Data

CONCLUSIONS

1. Reactor cycle data is best updated after the end of the cycle.

DISCUSSION

Each reactor operating cycle must be defined by its rated power, shutdown date, and shutdown power profile. While the rated power is well known, the shutdown date and shutdown power profile will often vary from what is intended. Only when the cycle is finished can these be known with certainty. Since the end of the cycle leads to an outage, a busy time, this update can be performed after the outage is complete.

2.1.6 ESC: Escape Coefficient Data

CONCLUSIONS

1. Every time a state point simulation is executed, observe the predicted versus measured pool silica plot to determine if the escape coefficient needs further tuning.

DISCUSSION

Pools with small Boraflex degradation may observe a very small increase in the escape coefficient over time, but more likely will not. If it is noticed, it will likely be after a large number of operating cycles have passed. Pools with moderate to large degradation, however, will generally observe an increase in the escape coefficient over the course of a few cycles. This effect will manifest itself as follows. In a RACKLIFE simulation, the escape coefficient is assumed to be constant for the duration of a state point simulation. The user will tune the escape coefficient to match the pool silica data and then make projections. When the model is updated after the next cycle or two, however, it may be found that the projections so carefully tuned for the preceding cycles are now starting to under predict the actual measured pool silica. If this continues, the under prediction may become significant. The user may then need to revise the escape coefficient for those cycles and rerun the simulations. Sensitivity studies are important for quantifying the effect of under predicting the escape coefficient like this.

2.1.7 GEO: Pool Geometry Data

This data will be constant for the life of a given spent fuel pool unless rack modifications and/or additions are performed. Changes to the pool geometry data file to account for additions or modifications are best performed in consultation with RACKLIFE Technical Support. Thus the

RACKLIFE Technical Support team should be notified when plans for the modifications or additions are finalized so as to prepare to work with the user in updating the pool geometry file. The RACKLIFE Technical Support team should be contacted again after the work has been completed to help translate the final as-built dimensions into a revised pool geometry data file.

2.1.8 Rnn: Reactor Data

The reactor data are input only once when first building a RACKLIFE model and will never change again.

2.2 Recommendations for When to Update a RACKLIFE Model

The above conclusions and discussion leads to the following recommendations for updating a RACKLIFE model.

Spent fuel pool reactive silica data should be tracked at least quarterly to alert users to any significant changes in Boraflex dissolution. This tracking does not have to be performed in RACKLIFE.

There are three principle approaches to tracking Boraflex degradation:

2.2.1 Post-Outage Updates

After a refueling outage is completed, all RACKLIFE model data is updated. This includes all available pool chemistry data since the last update (HIS), any cleanup system activity since the last update (CLE), all fuel moves (particularly the offloads during the outage) (MOV); data on every assembly discharged from the reactor to the spent fuel pool (ASB), and reactor cycle data for the just completed cycle (Rnn). The actual condition of the Boraflex can then be simulated. Prior to drawing any conclusions from the simulation, the measured versus predicted pool silica plot should be examined to verify that the escape coefficient remains valid. Since conditions in the pool will likely vary little from this point to the next outage, projections to the next outage can be made. These projections will include the effects of the just discharged fuel.

2.2.2 Pre-Outage Updates

Prior to a refueling outage, all RACKLIFE model data is updated. This includes all available pool chemistry data since the last update (HIS), any cleanup system activity since the last update (CLE), and any fuel moves within or out of the pool (MOV). The condition of the Boraflex going into the outage can then be simulated. Prior to drawing any conclusions from the simulation, the measured versus predicted pool silica plot should be examined to verify that the escape coefficient remains valid. Knowing the current condition of the Boraflex will greatly enhance the user's ability to manage the placement of discharged spent fuel during the upcoming outage.

2.2.3 Pre- and Post-Outage Updates

Combining approaches 1 and 2 is the optimal approach to the long-term management of the spent fuel pool. First the discharge of fuel can be planned to meet operational objectives (sacrificial racks versus racks to be preserved). Second, the effects of the actual discharge can be projected forward to predict with confidence the state of the Boraflex going into the next outage.

3

RACKLIFE MODELING ISSUES

3.0 RACKLIFE Modeling Issues

This section covers a number of modeling issues that may come up during the creation or modification of a RACKLIFE model.

3.1 Rack Module Geometry Limitations

RACKLIFE is limited to modeling only rectangular rack modules. Thus the code can not model L-shaped, U-shaped, or irregular boundary racks (such as those designed to fit next to a curved wall). This type of rack module can be handled by defining the module to be a rectangle which encompasses the actual rack, and then deleting the Boraflex panels from those cells that do not actually exist. There are only two drawbacks to this approach. First, when RACKLIFE is queried about the number of cells in the spent fuel pool, it will include these non-existent cells in its total; however, the number of rack modules and Boraflex panels will be reported correctly. Second, the user must take care to avoid mistakenly placing assemblies in the non-existent cells. This can be easily checked by the RACKLIFE user from the MOV file grid editor in RACKLIFE, per the User's Manual.

Another approach is to divide the module into a series of adjacent rectangles and declare each a separate module. This approach can be made to work in RACKLIFE even though the modules would appear to overlap. However, this is a very complicated and time consuming task that is best done in consultation with RACKLIFE Technical Support; it is not recommended if it can be avoided.

3.2 Tuning Cleanup System Efficiencies

Cleanup systems can represent a source of uncertainty in a RACKLIFE model. For example, demineralizers at PWRs are optimized to not remove the boron as boric acid dissolved in the spent fuel pool water. Because the selectivity (the affinity of an ion to be removed by the demineralizer resins) of silicic acid is comparable to that for boric acid, it is possible that the removal of silica from the pool water is negligible. However, studies at some plants have shown that there may be some removal of reactive silica, and that the rate of removal can affect RACKLIFE predictions. This rate of removal is likely specific to the type of resin used in a given demineralizer. Since there is no analytical model for this rate of removal (which is the efficiency of the demineralizer for removing reactive silica), the efficiency is thus another degree of freedom beyond the escape coefficient for matching the RACKLIFE predicted pool silica to what is measured in the pool. The recommended default in RACKLIFE is to set the demineralizer's reactive silica removal efficiency to 0.5%, but "best fit" models of various plants have ranged from 0% to 1%. Similarly, the efficiency of other types of cleanup systems can be considered a tuning parameter if the efficiency is not known.

3.3 Modeling Letdowns

Another component of the cleanup system data is not necessarily a cleanup activity: "letdowns" model reductions in pool silica that are not accounted for by the kinetics models in RACKLIFE. For example, fuel transfer operations during an outage mix higher silica concentration spent fuel pool water with the relatively clean reactor water. The reactor water cleanup systems then remove some of this silica, permanently removing it from the system. RACKLIFE does not contain a mixing mass transfer model to simulate this effect, but the physics of how the silica is removed is not important. What is important is that the reduction in reactive silica in the pool water volume is accounted for, and this is easily accomplished using a letdown in RACKLIFE. A letdown forces the RACKLIFE solution from its current value on a given date to a given value on the same or a later date. If the two dates are the same, an instantaneous drop is effected in the RACKLIFE predicted pool silica concentration. If the dates are different, RACKLIFE will linearly ramp the predicted concentration. The ramps can increase as well as decrease.

Typically letdowns are used to account for outage mixing and short-term cleanup activities. Sometimes the measured silica data contains decreases that can not be correlated with outage or cleanup activities. Using a letdown to account for these decreases is conservative since it removes silica from the system, thereby slightly increasing the silica release rate by lowering the silica concentration in the panel cavities via fluid exchange.

If letdowns are required to match measured pool silica data during outages, then letdowns should be used when using RACKLIFE to project into the future through anticipated outages. For these projections it is conservative to assume a letdown to zero reactive and zero polymerized silica. This will conservatively maximize the silica release rate.

3.4 Tuning the Escape Coefficient

In a typical RACKLIFE model development process, the escape coefficient is the only degree of freedom that is adjusted to make the RACKLIFE predicted pool reactive silica concentration match what was measured. However, it is not necessarily the only tuning parameter available. Tuning the escape coefficient has the greatest effect when trying to match the rate of silica release from the racks into the bulk pool. However, the shape of the predicted pool silica curve can be strongly influenced by the following tunable parameters:

1. The magnitude of escape coefficient growth with time.

This phenomenon has been observed in some models of spent fuel pools that have experienced higher rates of dissolution. As the Boraflex dissolves, the panel cavity volume increases. In particular, it increases most around areas of local dissolution such as scallops along panel edges, areas of dissolution around gaps, and paths of higher flow across the face or up the edge of a panel. This reduces the skin friction along these flow paths, allowing more flow along these dissolved areas. This locally increases the escape coefficient, which further increases local dissolution, giving rise to a positive feedback loop.

This effect generally manifests itself by the user observing that measured silica data is rising significantly more rapidly than predictions in the current cycle despite a good match of the data in the previous cycles with a well-tuned escape coefficient. The easiest way to handle this is to run a state point simulation to the transition point (usually the end of an outage), load a different escape coefficient data file (ESC), and run a subsequent state point simulation. By selecting the option to prepend the pool state file from the initial conditions all of the historical silica data can still be observed at the end of the run to gauge the overall effect of the increased coefficient.

2. The ratio of the escape coefficients between regions in multiregion racks.

PWRs often have Region 1 (fresh fuel) and Region 2 (depleted fuel) racks. The different designs can lead to different escape coefficients. The ratio of the escape coefficients is generally not tunable to the pool silica data. Instead, the ratio is tuned so that RACKLIFE predicted losses in each region match as closely as possible the losses observed in testing such as BADGER testing.

3. The efficiency of any cleanup systems

This is discussed in Section 3.2 above.

4. Two dose models are available for simulating the dose absorbed by Boraflex from spent fuel.

As discussed in Section 1.5, RACKLIFE can use either the LWRDose Methodology or the Cooling Time Corrected Methodology to simulate the dose absorbed by Boraflex from the decay of spent fuel. The LWRDose model is based on calculations of spent fuel isotopics and fuel/rack shielding. The cooling-time-correction to the LWRDose model is based on theoretical uncertainties in the development of the LWRDose model and comparison with experimental results. The Verification and Validation report for RACKLIFE shows that the most accurate model is somewhere between these two models. It is thus advisable to independently tune the escape coefficient to both models and observe which matches the data best.

The above four degrees of freedom can be adjusted iteratively over an extensive series of RACKLIFE simulations to best match the RACKLIFE predictions to pool chemistry reactive silica data as well as any panel loss targets from BADGER testing. The result will be a well tuned model to the extent that all other data needed by RACKLIFE (e.g., pool temperature, assembly power sharing, etc.) is available.

Pool silica data is matched by visually matching the general rate of increase in pool reactive silica concentration. It is not so important that the prediction and the data match exactly, but that the two are reasonably close and the trend is as close as possible. As discussed in Section 3.3, letdowns should be adjusted to reasonably match the data and to facilitate the visual comparison of rates.

3.5 Useful Information to Include in the Scenario Comments

Prior to executing a state point calculation, the user is given the opportunity to enter some comments. The following items are not easily found or are impossible to determine from an already run state point calculation and so are candidates to include in these comments.

1. The state point file being used as initial conditions for the simulation about to be executed.

2. The input data files used in the calculations. For example, there may be multiple pool history (HIS) files that are being used for sensitivity studies. RACKLIFE does not record which of these was used to run a particular state point.

3. The dose methodology selected: LWRDose or cooling-time-corrected.

4. Any descriptive comments that will remind future users why this state point was run and what its results can be used for.

4

USING RACKLIFE LOSS RESULTS

4.0 Using RACKLIFE Loss Results

Do you want guidance on using RACKLIFE for design basis criticality safety?

Yes: go to Section 4.1

Do you want to try to relate surveillance coupon analyses to RACKLIFE results?

Yes: go to Section 4.2

4.1 Guidance on Design Basis Criticality Safety

Section 1.2.4 of this document, "What Can You Do With the Results?", listed five principle applications of RACKLIFE:

1. Plan a BADGER campaign
2. Corroborate BADGER measurements
3. Estimate global dissolution B_4C losses
4. Make projections
5. Manage the movement of spent fuel in the pool

Collectively, these applications can be used to give guidance on:

- extending the life of the existing racks to meet current design basis analyses,
- deciding when the criticality safety analysis may need to be revised to account for continuing degradation, and
- deciding if and when a partial or full rerack may be advisable or necessary.

Insuring the design basis of the racks with respect to criticality safety is a safety-related issue. However, when the RACKLIFE computer code was designed and rapidly developed (see Section 1.2.3) it was not intended to be a safety-related application. Typically RACKLIFE is used in conjunction with a direct measurement of a sample of Boraflex panels in the racks (e.g., BADGER testing) to verify that the racks continue to meet their design basis. The following two sections make the case for why RACKLIFE should not be used alone for a formal criticality safety analysis.

4.1.1 Modes of Boraflex Degradation

Boraflex panel degradation can be divided into three modes which are characterized by different degradation mechanisms, as described below.

1. Shrinkage, including gaps

Radiation-induced shrinkage reduces the volume of a Boraflex panel; however, shrinkage does not reduce the mass of interposing absorber – that is, the material undergoes densification as it shrinks. If a Boraflex panel is not allowed to shrink uniformly (e.g., it is mechanically restrained), gaps will develop.

2. Uniform dissolution

The exchange of fluid between the bulk pool and each panel cavity (measured by the escape coefficient) results in a flow across the surfaces of each Boraflex panel. This can lead to a relatively uniform dissolution of the amorphous silica from Boraflex panel surfaces and consequent loss of absorber.

3. Local dissolution

The dissolution described as mode 2, above, is relatively uniform. However, local non-uniformities in the panel, panel cavity, and cavity inlet/outlet geometry can accentuate dissolution locally. For example, a gap in a panel locally increases the cavity volume, which locally reduces the effects of wall friction, and thereby increases the local flow rate that causes degradation. As another example, a bend, bow, or crease in a cover plate can create an orifice allowing increased flow into or out of the panel cavity, thereby increasing local degradation. These local effects can exhibit a positive feedback: they accelerate the local dissolution of Boraflex, which decreases the local volume of Boraflex, which increases the local cavity volume, which decreases wall friction losses, which increases local flow rates, which further accelerates local Boraflex dissolution.

Each of the three modes of degradation will affect the spent fuel pool reactivity differently. The synergistic reactivity effects may be strongly non-linear. Criticality safety calculations using highly bounding assumptions (e.g., very large gaps all at the assembly mid-plane, complete dissolution of the Boraflex, etc.) lead to reactivity increases far in excess of the actual reactivity state of the spent fuel pool. On the other hand, the non-linear synergy necessitates a robust analysis of the degradation if one desires to (conservatively) take some credit for the Boraflex that remains in the racks.

4.1.2 RACKLIFE Predictions of Boraflex Degradation

When RACKLIFE predicts Boraflex panel degradation, it does not distinguish between the three loss modes described in the previous section. Effectively, RACKLIFE treats all losses as uniform dissolution from the face of the Boraflex panel, resulting in a uniform thinning. This simplified interpretation of loss should not be used in developing a criticality safety analysis, however. The following results from a recent criticality safety analysis should make this clear.

Consider a model of an infinitely repeated array of rack cells and their associated panels. Each panel in the array is unique in its distribution of shrinkage, uniform dissolution, and local dissolution. The distribution of total panel loss in the array is characterized by

> 20.8% ± 2.5% uniform thinning loss, plus various gaps and local dissolution.

Next a model was developed where the panels had the identical distribution of gaps and local dissolution, but the uniform thinning of the panels was made constant. This uniform thinning was adjusted until the reactivity (k_{eff}) of the model was identical to the previous one. The result was

> 21.6% uniform thinning loss (plus the same gaps and local dissolution).

If there were no synergistic reactivity effects between shrinkage, uniform dissolution, and local dissolution, the constant uniform thinning that gave an equivalent reactivity would be expected to be the mean value of 20.8%.

Finally, a model was developed where all of the gaps and local dissolution features were removed so that every panel was identical. Again the constant uniform thinning of the panels was adjusted until the reactivity of the model was identical to the previous two. The result was

> 44% uniform thinning loss.

This clearly indicates a strong reactivity effect synergy between the modes of degradation. RACKLIFE predictions of 20.8% ± 2.5% loss in these panels, if translated into a criticality safety analysis as uniform thinning, would greatly underestimate the actual equivalent-reactivity uniform thinning of 44% for these particular racks. Even at three sigma the uniform thinning would be set to only 28.3%.

The conclusion is that RACKLIFE results for B_4C loss should not be used in a criticality safety analysis without a clear understanding of how that loss manifests itself in a particular rack. Once this is understood, however, RACKLIFE is a powerful tool for predicting loss, managing the pool, and deciding when an updated criticality safety analysis is warranted.

4.2 Relating Surveillance Coupon Analyses to RACKLIFE

In addition to direct (e.g., BADGER) measurements of the Boraflex panels, RACKLIFE results can also be compared with any other available data, such as surveillance coupon test results. At many plants the surveillance coupons are of limited value in this regard because they do not have the same geometry characteristics of the panels. This means that the escape coefficient of the coupons may be substantially different from the rack panel cavities, so the dissolution of the coupons proceeds at a different rate from the rack panels. Further, the proportions of each mode of degradation are likely significantly different between the coupons and the panels. Regardless of how well the coupon geometry matches the racks, shrinkage degradation, including gapping, can often be strongly correlated between coupons and panels with similar doses.

For those plants with coupons that do closely correspond to the racks, the loss from the coupons can be compared to RACKLIFE loss estimates. Further, the proportion of each mode of degradation might be identifiable. Care should be exercised in drawing conclusions for a formal criticality safety analysis, however. It is recommended that direct panel measurements (such as BADGER testing) be used for this purpose.

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